

AIR AND GAS DUCT STRUCTURAL DESIGN COMMITTEE OF THE
ENERGY DIVISION OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS

James S. Whitcraft

1801 ALEXANDER BELL DRIVE
RESTON, VIRGINIA 20191-4400

ABSTRACT

This document, The Structural Design of Air & Gas Ducts for Power Stations & Industrial Boiler Applications, has been created to assist structural engineers when performing the structural analysis and design of ductwork. Air and gas ducts for fossil fuel power stations and industrial boiler applications are unique structures. Considering that ductwork structural analysis and design is not currently referenced or governed by any national code or design standard, this publication presents the structural engineer with current approaches for the structural analysis and design of air and flue-gas ductwork. Included are sections on: 1) Material selection, behavior and performance; 2) design loads, loading combinations and allowable stresses; 3) thermal considerations; 4) vibration considerations; 5) structural arrangement and behavior; 6) toggle duct behavior and expansion joint considerations; 7) overall duct structural analysis and design methods; and 8) design considerations for local elements of the structure, such as stiffeners, internal braces, connections, turning vanes, and other flow distribution devices. This document also discusses drawing and specification content, fabrication and construction techniques and considerations, duct support methods, and special considerations regarding the design of duct support structures. Finally, it talks about field maintenance examinations and inspections for the purpose of preventative maintenance or condition assessment.

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PREFACE

This ASCE Special Publication has been created by a select committee of structural and mechanical engineers who are extremely experienced in the structural analysis and design of air and flue-gas ductwork for power stations and large industrial boiler applications.

The need for this document was identified in 1991 by the ASCE Fossil Power Committee under the chairmanship of Thomas Longlais. Tom obtained the authorization of the ASCE through the Energy Division to create the Task Committee assigned to produce this Special Publication. Subsequently, the ASCE Task Committee on the Structural Design of Air & Gas Ducts was created late in 1991 under my chairmanship. My first, and most important task, was to form a working committee of qualified individuals from various sectors of the power and boiler industries. I believed that the best committee would consist of representatives from all facets of the ductwork industry: owners, consulting engineers, equipment suppliers and duct suppliers. I tried to recruit individuals from these types of representative major companies that perform the structural analysis and design of ducts. The committee started out in January of 1992 with about 25 members, but gradually shrunk to a working group of 19. All of these individuals put a considerable amount of work into this effort and I thank them all.

Air & Gas Duct Structural Design Committee

Ron Schneider	*	Gilbert/Commonwealth Engineers
Dan Blackwood		Southern Company Services
Vic Bochicchio		Zurn Balcke-Durr, Inc.
Bob Bucelwicz		Boston Edison Co.
Joe Clark	*	ABB Combustion Engineering Systems
Roy Hogan	*	ABB Environmental Systems
Bill Jacks		Tennessee Valley Authority
Ron Johnson	*	Babcock & Wilcox
Paul Kokosinski	*	Public Service Electric & Gas
Tim Laughlin	*	Sargent & Lundy Engineers
Tom Longlais		Sargent & Lundy Engineers
Jim Newell		Stone & Webster Engineering Corp.
Rod Simonetti	*	Gilbert/Commonwealth Engineers
Mike Stieffermann	*	Central Electric Company
Ken Tamms		American Electric Power
Walt Van Dyke	*	Foster Wheeler Energy Corp.
Ray Warren	*	Warren Engineering
Heim Weinstein		Public Service Electric & Gas
Jim Whitcraft	*	Bechtel Power Corp.

The most significant and time consuming contributions were made by the individuals who actually authored the various sections of this ASCE Special Publication. These individuals are noted on the previous page with an asterisk after their name. They all deserve a special thanks for their commitment and hard work.

In addition, many of the task committee members obtained important help from other engineers and designers within their organizations. I give my thanks to all of them. Some of the more significant contributors to the success of this ASCE Special Publication were: Daniel Biss, David Wagner, Timothy Frymoyer, and Kenneth Bauer from Gilbert/Commonwealth and Edward Hanko from Sargent & Lundy.

Ronald L. Schneider
ASCE Member
June 1995

American Society of Civil Engineers Special Publication

The Structural Design of Air & Gas Ducts for Power Stations & Industrial Boiler Applications

CONTENTS

	<u>Page</u>
1 INTRODUCTION	1
1.1 Statement of Intent and Expected Use of this Document	3
1.2 Limitations and Scope of this Document	5
1.3 Ductwork Systems Descriptions	7
1.4 Glossary/Definitions	17
1.5 Descriptions of Major Ductwork Equipment	26
1.6 Descriptions of Ductwork Accessories	30
2 DUCTWORK ARRANGEMENT AND BEHAVIOR	33
2.1 Overview	35
2.2 Interfaces with Equipment	37
2.3 Thermal Expansion	45
2.4 Supports	54
2.5 Duct Geometries	66
2.6 Internal Trusses and Struts	70
2.7 Effects of the Arrangement on Loads	74
3 STRUCTURAL MATERIAL - SELECTION, APPLICATIONS AND PROPERTIES	81
3.1 Introduction	83
3.2 Availability of Materials	83
3.3 Material Properties	84
3.4 Material Selection	92
3.5 Bolts	95
3.6 Welding Electrodes	95
3.7 Ductwork Protection	96
3.8 Hanger Elements	99

STRUCTURAL DESIGN OF AIR & GAS DUCTS

4	SERVICE CONDITIONS AND DESIGN LOADS	<u>Page</u> 101
4.1	Service Conditions	103
4.2	Design Loads	109
5	LOADING COMBINATIONS AND ASSOCIATED DESIGN STRESSES	119
5.1	Design Stress Considerations	121
5.2	Recommended Analysis and Design Approach	124
5.3	Load Definitions and Considerations	124
5.4	Loading Combinations	125
6	PLATE DESIGN AND STIFFENER LOCATION CONSIDERATIONS	129
6.1	Introduction	131
6.2	Rectangular Duct Plate Design	132
6.3	Plate and Stiffener Composite Action	140
6.4	Circular Ductwork Plate Design	142
6.5	Other Considerations	145
7	DUCTWORK GLOBAL STRUCTURAL ANALYSIS	149
7.1	Introduction	151
7.2	Global Approach	152
7.3	Structural Model Considerations	159
8	STRUCTURAL ELEMENT DESIGN	171
8.1	General Considerations	173
8.2	Rectangular Ducts	174
8.3	Internal Trusses and Struts for Rectangular Ducts	185
8.4	Circular Ducts	193
8.5	Lateral External Tie Elements	197
9	STRUCTURAL DESIGN OF FLOW DISTRIBUTION DEVICES	199
9.1	Function of Flow Distribution Devices	201
9.2	Flow Layout and Structural Considerations	203
9.3	Support Considerations	205
9.4	Structural Analysis	205
9.5	Structural Design	210

10	DRAWING, FABRICATION AND CONSTRUCTION TECHNIQUES AND CONSIDERATIONS	<u>Page</u> 213
10.1	General Considerations	215
10.2	Drawings and Specifications	223
10.3	Fabrication	228
10.4	Welding	230
10.5	Shop Inspection	233
10.6	Surface Preparation	234
10.7	Handling and Shipping	235
10.8	Erection	238
11	INSULATION AND LAGGING	241
11.1	Introduction	243
11.2	Purpose of Insulation and Lagging	243
11.3	Types of Insulation and Lagging	245
11.4	Affects of Insulation and Lagging on the Structural Design of Ducts	247
11.5	Methods of Installation and Quality of the Work	249
11.6	Construction Details	253
12	MAINTENANCE EXAMINATION OF EXISTING DUCT SYSTEMS	259
12.1	Factors that Influence the Need for Structural Examinations ..	261
12.2	Field Examination Techniques	265
12.3	Potential Damage Areas	273
12.4	Examination Data, Evaluation and Disposition	278
	APPENDIX I - REFERENCES	283
	INDEX	289

STRUCTURAL DESIGN OF AIR & GAS DUCTS

LIST OF FIGURES

	<u>Page</u>
Figure 1.1 Typical Pressurized System Ductwork Arrangement for a Coal-Fired Power Plant	9
Figure 1.2 Typical Balanced Draft System Ductwork Arrangement for a Coal-Fired Power Plant	10
Figure 1.3 Typical Ductwork Arrangement for a Combined Cycle Power Plant	11
Figure 1.4 Typical Air Duct Arrangement for a Fluidized-Bed Boiler . . .	12
Figure 1.5 Typical Air Duct Arrangement for a Pulverized Coal-Fired Boiler	14
Figure 1.6 Typical Pressure Profile for a Coal-Fired Power Plant	16
Figure 1.7 Typical Toggle Duct Arrangement	18
Figure 2.1 Damper Types	40
Figure 2.2 Preferred Damper Location Relative to an Expansion Joint . .	41
Figure 2.3 Example of a Dead Leg Duct Section	42
Figure 2.4 Example of the Effect of Expansion Joint Placement on Loads	46
Figure 2.5 Typical Arrangement with a Toggle Duct Section	47
Figure 2.6 Typical Duct Anchor and Guide Arrangement	48
Figure 2.7 Locating the Anchor Point at the Center of Mass	49
Figure 2.8 Typical Guided Bottom Support Detail	50
Figure 2.9 Virtual Anchor Point	50
Figure 2.10 Typical Spherical Slide Bearing Plate Assembly	51
Figure 2.11 Initial Offset of Bottom Support to Reduce Eccentricity	53
Figure 2.12 Example of Support Steel Framing Which Allows Friction Forces to Cancel	55
Figure 2.13 Example of an Indeterminate Duct Section	57
Figure 2.14 Example of a Determinate Duct Section	59
Figure 2.15 Effect of Hanger Rotation	61
Figure 2.16 Example of the Proper Arrangement of Supports at Different Elevations	64
Figure 2.17 Typical Rectangular Duct Construction	67
Figure 2.18 Internal Truss at a Duct Branch	71
Figure 2.19 Internal Struct	72
Figure 2.20 Typical Flexible and Inflexible Truss Arrangements	73
Figure 3.1 Coefficient of Thermal Expansion Versus Temperature	85
Figure 3.2 Modulus of Elasticity Versus Temperature	86
Figure 3.3 Yield Strength Ratio Versus Temperature	86
Figure 3.4 Ultimate Strength Ratio Versus Temperature	88

STRUCTURAL DESIGN OF AIR & GAS DUCTS

LIST OF FIGURES (cont.)

	<u>Page</u>
Figure 4.1 Typical Locations of Ash Accumulation	112
Figure 4.2 Effect of Unbalanced Pressure Forces on Ductwork and Its External Supports	116
Figure 6.1 Example of Poor Duct Support Arrangements	133
Figure 6.2 Sample Rectangular Duct Stiffener Framing	135
Figure 6.3 Large Deflection Theory Behavior	136
Figure 6.4 Example of Circular Duct Loading Considerations	144
Figure 7.1 Typical Path for Dead Load	154
Figure 7.2 Typical Path for Wind Load	155
Figure 7.3 Typical External Support Structure	156
Figure 7.4 Typical Support Model	159
Figure 7.5 Effective Area Considered for Duct Stiffness	160
Figure 7.6 Equivalent Wind Load for Model Analysis	163
Figure 8.1 Stiffener Composite Section	175
Figure 8.2 Typical Stiffener to Plate Connections	176
Figure 8.3 Example Stiffener Arrangement	178
Figure 8.4 Typical Stiffener Loading Conditions	179
Figure 8.5 Example of a Stiffener Stress Profile Calculation Sheet	181
Figure 8.6 Duct to Hopper Interface	182
Figure 8.7 Examples of Stiffener Connections	185
Figure 8.8 Typical Truss Connection	186
Figure 8.9 Typical Hanger Rod Support Arrangements	192
Figure 8.10 Typical Bottom Support Arrangements	193
Figure 8.11 Local Stresses in Circular Rings	194
Figure 8.12 Typical Circular Duct Support Hanger Arrangements	195
Figure 8.13 Typical Bottom Supported Circular Duct Arrangement	195
Figure 8.14 Typical Circular Duct Saddle Support	196
Figure 9.1 Typical Flow Distribution Device Configurations	202
Figure 9.2 Dynamic Thrust on Turning Vanes	208
Figure 10.1 Common Shipping Trailer Dimensions	218
Figure 10.2 Typical Rail Shipping Widths	219
Figure 10.3 Typical Field Splices for Ducts	222
Figure 10.4 Duct Cross Section Bowing Tolerance	230
Figure 10.5 Typical Temporary Bracing Schemes	237

LIST OF FIGURES (cont.)

	<u>Page</u>
Figure 11.1 Typical External Insulation Attached to the Duct Plate	250
Figure 11.2 Typical External Insulation Attached to Duct Stiffeners	251
Figure 11.3 Typical Internal Insulation Details	252
Figure 11.4 Typical Insulation Detail at Expansion Joints	254
Figure 11.5 Alternate Insulation Detail at Expansion Joints	254
Figure 11.6 Typical Hopper Crotch Insulation Detail	255

LIST OF TABLES

	<u>Page</u>
Table 3.1 Typical Allowable Creep Stresses for Steels Common to Ductwork Applications	90
Table 4.1 Air and Gas Duct EXAMPLE Pressures and Temperatures for a Pressurizer Coal-Fired Power Plant	105
Table 4.2 Air and Gas Duct EXAMPLE Pressures and Temperatures for a Balanced Draft Coal-Fired Power Plant	106
Table 4.3 Air and Gas Duct EXAMPLE Pressures and Temperatures for Pressurized and Balanced Draft Industrial Boilers	107
Table 4.4 Flyash Density Ranges	112
Table 10.1 Shipping Cost Factors	216
Table 12.1 Structural Maintenance Examination - Equipment Checklist	267

SECTION 1

Introduction

	<u>Page</u>
1.1 STATEMENT OF INTENT AND EXPECTED USE OF THIS DOCUMENT.....	3
1.2 LIMITATIONS AND SCOPE OF THIS DOCUMENT	5
1.2.1 Limitations and Scope	5
1.2.2 Application of Building Codes and Design Codes	6
1.3 DUCTWORK SYSTEMS DESCRIPTIONS	7
1.3.1 Ductwork Systems	8
1.3.2 Air Ducts	11
1.3.3 Flue-Gas Ducts, or Flues	13
1.3.4 Typical Pressures and Temperatures	15
1.4 GLOSSARY/DEFINITIONS	17
1.4.1 Ductwork	17
1.4.2 Duct Supports	19
1.4.3 Duct Appurtenances	21
1.4.4 Duct Service Conditions	23
1.4.5 Duct Conveyances	25
1.5 DESCRIPTIONS OF MAJOR DUCTWORK EQUIPMENT	26
1.6 DESCRIPTIONS OF DUCTWORK ACCESSORIES	30

SECTION 1

Introduction

1.1 STATEMENT OF INTENT AND EXPECTED USE OF THIS DOCUMENT

This American Society of Civil Engineers Special Publication has been created to assist structural engineers when performing the structural analysis and design of air and flue-gas ducts for power stations and industrial boiler applications. It is not intended to be used to size or configure ductwork for flow and pressure drop considerations.

The information presented in this Special Publication was written specifically for structural engineers. The ASCE committee responsible for creating this document highly recommends that the structural analysis and design of ducts be performed by qualified structural engineers, not by technicians, designers or drafters.

The structural engineer is cautioned against using the information in any section of this Special Publication without first reading and understanding the entire document. There is information in the later sections that are important when performing the ductwork structural analysis and design. The structural engineer should not read selected sections as the design progresses. Much of the information presented in each section is very dependent on information in other sections. The structural engineer should read all of the information presented here in Sections 1 through 12 and understand how it is all interrelated before proceeding with analysis and design activities.

Air and gas ducts for fossil fuel power stations and industrial boiler applications are unique structures. The structural analysis and design of these ducts is currently not referenced or governed by any national code or design standard, and little published data on ductwork structural analysis and design procedures is available. Ductwork structural analysis and design is complicated by the need to accommodate large thermal

movements and the need to assess the behavior of the materials at high temperatures, sometimes in a corrosive environment. The structural behavior of steel ductwork can be difficult to understand for structural engineers inexperienced in ductwork analysis and design. Usually, ductwork is initially routed and configured considering only flow and pressure drop requirements. However, the final arrangement must also consider structural support and structural behavior. In some organizations, ductwork design responsibility is divided between the mechanical process engineering and structural engineering disciplines. Quite often, problems that arise can be attributed to the failure to clearly assign and accept responsibilities between the disciplines. Communication between the disciplines and establishment of clear areas of responsibility is vital to ensure a successful ductwork installation.

As flue-gas emission requirements became more stringent over the years and precipitators or fabric filters and scrubbers became part of a boiler exhaust system, the ductwork arrangements have become more complex and the design pressures have increased in magnitude significantly. Retrofitting or modifying this equipment can result in a ductwork arrangement that is extremely complicated. If the experienced structural engineer is not permitted to have input into the ductwork arrangement, it is possible that a structural system could evolve that is prone to structural distress. Additionally, higher boiler outlet temperatures and more corrosive scrubber outlet gas chemistry have increased the importance of choosing the proper materials and the proper allowable design stresses. There is also a history within the power industry of failures and major degradation of flue-gas ductwork. There are many reasons for failures or degradation, but in many cases the problems may have been avoided by a better initial design.

This ASCE Special Publication presents current approaches for the structural analysis and design of air and flue-gas ductwork. Included are sections on material selection, behavior and performance; design loads, loading combinations and allowable stresses; thermal considerations; vibration considerations; structural arrangement and behavior; toggle duct behavior and expansion joint considerations; overall duct structural analysis and design methods; and design considerations for local elements of the structure, such as stiffeners, internal braces, connections, turning vanes, and other flow distribution devices. This document also discusses drawing and specification content, fabrication and construction techniques and considerations, duct support methods, and special considerations regarding the design of duct support structures. Finally, this document discusses field maintenance examinations and inspections for the purpose of preventative maintenance or condition assessment.

The information presented in this Special Publication may be used for international projects. However, the availability of materials overseas requires special attention from the structural engineer.

1.2 LIMITATIONS AND SCOPE OF THIS DOCUMENT

This ASCE Special Publication should be viewed differently than a design standard or code. It is broader in scope and does not necessarily endorse a single or specific design approach. With this Special Publication, the ASCE hopes to fill a void in the structural engineering field. This document is expected to be used as a guide for structural engineers as they participate in the routing and configuration of a ductwork system, including the ducts themselves and their support structures. This Special Publication is also expected to be a valuable tool for structural engineers in understanding the structural behavior of duct systems and in analyzing and designing the many structural components of a duct system.

1.2.1 Limitations and Scope

This ASCE Special Publication is intended to be used for the structural analysis and design of ductwork where the metal temperature is below 1,100°F (600°C). The user is also cautioned that additional criteria not addressed in this special publication may be appropriate for very specific ductwork applications where the gas environment is chemically extremely harsh. This Special Publication is intended to be used for the structural analysis and design of steel ductwork and is not necessarily applicable for ductwork made from any non-metal material, such as fiberglass reinforced plastic (FRP).

This Special Publication does not specifically address the structural analysis and design of flyash collection hoppers that are often part of ductwork systems. Hoppers are usually considered as material storage bins and their design requirements can be found elsewhere. However, this document discusses in various sections the interface of flyash collection hoppers with ductwork.

Quite often, the structural engineer must address the vibration of ductwork structural elements. This consideration is especially important in duct sections immediately upstream and downstream of large fans in the duct system. This document addresses the need to perform designs that consider vibration concerns, but generally it is the responsibility of the structural engineer to take the proper actions so that excessive vibration does not occur. Vibration of local structural elements is discussed in Sections 6, 8 and 9.

This ASCE Special Publication is not specifically intended to be used for the structural analysis and design of ductwork system equipment, such as those listed in Section 1.5. However, the structural engineer performing the structural analysis and design of this equipment has the discretionary choice to use any information presented in this document. The user is cautioned, however, to check the design of the equipment against any other applicable design requirements or codes that have been published by others. Specifically, the structural design of precipitators is presented by the Institute of Clean Air Companies (ICAC) in the document EP-8, *Structural Design Criteria for Electrostatic Precipitator Casings*.

This ASCE Special Publication is also not intended to be used for the structural analysis and design of stacks, chimneys or chimney liners. For the design of these structures, consult the following publications as appropriate: the American Society of Mechanical Engineers (ASME) publication STS-1-1992, *Steel Stacks*; the ASCE Task Committee on Steel Chimney Liners publication *Design and Construction of Steel Chimney Liners*; the American Concrete Institute publication ACI-307, *Standard Practice for the Design and Construction of Cast-in-Place Reinforced Concrete Chimneys*; the International Committee on Industrial Chimneys (CICIND) publications *Model Codes for Concrete Chimneys and Liners* and *Model Code for Steel Chimneys*; and the ASME publication RTP-1, *Reinforced Thermoset Plastic Corrosion Resistance Equipment*.

1.2.2 Application of Building Codes and Design Codes

This ASCE Special Publication is not to be interpreted as a design code for air and flue-gas ductwork, nor should it be interpreted to include all of the restrictions and requirements presented in the various national, state and local building codes and design codes, standards and specifications. It is the responsibility of the structural engineer to review and consider the applicable design requirements, if any, presented in the governing building codes in force for the location of the project. This includes local building codes, which may have more stringent requirements than state and federal codes.

Traditionally, structural engineers have used the provisions of the American Institute of Steel Construction's (AISC) *Specification for Structural Steel Buildings - Allowable Stress Design and Plastic Design (ASD)* presented in the *AISC Manual of Steel Construction - Allowable Stress Design (AISC-ASD)* when performing the structural design of air and flue-gas ductwork. Since the AISC-ASD Specification is intended to apply to conventional structures at

ambient temperatures, the design of structural steel considering the effects of high temperatures has always been left up to the judgement of the responsible structural engineer. This ASCE Special Publication anticipates the traditional use of the AISC-ASD Specification with adjustments and additional considerations for the high metal temperatures. This ASCE Special Publication presents ways to consider the behavior of the steel structures, such as ducts, when exposed to high temperatures, such as those seen when the structure is exposed to flue-gas.

This ASCE Special Publication has been prepared using United States Customary Units, or what has been commonly called Standard English Units (feet, pounds and °F). This is because, as explained above, this Special Publication is based on the expected use of the AISC-ASD Specification, which currently is not presented in metric units. There are also some empirical equations presented here which have relatively complicated constants that are based on United States Customary Units. Where applicable, metric and celsius units are presented in this Special Publication next to the english units in parenthesis.

1.3 DUCTWORK SYSTEMS DESCRIPTIONS

For the purpose of this document, ducts are defined as air tight conduits that convey air or flue-gas under positive or negative pressure. They may or may not be exposed to high temperatures. Ducts may be circular or rectangular in cross section, or sometimes they may be very unusual in shape as they transition into a piece of major equipment, such as a fan, precipitator or scrubber. To accommodate temperature changes, ducts are usually independent structures which "float" on slide bearing plates or are suspended by a hanger system. Ducts typically connect pieces of major equipment, but are not necessarily considered part of the equipment. The terms "ducts" and "ductwork" are usually used interchangeably. Ducts that convey flue-gas are also commonly called "flues" or "breechings".

Due to the ambiguity with the definition of the term ductwork, especially at the interface with major equipment, the user is responsible to define the term ductwork and to properly apply the information presented in this document. Ductwork should not be defined by contract supply scope alone. For example: ductwork attached to a precipitator's inlet flange and supplied by the precipitator manufacturer should be considered as ductwork and not as part of the precipitator, but chambers that convey gas internal to a fabric filter are normally considered as part of the fabric filter and not as ductwork.

1.3.1 Ductwork Systems

Conventional Boiler Plants

Usually, there are two possible types of ductwork systems which could exist in a conventional power plant or industrial boiler. The systems are called - **pressurized and balanced draft**. In a large fossil fuel power plant, there are usually two distinct yet identical parallel sides of the unit, each having its own duct system and set of identical equipment. For smaller power plants or industrial boilers there is usually only one duct system and one piece of each equipment.

A **pressurized system**, also called a forced draft system, has Forced Draft (FD) Fans upstream of the boiler which force air through the entire combustion system and eventually force the resulting flue-gas out to the atmosphere through the stack. Sometimes Primary Air (PA) Fans are also in the system. These fans and their purpose in the combustion system is discussed in detail in Section 1.3.2. A pressurized system results in positive pressures in all of the ducts. See Figure 1.1 for a sketch of a typical pressurized system for a coal-fired power plant. The PA Fans have been left off of this sketch for simplicity.

In a **balanced draft system**, a combination of FD fans and Induced Draft (ID) Fans are used. The FD fans are located upstream of the boiler and the ID fans are located between the boiler and the stack. As with a pressurized system, PA Fans may also be present in a balanced draft system. A balanced draft system results in positive pressures in the air ducts leading to the boiler and negative pressures in the flue-gas ducts between the boiler outlet and the ID fan inlet. The ductwork from the ID fan outlet to the stack is usually under a relatively small positive pressure. See Figure 1.2 for a sketch of a typical balanced draft system for a coal-fired power plant. The PA Fans have also been left off this sketch in order to keep it simple.

In any ductwork system there also may be various bypass ducts. Bypass ducts are used when the operators of the installation wish to, or must, shut off a major piece of equipment, such as an air preheater or a flue-gas desulfurization scrubber, on one or both sides of the unit. Bypass ducts are also used for reheat or tempering. In all of these cases, the operator is required to open and close various dampers to send the air or flue-gas through the bypass duct.

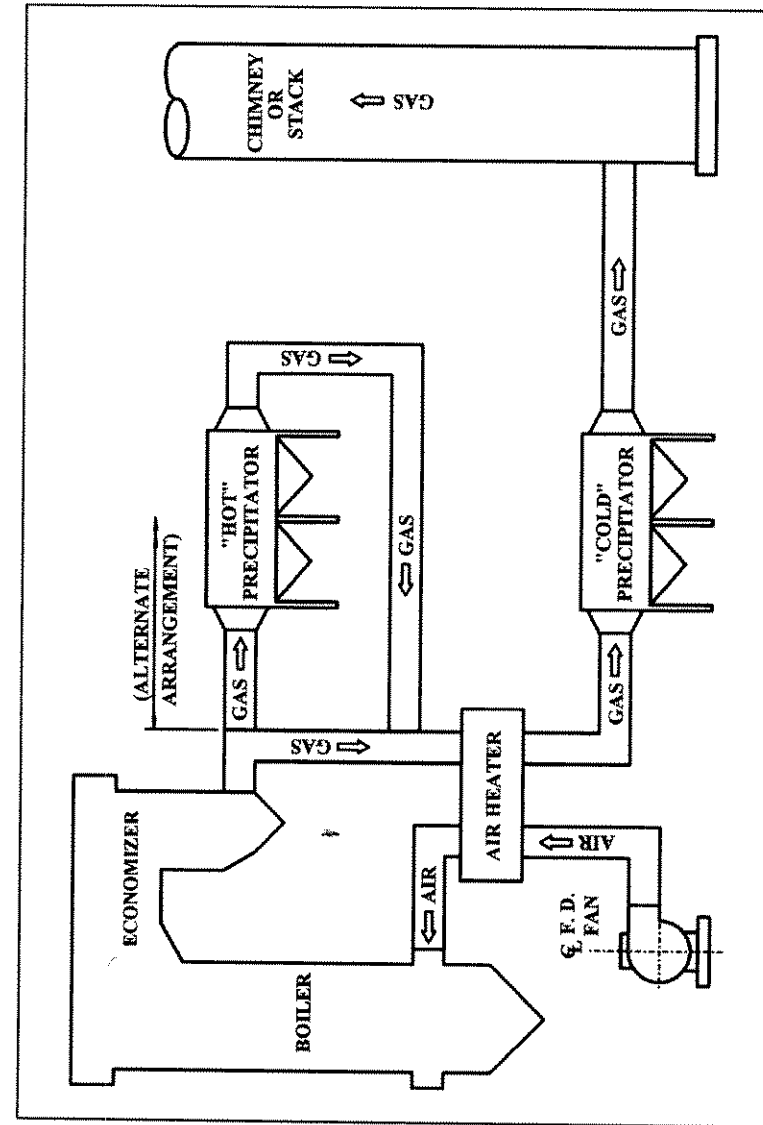


Figure 1.1
Typical Pressurized System
Ductwork Arrangement for a Coal-Fired Power Plant

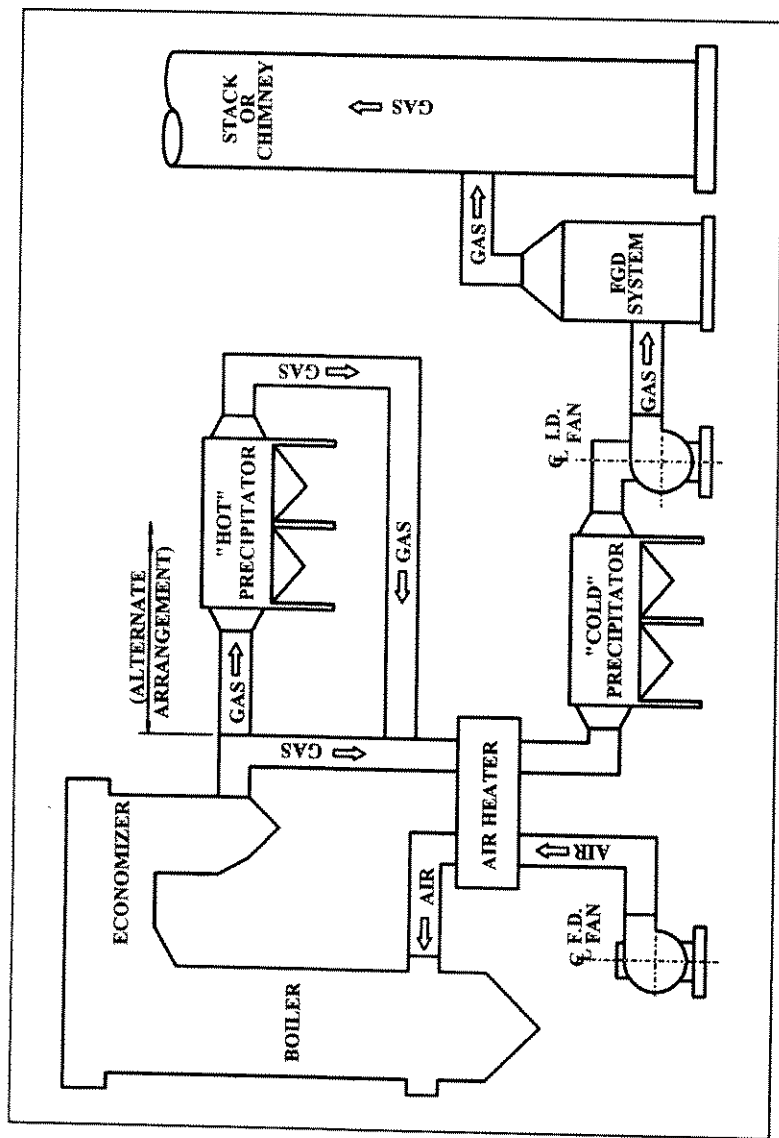


Figure 1.2
Typical Balanced Draft System
Ductwork Arrangement for a Coal-Fired Power Plant

Combustion Turbine or Combined Cycle Power Plants

The ductwork system in a combustion turbine or combined cycle power plant is very different and much simpler as compared to a conventional power plant. This is because these plants burn natural gas as a fuel and the exhaust flue-gas does not require clean-up. For a combined cycle power plant, as shown in Figure 1.3, there are three sections of duct: the air inlet duct, the turbine exhaust duct, and the heat recovery steam generator (HRSG) outlet duct. The stack is usually nothing more than an extension of this HRSG outlet duct. The turbine exhaust duct is under a positive pressure and carries combustion exhaust flue-gas at temperatures as high as 1,100°F (600°C) or more. These ducts are usually internally insulated to protect the duct plate. The temperature in the HRSG outlet duct is typically around 450°F (230°C).

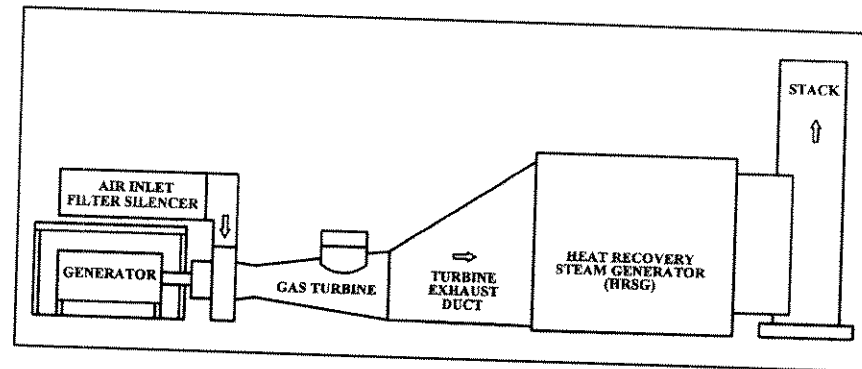


Figure 1.3
Typical Ductwork Arrangement for a Combined Cycle Power Plant

1.3.2 Air Ducts

Fluidized Bed Boiler System

In a fluidized bed boiler system, a combination of one PA Fan and one FD Fan supply the combustion air to the boiler. In this system, a FD Fan is sometimes called a Secondary Air Fan. The Primary Air Duct extends from the PA Fan to the air preheater; downstream of the air preheater this duct is transformed into a manifold system that provides a uniform supply of fluidized air for combustion across the bottom of the furnace. The Secondary Air Duct also extends from the FD Fan to the air preheater. However, downstream of the air preheater this duct connects to the furnace section at a higher elevation to provide additional heated air for combustion. Figure 1.4 shows a typical air duct arrangement for a fluidized bed boiler.

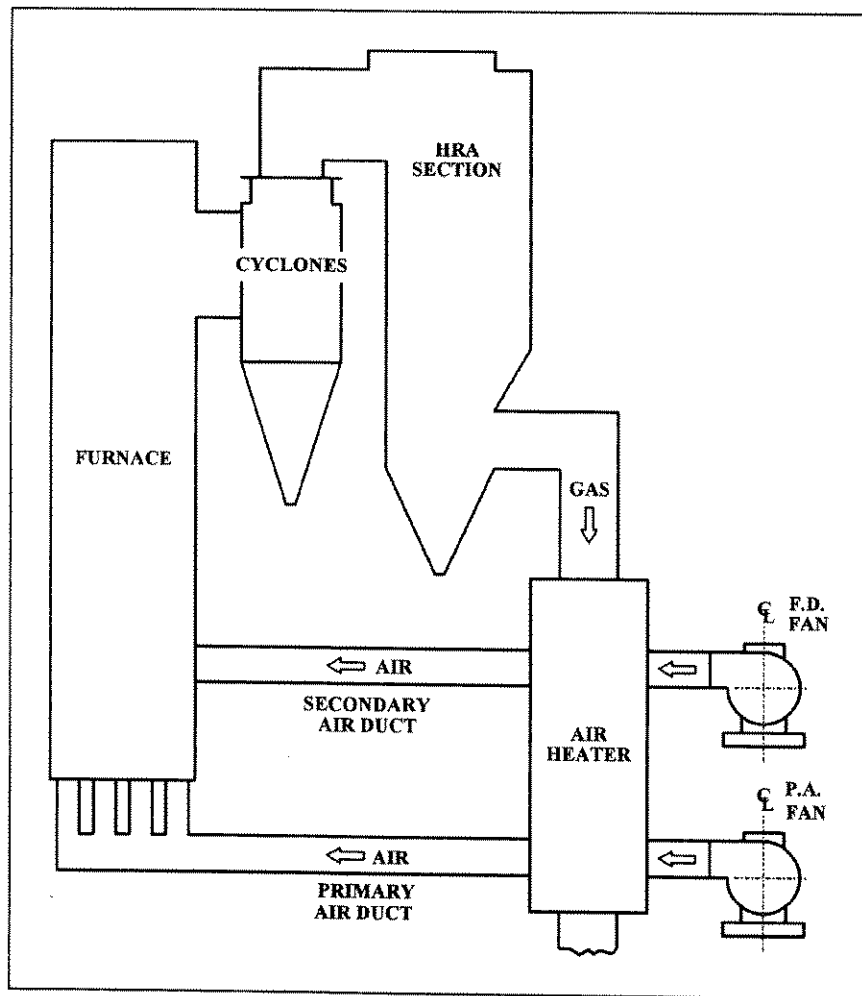


Figure 1.4

Typical Air Duct Arrangement for a Fluidized-Bed Boiler

Conventional Boiler Systems

The ducts connecting the FD fans and the boiler convey the combustion air. These ducts are called the Secondary Air Ducts. The air usually goes through an air preheater, which increases the temperature of the air for more efficient combustion in the boiler. These ducts may also pass through a glycol or steam coil combustion air heater which raises the air temperature to the level required by

the air preheater manufacturer. The air is at ambient temperature upstream of the heaters and at a higher temperature, typically 200°F to 500°F (90°C to 260°C), between the air preheater and the boiler. These ducts are usually under a positive pressure.

In a pulverized coal-fired boiler system, Primary Air (PA) Fans supply air which conveys the pulverized coal from the pulverizers into the boiler. The ducts which supply the forced air from the outlets of the PA Fans to the pulverizers are called the Primary Air Ducts. In units that do not have PA Fans, primary air is supplied from the secondary air ducts directly downstream of the air preheater. PA fans function similar to FD fans. The ducts connecting the PA fans to the pulverizers also go through an air preheater, and possibly a glycol or steam coil combustion air heater also. They are also usually under a positive pressure at approximately the same temperatures as the secondary air ducts.

Another type of air duct used in some pulverized coal-fired boiler systems is the Tempering Air Duct. The purpose of the tempering air duct is to convey ambient temperature air to the primary air duct mixing section. Tempering air is used to reduce primary air temperature to the proper temperature as it enters the pulverizers. Figure 1.5 shows a typical air duct arrangement in a pulverized coal-fired power plant. As shown in Figure 1.5, coal pipes or conduits transport the airborne coal from the pulverizers to the furnace. These coal pipes or conduits should not be considered as ducts.

Other Air Ducts

Depending on the fuel, the application, the vendor and the size of the boiler, there also may be other types of air ducts that are part of the duct system. For example, some boiler systems, such as recovery boilers, usually have tertiary fans and their associated air ducts. The air ducts discussed here are the most common ducts.

1.3.3 Flue-Gas Ducts, or Flues

The flue-gas ductwork system between the boiler outlet and the chimney is usually more complicated. There can be many large pieces of equipment in the system. For a coal-fired boiler, the outlet flue-gas usually passes through: an air preheater where it is cooled; an electrostatic precipitator or a fabric filter (baghouse) where most of the flyash particles are removed from the flue-gas; the ID fans; and a flue-gas desulfurization system (FGD system), or scrubber, where Sulfur is removed from the flue-gas.

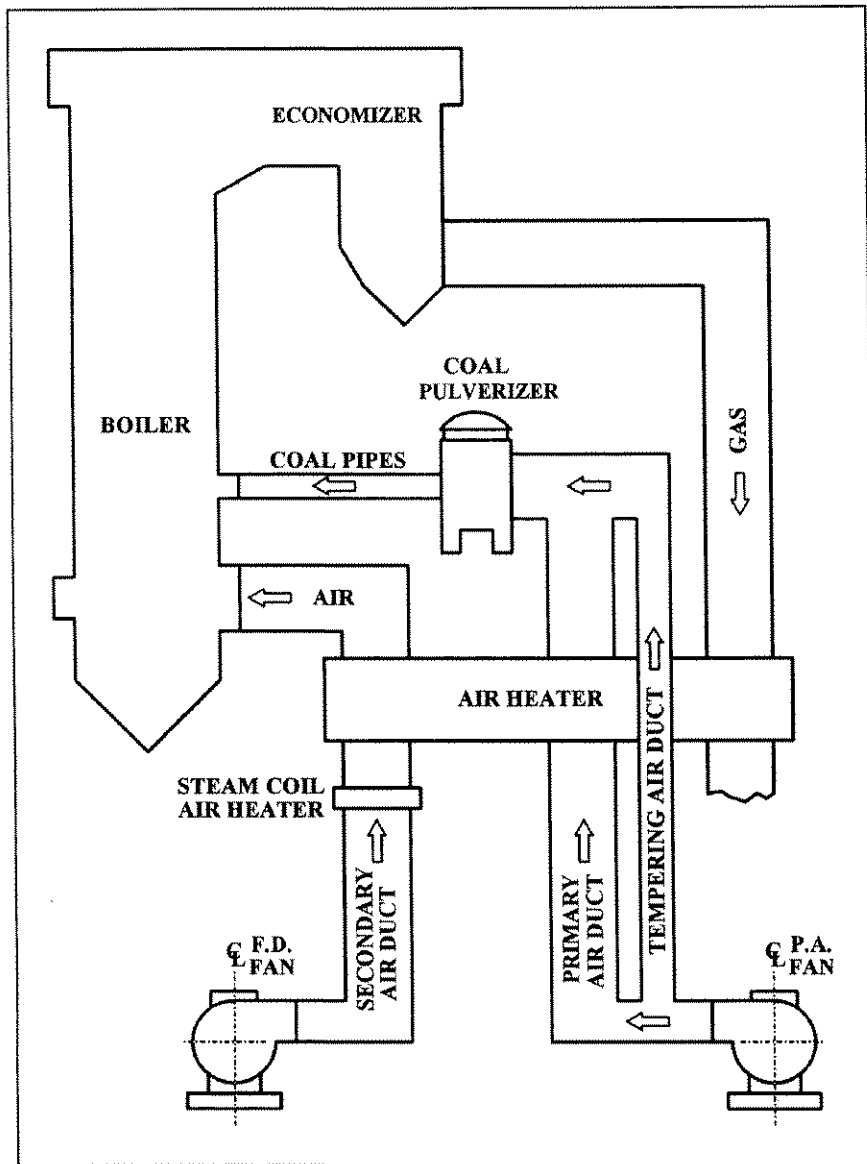


Figure 1.5
Typical Air Duct Arrangement for a Pulverized Coal-Fired Boiler

Precipitators may be situated in the system in either of two locations. The precipitators may be before the air preheater, on its hot-side, or after the air preheater, on the cold-side. Baghouses are always located on the cold-side. The ductwork system may or may not have a scrubber, depending on the age of the plant and the characteristics of the fuel burned. A description of these major pieces of equipment follows in Section 1.5.

The ducts from the boiler outlet to the air preheater convey very hot flue-gas from 600°F to over 900°F (320°C to 480°C). In the air preheater, to increase plant efficiency, heat is transferred from the exiting flue gas to the incoming combustion air. The flue-gas exiting the air preheater is cooled to approximately 250°F to 450°F (120°C to 230°C). In the air preheater, heat is transferred to increase plant efficiency. If the system has a scrubber, the flue-gas typically will be cooled further to between 120°F and 350°F (50°C to 180°C) as it passes through the scrubber. The structural engineer should understand that some systems have a scrubber bypass duct, which should be treated the same as the scrubber inlet ductwork.

Some power plants also have Gas Recirculation Fans (GRF) and their associated Gas Recirculation Ducts. These ducts convey a portion of the combustion flue-gas back into the boiler furnace for steam temperature control and/or NO_x control. These ducts should be treated the same as the boiler outlet ducts.

Figures 1.1 and 1.2 show typical flue-gas duct arrangements in a pulverized coal-fired power plant.

1.3.4 Typical Pressures and Temperatures

As stated earlier, each section of ductwork in a system is exposed to a different pressure and possibly a different temperature. In a coal-fired power plant, the air temperature increases as it goes through the air preheaters and the flue-gas temperature is lowered as it passes through the air preheaters and the scrubber. The pressure normally changes significantly as the flow passes through the following equipment: the air preheater, the boiler, the precipitator or baghouse, the scrubber, and all of the major fans. See Figure 1.6 for the typical pressure profile for a coal-fired power plant.

The structural engineer must obtain the proper design operating pressures from the responsible mechanical process engineer prior to starting the analysis and design of the ductwork. The minimum design pressure requirements given in chapters 4 and 5 of the

National Fire Protection Association documents NFPA 85C, *Standard for the Prevention of Furnace Explosion/Implosions in Multiple Burner Boiler-Furnaces*, NFPA 8504, *Standard on Atmospheric Fluidized-Bed Boiler Operation*, and NFPA 8505, *Recommended Practice for Stoker Operation*, may be applicable.

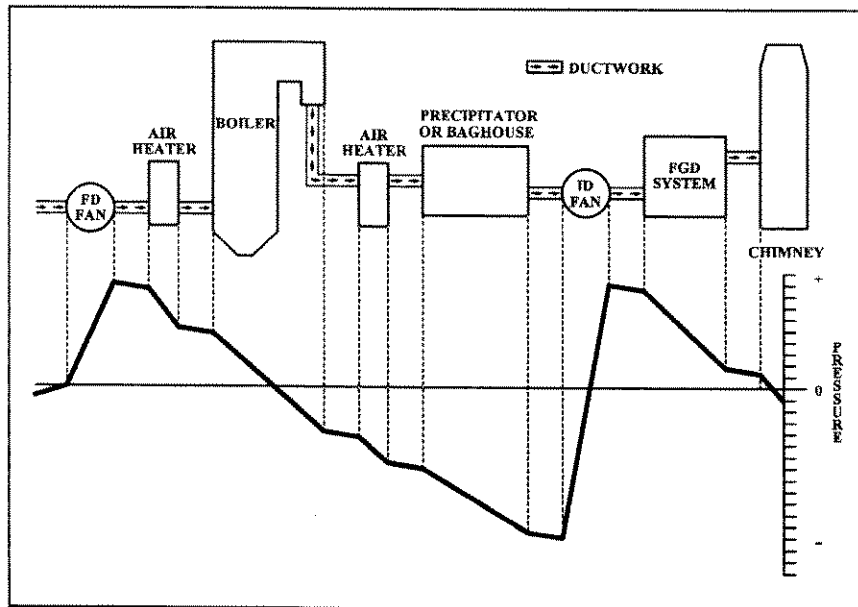


Figure 1.6
Typical Pressure Profile for a Coal-Fired Power Plant

Typical representative air and flue-gas pressures and temperatures for a pressurized coal-fired power plant are shown as an EXAMPLE in Table 4.1. Typical representative values for a balanced draft coal-fired plant are shown as an EXAMPLE in Table 4.2. Typical representative values for a pressurized and balanced draft industrial boilers are shown as an EXAMPLE in Table 4.3. The values in these tables are only representative EXAMPLES. They should not blindly be used for ductwork design. The structural engineer must obtain the proper operating and transient pressures and operating and excursion temperatures for the duct system under consideration from the appropriate sources.

1.4 GLOSSARY/DEFINITIONS

Following are definitions of some common terms relating to ductwork and ductwork design which are found in this ASCE Special Publication. The definitions presented in this section are separated into five groups: ductwork terms, duct support terms, duct appurtenances, duct service conditions and duct conveyances.

1.4.1 Ductwork

Ducts, Ductwork:

Ducts or ductwork can be any pressure tight conveyance that transfers pressurized air or flue-gas from one point to another. See Section 1.3.

Flues:

Ducts that convey flue-gas are sometimes called flues. Chimney liners and short square stacks used in natural gas burning plants are also sometimes called flues.

"Hot-Side" Ducts:

Ducts or flues that convey the flue-gas from the boiler outlet or the economizer to the air preheater inlet are typically called "hot-side" ducts, just as precipitators that are located between the boiler outlet and the air preheater inlet are called "hot-side" precipitators. This definition arose because these ducts are on the hot side of the air preheater. The flue-gas temperatures in hot-side ducts are typically between 450°F and 900°F (230°C and 480°C). See Section 1.3.3 for more discussion on flue-gas ducts.

"Cold-Side" Ducts:

Ducts or flues that convey the flue-gas from the air preheater outlet through various pieces of major equipment to the stack or chimney are typically called "cold-side" ducts, just as precipitators that are located downstream of the air preheater are called "cold-side" precipitators. These flue-gas ducts are on the relative cold side of the air preheater. The flue-gas temperature in cold-side ducts is typically between 250°F and 425°F (120°C and 220°C). See Section 1.3.3 for more discussion on flue-gas ducts.

Toggle Duct Section:

A toggle duct is a straight section of ductwork between two expansion joints that is allowed to freely move in one, two, or three directions with one or two of the adjacent duct sections (or pieces

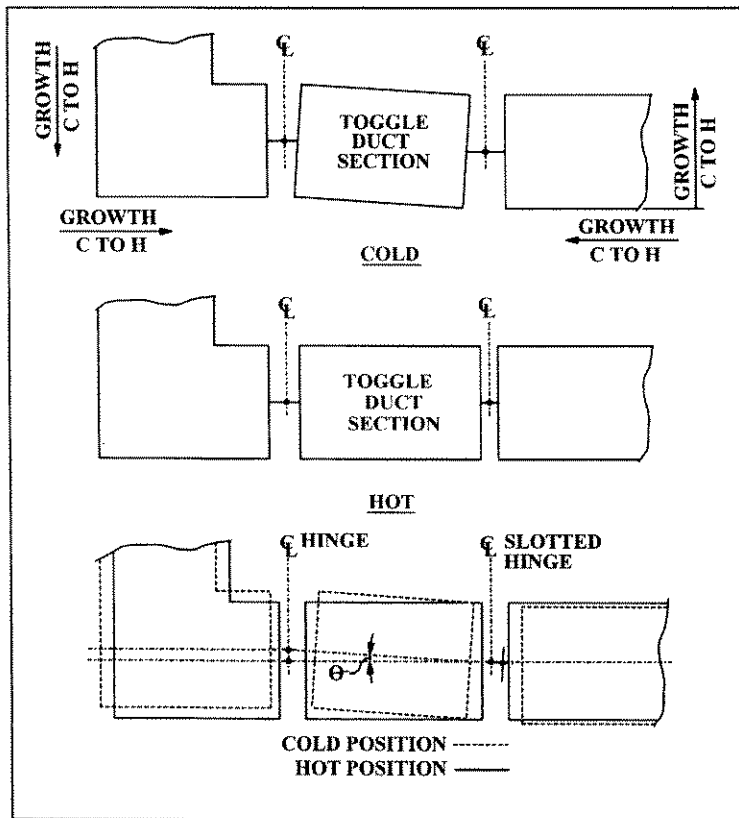


Figure 1.7
Typical Toggle Duct Arrangement

of equipment) which are on the other side of an expansion joint. It is a section of ductwork that behaves like it has a hinge at each end. See Figures 1.7 and 2.5 for sketches showing a typical toggle duct arrangement. A toggle duct section typically does not have any external supports, although it may have one usually at or near its center of expected rotation. A toggle duct is usually connected to the adjacent ducts across the expansion joints by shear ties or internal hanger rods, although, carefully designed metal expansions joints sometimes may be used to transmit the calculated shear force. The purpose of a toggle duct section is to accommodate thermal movements that are too large for a single expansion joint, especially shear movements. The most common location for a toggle duct section is at the boiler outlet. At this location, the boiler thermally

expands down as much as 6 or 7 inches (15 or 18 mm). The toggle duct is connected to the boiler on one end and the main duct on the other end. The main duct is usually supported vertically at this location so that the vertical growth is close to zero. Therefore, the one end of the toggle duct goes down and up with the boiler and the other end stays with the main duct. This same type of action also occurs in the horizontal plane. All rotation is taken out through the expansion joints. For an additional discussion on toggle ducts, see Section 2.3.3.

Breeching Duct:

Breeching is the term commonly used for the section of ductwork that enters the stack or chimney or any piece of major equipment.

Hoppers:

In ductwork applications, ash collection hoppers are located in sections of the ducts where significant dropout of flyash is anticipated. Two typical locations for hoppers are at the boiler outlet ducts below the air preheater and at the bottom of vertical runs of ducts. The purpose of a hopper is to temporarily store the ash collected from the flue-gas flow until it is removed by the ash removal system.

1.4.2 Duct Supports

Anchor Point:

All ducts exposed to elevated temperatures experience thermal growth. Each section of duct must be secured to the supporting structure in one and only one location so that it may thermally grow in all directions without resistance. This location is called the anchor point or fixed point. The anchor point does not have to be a gravity support. Also, an anchor point may be artificial, as further explained in Section 2.3. The intersection of two perpendicular lines of duct guides is the point of zero movement. This is considered the anchor point, even though there may be no physical attachment to the support structure at that location. The anchor point should be located as to minimize the shear across expansion joints, to simplify the duct expansion behavior, to simplify the support structure arrangement and to equalize the duct expansions.

Duct Guides:

A duct guide is a connection between the duct and its support structure where the wind loads, seismic loads, expansion joint actuation forces, unbalanced pressure, and unbalanced friction loads acting perpendicular to one direction of thermal expansion are

transferred from the duct to the support structure. Duct guides should be on one of the principal anchor lines of the duct section and always must allow thermal growth away from the anchor point. A duct guide may or may not be a gravity support for the duct. If it is a gravity support on a bottom supported duct, a friction force is developed acting along the anchor line as the duct thermally expands. A slide bearing plate is usually under the gravity support baseplate to keep this friction force to a minimum.

Duct Sliding Supports:

The gravity connections between the duct and its support structure, where unrestrained thermal growth is allowed, are called sliding supports. As the duct thermally grows, friction forces are developed acting in both global directions away from the anchor point. A slide bearing plate is usually used under the gravity support base plates to keep these friction forces to a minimum.

Slide Bearing Plate Assembly:

Slide bearing plates are typically used under all bottom supported duct gravity support locations except the anchor point. There could be special cases where the gravity force is so low that the use of a slide assembly is not cost effective and therefore not used. The purpose of a slide bearing plate assembly is to reduce the coefficient of friction between the duct support baseplate and the support steel as the duct grows or contracts due to thermal expansion. A typical bearing assembly consists of a plate covered with low friction material, such as teflon or lubricated bronze, that rubs against a polished stainless steel surface. The slide plate is usually attached to the fixed support structure while the stainless steel plate is attached to the moving duct support.

Constant Support Spring Hangers:

Constant support spring hangers allow a predetermined vertical movement with a constant support resistance. They are used as vertical supports for duct sections at locations where the design engineer wants to control the load going to the support structure. They can be provided to take a local dead load, such as a damper, to the support structure. As their name indicates, this type of hanger loads the support structure with a constant force, even if the forces or loads within the duct change. This type of hanger should only be used in conjunction with a very accurate structural analysis. The dead load must be very accurately determined and the engineer must know where any additional load will go. To get the proper results, this hanger force must be applied as an external load in the duct analysis, not as a support.

Rigid Hangers:

Rigid hangers are usually rods. This type of hanger will act as a pinned support, transmitting all loads to the support structure up to the capacity of the hanger with no vertical movement.

Variable Support Hangers:

Variable support spring hangers allow a predetermined vertical movement with a varying support resistance. They are used as vertical supports for duct sections at locations which will experience vertical thermal movement. They are used in locations where the structural design engineer does not care if the load going to the support structure varies.

1.4.3 Duct Appurtenances

Dampers:

Dampers are placed in a duct system to allow the plant operator to control or redirect the flow within the duct system. Isolation dampers are also used to isolate sections of ductwork. There are four types of dampers that are generally used in ducts: guillotine, louver, butterfly and poppet. A damper always comes with its own frame, which matches up with the duct so that it effectively becomes part of the duct. The location of dampers dictates the design and transient pressure forces acting on the duct and its support structure. Guillotine dampers are usually used for isolation because they generally are more leak-tight than multi-blade louver dampers. Sometimes double blade guillotine dampers are used where isolation is an absolute necessity. Guillotine dampers are usually very heavy and require a considerable amount of space when the blade is out of the duct. In order to assure complete isolation, pressurized seal air frames are installed around dampers such that any leaks are always into the flue-gas stream instead of out to the atmosphere.

Expansion Joints:

Duct sections are isolated from each other by the use of relatively flexible joints. These joints are used by the engineer to control thermal expansion and enhance the predictability of the structural analysis. Expansion joints are either made out of some sort of fabric or rubber-like material or light gauge metal. These joints are termed as being either non-metallic expansion joints or metal expansion joints. Expansion joints can be sized to accommodate duct axial movement and rotation. Some joints, which are usually non-metallic material, can allow a small amount of shear movement and others, which are usually metal, can be designed to transfer a shear force and allow no shear movement.

Insulation:

Insulation is used either on the inside or the outside of ducts to keep the heat inside and to protect personnel from injurious burns on the outside of the duct. Some older ducts were insulated on the inside with either masonry or mortar. Newer ducts are usually insulated on the outside with some sort of spun fiberglass wool. If ducts are not insulated properly and there are cold spots, condensation will occur on the inside of the duct at these locations and extensive corrosion of the steel will result. If hot-side ducts are not insulated properly, thermal shock could cause the ducts to crack on or near the cold spots. See Section 11 for expanded discussions on ductwork insulation.

Lagging:

Lagging is the term for the fiberglass, aluminum or light gauge steel sheets that cover the ductwork insulation. Lagging keeps the insulation in place, protects the insulation from damage by weather or personnel, and keeps water off of the insulation and the duct. See Section 11 for additional information on ductwork lagging.

Corner Angle:

Angles or bent plates are usually placed on the inside, or sometimes the outside, of ducts in the corners between the wall plates and the floor and roof plates. Corner angles make erection easier, provide an air tight seal, and provide strength and stiffness to the roof, floor and wall plates.

Internal Truss:

Trusses are sometimes added to the inside of ducts to: provide additional support to the roof and floor of very wide ducts; stiffen the walls of very tall ducts; and transmit wind, seismic and pressure loads from the duct plate to the duct supports. The use of internal trusses is usually minimized, if possible, because they tend to constrict the flow and increase the pressure losses in the ducts. Their use must be evaluated by the structural engineer for duct economy and structural stiffness and by the mechanical engineer for flow considerations.

Perforated Plates:

Perforated plates are flow distribution devices within ducts usually positioned perpendicular to the flow that are sometimes necessary at the inlet and outlet of precipitators, baghouses and other locations to ensure that all of the chambers are receiving a uniform distribution of flow. A perforated plate is usually a flat, sometimes stiffened, plate with circular or slotted holes usually punched in a

pattern. Perforated plates are described as having X% open area. The open area could typically be as great as 75% or as little as 30%. Perforated plates are always hung from the inside roof of the duct and are free from the floor and sides. They must be free so that they don't restrain the duct from moving unequally due to any thermal expansion and contraction, wind deformation, pressure deformation or gravity deformation. See Section 9 for the structural design of perforated plates.

Splitter Plates:

Splitter plates are internal flow distribution devices that are parallel to the flow. They are usually placed in a transition duct section to maintain an even flow within the duct and/or into a large piece of equipment, such as a precipitator. See Section 9 for the structural design of splitter plates.

Turning Vanes:

Turning vanes are internal flow distribution devices which help change the direction of flow while minimizing pressure drop. They direct the flow around duct corners, through duct transition pieces, and into major equipment. Turning vanes may be staggered flat plates called ladder vanes or they may be parallel curved plates. Turning vanes are sometimes used in conjunction with splitter plates and perforated plates. See Section 9 for the structural design of turning vanes.

1.4.4 Duct Service Conditions

All of these service conditions as they apply to loads are described in detail in Section 4.

Operating Pressure:

Ducts usually are exposed to a relatively predictable static pressure range. Ducts may be pressurized or they may be under a partial vacuum. The static pressure is defined by the capabilities of the fans and the losses through the duct system, including the major equipment in the system. Each section of ductwork experiences a different static pressure, which is constant in that section during a given mode of operation. The maximum positive or minimum negative expected static pressure during normal operation is the operating, or design, pressure for the duct section. See Figure 1.6 for the typical operating pressure profile for a conventional coal-fired power plant. Pressures are normally specified in inches of water column or millimeters of mercury.

Unbalanced Pressure:

Whenever a section of duct has an expansion joint located so that there is a duct wall that does not have another duct wall directly across from it, an unbalanced pressure occurs in that duct section. When this occurs, the resulting unbalanced pressure force must be transferred through the duct to its support structure. If no mechanism is available to resist the unbalanced pressure force, it will cause the duct section to move off of its supports, which could cause considerable damage to the duct, its support structure, and nearby structures and equipment. Unbalanced pressure forces will only occur opposite openings or expansion joints directly upstream or downstream of bends or transitions. The unbalanced operating pressure force is the static operating pressure multiplied by the area of the opening. The structural engineer may often be able to exercise some level of control over these forces through judiciously orienting openings, improving the geometry of transition sections, keeping the duct runs as straight as possible, and ensuring the proper placement of dampers and expansion joints. This unbalanced force must be accounted for in the design of the ductwork supports and the support structure as shown in Figure 4.2.

Dynamic Unbalanced Pressure:

Dynamic pressure is associated with the velocity and density of the flow. This pressure fluctuates with time and flow rate and does not remain constant. Due to the low density of air and flue-gas, dynamic unbalanced pressure is normally only considered when designing the flow distribution devices and sometimes on duct walls at turns. See Sections 4 and 9 for discussions on dynamic unbalanced pressure.

Transient Pressure:

During an abnormal event, ducts may experience a very high or very low static pressure for a relatively short period of time. Examples of an abnormal event that would produce a transient pressure are: the failure of a major piece of equipment, such as an ID fan; the improper closing of a damper; or a master fuel trip of the unit. This abnormally high (positive) or low (negative) pressure is defined as the transient pressure. Ducts must be designed considering the likelihood of experiencing the transient pressure, but a lower factor of safety may be used because of the infrequent and low chance of occurrence and the expected brief duration of the pressure spike.

Operating Temperature:

Ducts usually are exposed to a relatively predictable temperature range as governed by the boiler and air preheater design. The

maximum expected temperature during normal operation is the operating or design temperature for each particular section of duct. Friction forces from thermal growth at the duct's sliding support points are a type of thermal load.

Excursion Temperature:

During an abnormal event, such as the failure of a major piece of equipment, such as an air preheater, to perform properly, the ducts may experience a very high temperature for a relatively short period of time. This occurrence is defined as the excursion temperature. Ducts must be designed considering the likelihood of experiencing the excursion temperature, but a lower factor of safety may be justified because of the infrequent and low chance of occurrence and the expected brief duration of the temperature rise.

Thermal Gradient:

Due to unusual or unexpected flow, ducts sometimes experience uneven temperatures from top to bottom and/or from side to side. This condition results in thermal gradients within the duct. Because of a thermal gradient, the duct steel will experience differential temperatures which should be considered in the analysis and design if they are known to be large or if they are expected to create significant stresses. Obviously, thermal gradients are a type of thermal load.

1.4.5 Duct Conveyances**Primary Air:**

Primary air is that part of combustion air which is mixed directly with the coal before ignition takes place.

Secondary Air:

Secondary air is that part of combustion air which is added shortly after ignition to help complete the combustion process.

Tempering Air:

Tempering air is air that is used to control temperature. It is used to reduce primary air temperature to the proper temperature required as it enters the pulverizers.

Tertiary Air:

Tertiary air is that part of combustion air which is added to the burning mixture to complete the combustion process and to further mix the air and the coal.

Flue-Gas:

Flue-gas is the exhaust from the combustion process that takes place within the boiler. Flue-gas is conveyed from the boiler to the stack via ducts.

Recirculated Gas:

Recirculated gas is flue-gas which is fed back into the combustion zone for steam temperature control and/or NO_x control.

Flyash:

Flyash is the term for the products of solid or liquid fuel combustion that remained unburned and are entrained in the flue-gas stream. Most of the flyash is extracted from the flue-gas by the air pollution control equipment, usually precipitators or fabric filters. Flyash also tends to fall out of the flue-gas and accumulate in the ducts in locations where the flow velocity is reduced and at turns and obstructions in the duct.

Salt Cake:

Salt cake is the term for the ash from a black liquor recovery boiler.

Scrubber Sludge:

Sludge is the term for the by-product of the wet flue-gas desulfurization process. Sludge is collected in the scrubber. Scrubber outlet ducts sometimes have an accumulation of sludge on the duct internal surfaces.

1.5 DESCRIPTIONS OF MAJOR DUCTWORK EQUIPMENT

Following is a list of the major equipment that can be involved with a ductwork system. Not every piece of equipment listed below will be found in a single duct system. The ductwork is typically designed around the requirements of this equipment. Also included is a short description of their function in the system and how the equipment interfaces with the ductwork. This equipment is typically not designed with the ductwork, but is typically purchased from specialty manufacturers.

Air Preheater:

An air preheater is a device which transfers heat from the exiting flue-gas to the incoming combustion air. This process promotes more efficient combustion in the boiler and sends less unused energy up the chimney. There are many types of air preheaters, including: regenerative circulating air preheaters, tubular air preheaters and heat pipes. There are large pressure losses through most air preheaters.

Ash Removal Equipment:

For flue-gas ductwork system to operate properly as designed, all ash collection hoppers must be periodically emptied. Various ash removal systems may be used, but a common type is a vacuum removal system where ash removal piping is attached to the bottom of the hoppers and the collected ash is intermittently vacuumed out. A continuous mechanical ash removal system has become the frequent choice in boiler systems that burn one of many high ash fuels, such as waste wood and refuse. Quite often the ash removal system is supported directly from the hoppers and the additional weight must be considered in the structural analysis and design.

Boiler or Furnace:

The boiler or furnace is where the fuel is burned and water is heated within pressurized tubes to create steam. The boiler is normally not considered to be ductwork, except for the outlet casing downstream of the tubes.

Combustion Air Heater:

Combustion air heaters heat the air before it enters the air preheater. Combustion air heaters usually use either glycol or steam coils to heat the air. Not all systems have combustion air heaters.

Continuous Emission Monitoring System (CEMS):

Flue-gas continuous emission monitoring was mandated by the 1991 Clean Air Act. A continuous emission monitoring (CEM) system collects and analyzes the flue-gas. The concentrations of pollutants, NO_x and SO₂, plus diluents, CO₂ or O₂, are measured. In addition, the amount of flue-gas flow is also measured. This data is reported to state, local, and federal agencies. High levels of accuracy and availability are required for this equipment.

Economizer:

An economizer is located at the rear of a boiler and utilizes the furnace exit flue-gas to preheat the deaerated boiler feedwater.

Heat Recovery Steam Generator (HRSG):

A heat recovery steam generator is a relative large heat transfer device that is located in the ductwork system of a combined cycle power plant downstream of the gas turbine. A HRSG is composed of groups of water-filled tubes that are heated by the turbine exhaust flue-gas. In a HRSG, the temperature of the flue-gas is considerably reduced and the water in the tubes is converted to steam. This steam can then be used for a commercial purpose or can be used to drive a companion steam turbine.

Air Pollution Control Device (APCD):

Air pollution control device (APCD) is a term for mechanical ash collectors, precipitators, fabric filters (baghouses), flue-gas desulfurization systems (scrubber), and similar pieces of equipment that are designed to remove the pollution particles from the flue-gas.

Electrostatic Precipitator:

Electrostatic precipitators remove most of the flyash from the flue-gas using electrostatic energy. Within the precipitator, the flue-gas passes between vertical hanging parallel ash collecting plates. Between the plates are electrically charged wire electrodes which induce an electric charge on the fly ash. This arrangement causes the flyash to be attracted onto the collecting plates. The collecting plates are periodically rapped to dislodge the ash and allow it to fall into large collecting hopper at the bottom of the precipitator before it is removed by the ash removal system. There are usually large pressure losses as the flue-gas passes through a precipitator and its transition ductwork.

Fabric Filter or Baghouse:

Fabric filters or baghouses also remove most of the flyash from the flue-gas. The flue-gas is pulled through fabric bags which act as filters to catch the flyash. The bags are periodically emptied into collection hoppers at the bottom of the fabric filter. Large ID fans are required if a fabric filter is in a ductwork system because of the large pressure losses as the flue-gas passes through the filter bags.

Flue-gas Conditioning:

Flue-gas is sometimes conditioned by injecting chemicals into the flue-gas stream downstream of the boiler or economizer outlet. One of the processes is called selective catalytic reduction (SCR). This process reduces the oxides of Nitrogen (NO_x) in the flue-gas by injecting ammonia into the flue-gas stream in the presence of a catalyst. Another process involves injecting SO₃ into the flue-gas stream. These processes enhance the collection efficiency of precipitators in systems that utilize low sulfur coal and thereby reduces pollution.

Flue-gas Desulfurization System or Scrubber:

The flue-gas desulfurization (FGD) system removes the Sulfur dioxide (SO₂) from the flue-gas using limestone, lime, or some other reagent. FGD systems may be of the wet or dry variety. There may be very great pressure losses and a significant reduction in temperature as the flue-gas passes through the scrubber system.

Forced Draft (FD) Fan:

Forced Draft fans are located within the ductwork system upstream of the boiler. They take in air from the atmosphere or the boiler enclosure and force it into the boiler for combustion. Depending on the size and type of boiler, there may be between one and four FD fans associated with a combustion system.

Gas Recirculation (GRF) Fan:

Some power stations also have Gas Recirculation fans. These fans return a portion of the combustion flue-gas from the boiler outlet to the boiler furnace for steam temperature control and the control of NO_x formation. If any, there are usually one or two GRF fans associated with a coal-fired combustion system.

Induced Draft (ID) Fan:

Induced Draft fans are located within the ductwork system downstream of the boiler between the precipitator or baghouse and the chimney. They pull the flue-gas out of the boiler and through the precipitator or baghouse and push it through the scrubber, if present, and out to the atmosphere through the chimney or stack. Depending on the size and type of boiler, there may be between one and four ID fans associated with a combustion system.

Primary Air (PA) Fan:

Primary Air fans are also located upstream of the boiler, usually adjacent to the FD fans. They take in air from the atmosphere or the FD fan discharge and force it through the coal pulverizers, where the pulverized coal is entrained, and into the boiler for burning. They are usually only used with coal-fired boilers. There are usually one or two PA fans associated with a coal-fired combustion system.

Other Types of Fans:

There may be fans in duct systems other than those mentioned here. Some others are: the Secondary Air Fan, which is used within the secondary air duct; the Tertiary Air Fan, which is used within the tertiary air duct; the Reheat Air Fan, which is used within a reheat duct; and the Reverse Air Fan, which is used to move reverse air within a fabric filter. All types of fans generally have the same pressure changing impact to the duct design.

Stack or Chimney:

The stack or chimney liner is the orifice at the end of the ductwork system through which the flue-gas enters the atmosphere. In common usage, the terms stack and chimney are used

interchangeably. Generally, chimney refers to a concrete wind screen structure that protects a liner or liners that convey the flue-gas. Sometimes these liners are also called flues. A concrete chimney is typically cost effective when the required flue-gas exit height is above about 200 to 300 feet (60 to 90 meters) depending on the diameter. An unprotected carbon steel liner or stack cannot usually be used in conjunction with a scrubber because of the corrosive nature of the flue-gas exiting the scrubber. Brick or fiberglass reinforced plastic chimney liners are usually used in conjunction with scrubbers, although high alloy metal and special acid resisting coatings have merit for consideration. For the design of these structures consult the following publications as appropriate: the ASME publication STS-1-1992, *Steel Stacks*; the ASCE Task Committee on Steel Chimney Liners publication *Design and Construction of Steel Chimney Liners*; the ACI publication ACI-307, *Standard Practice for the Design and Construction of Cast-in-Place Reinforced Concrete Chimneys*; CICIND's publications *Model Codes for Concrete Chimneys and Liners* and *Model Code for Steel Chimneys*; and the ASME publication RTP-1, *Reinforced Thermoset Plastic Corrosion Resistance Equipment*.

1.6 DESCRIPTIONS OF DUCTWORK ACCESSORIES

Following is a list of ductwork accessories that are typically supplied with the ductwork. These accessories are usually designed along with the ductwork and/or affect the design of the ductwork. Also included is a short description of their function in the ductwork system and how they interface with the ductwork.

Access Doors:

Access doors are usually installed in duct walls so that the ducts can be entered for maintenance when the boiler is out of service. The doors should be large enough for relatively easy entry, but not so large that they weaken the duct wall. They must be designed to withstand the same pressures and wind loads as the duct wall. Door hinges and latches, or bolts, must also be sized for these same loads. Doors must be air tight. This is typically accomplished by providing a gasket seal around the entire door perimeter. Doors must also be properly insulated and lagged to prevent cold spots so that they are not damaged by corrosion.

Dampers:

For a detailed discussion on dampers, refer to Sections 1.4 and 2.2.

Expansion Joints:

For a detailed discussion on expansion joints, refer to Sections 1.4 and 2.3.1. For information on loads from expansion joints, refer to the discussion on unbalanced pressure in Sections 1.4.4 and 4.2 and the discussion on expansion joint actuation forces in Section 4.2.

Gaskets:

Access doors should be sealed with an air-tight gasket material. The gasket material must be chosen considering the design pressure and temperature and the flow chemistry. Sometimes gaskets are also used where a duct section connects to equipment, expansion joints and dampers.

Instrumentation and Tests Ports:

Flanged pipe pieces typically penetrate the duct roof or walls at various locations so that air or gas measurement equipment can be inserted into the stream. Some of the instrumentation is permanently attached to the ports but some of the pipe pieces are capped so that temporary or portable instruments can be inserted at any time. The locations of the ports are set by regulatory requirements, duct configuration, test data, operating needs, instrument manufacturer recommendations, and major equipment manufacturer recommendations.

Insulation and Lagging:

For detailed information on insulation and lagging, refer to Section 1.4.3 and Section 11.

Internal Air/Flue-gas Flow Distribution Devices:

Flow distribution devices are items such as turning vanes, splitter plates and perforated plates. For information on flow distribution devices, see the discussions in Section 1.4 and Section 9.

Internal Handrail:

Quite often it is necessary to install handrail within ducts to prevent personnel from falling off the floor of a horizontal duct section into the shaft of an adjacent vertical duct section.

Platforms and Ladders:

Quite often, access platforms and ladders are supported directly off of ductwork. If this is done, care must be taken during the structural design. The differential thermal expansion between the hotter duct and the cooler ladder or platform support steel must be accounted for when connecting the ladder or steel to the duct.

Slide Bearing Plates:

For a detailed discussion on slide bearing plates, refer to Sections 1.4.2 and 2.3.4.

Spring Hangers:

For information on spring hangers, refer to Sections 1.4.2 and 2.4.

SECTION 2**Ductwork Arrangement and Behavior**

	<u>Page</u>
2.1 OVERVIEW	35
2.1.1 Flow Considerations	35
2.1.2 Design Process	36
2.2 INTERFACES WITH EQUIPMENT	37
2.2.1 Isolation of Major Equipment From the Ductwork	38
2.2.2 Fans	38
2.2.3 Equipment Removal	39
2.2.4 Dampers	39
2.2.5 Flue-Gas Monitoring Instruments	44
2.2.6 Access Doors	44
2.3 THERMAL EXPANSION	45
2.3.1 Expansion Joints	45
2.3.2 Toggle Duct Sections	47
2.3.3 Location of Anchors and Guides	47
2.3.4 Slide Bearing Plates	51
2.3.5 Clearances	52
2.3.6 Support Eccentricities	52
2.3.7 Attachment of Cold Items to Ducts	53
2.4 SUPPORTS	54
2.4.1 Support Locations	55
2.4.2 Structural Determinacy of Ductwork	56
2.4.3 Hangers Versus Bottom Supports	59
2.4.4 Spring Hangers Versus Rigid Hangers	63
2.4.5 Support Elevations	63
2.4.6 Support Structure Stiffness	63
2.4.7 Ductwork Stiffness	65
2.4.8 Supporting Ducts from Equipment	65
2.4.9 Retrofitting Ductwork	65
2.5 DUCT GEOMETRIES	66
2.5.1 Basic Ductwork Configuration	66
2.5.2 Rectangular Ducts	67
2.5.3 Circular Ducts	68
2.5.4 Hoppers	69
2.5.5 Transition Duct Sections	69

	<u>Page</u>
2.6 INTERNAL TRUSSES AND STRUTS.....	70
2.6.1 Location and Layout	70
2.6.2 Vibration Considerations	74
2.7 EFFECTS OF THE ARRANGEMENT ON LOADS	74
2.7.1 Static Pressure	74
2.7.2 Dynamic Pressure	75
2.7.3 Vibrations	75
2.7.4 Ash Deposition	76
2.7.5 Metal Expansion Joints	77
2.7.6 Thermal Gradients	77

SECTION 2

Ductwork Arrangement and Behavior

2.1 OVERVIEW

This section discusses how decisions made during the layout of a duct system may affect factors such as initial cost, structural behavior, system reliability and maintenance. The design of large air and gas ducts is an extremely complex task which requires the satisfaction of both mechanical and structural design criteria. Structural engineers must remember that the purpose of ducts is to efficiently convey the air or flue-gas from one location to another while, as much as possible, maintaining the temperature and pressure. The combustion process and pollution control considerations are just as important as the structural aspects addressed in this publication. Flow considerations, such as minimizing pressure drop and controlling ash deposition, are also essential to a good overall design. The ability to easily and accurately monitor pollutant levels and operating parameters, and the ability to easily perform maintenance, may be very important to the customer. Therefore, it is imperative that the structural engineer works closely with the other disciplines to coordinate the various design inputs and optimize the final overall duct design. This teamwork is especially critical in the early stages of a project - during the development of the duct and equipment arrangements.

2.1.1 Flow Considerations

Flow-related phenomena often have a large impact on both the initial cost and operating cost related to ducts. For example, significant flyash deposition caused by low flue-gas velocities or poor flow distribution will require a heavier duct and support structure to support the high ash loads. Also, an increase in pressure drop will require more auxiliary power to run the fans. Flow model tests can predict pressure drops, flow stratification, thermal gradients, ash deposition and liquid droplet re-entrainment. Flow model tests can also be used to help optimize duct layouts and the arrangement of flow distribution devices such as turning vanes, splitter plates and

perforated plates. If flow model tests are performed, the structural engineer should actively participate in the process so that structural design and constructability issues are addressed.

2.1.2 Design Process

The arrangement of a ductwork system, like any other engineered structure, should be performed with the goal of minimizing initial cost, optimizing overall constructability, optimizing system performance, and minimizing future maintenance costs. In some cases, these four general criteria influence design decisions similarly. For example, taking the most direct path between two points in the system is likely to result in both the most economical duct, because its length is minimized, and the lowest pressure drop, because turns have been avoided. In other cases, the design team must compromise between conflicting criteria. An example of this would be when the mechanical process engineer suggests using rounded corners, which would enhance the flow characteristics but would complicate the structural behavior and construction details.

The ductwork design process may vary considerably from individual to individual or company to company, but a typical design approach might have the following steps:

- 1) A mechanical process engineer prepares a flow diagram of the duct system, which indicates the path(s) the air and flue-gas must follow from its entry into the system, through the various pieces of equipment, and out the chimney or stack.
- 2) The mechanical process engineer reviews the combustion process and identifies the flow rates, pressures and temperatures in each section of ductwork. All transient pressures and excursion temperatures must also be included in this determination.
- 3) Physical arrangements of the duct system are developed based on actual or estimated equipment sizes. Initial duct sizing is usually based on maintaining the velocities in the various duct sections within an acceptable range; these initial sizes are then modified to take into account other factors such as space constraints, the flange size at equipment connections and possible fabrication, shipping and erection constraints. Routing of the duct segments from point to point within the system is influenced by space constraints, flow considerations, equipment criteria, available means of support and cost. Changes in duct

cross-section and changes in direction are typically minimized because of the effect on flow stratifications, turbulence and pressure drop. Flow model tests are often performed at this stage to verify performance assumptions and finalize pressure and flow criteria.

- 4) Expansion joints, dampers, supports, access doors, flow distribution devices, and internal structural elements are located by the project team. This step is often an iterative process involving both the structural and mechanical process engineers. Instrumentation and equipment to monitor flow, performance and pollutant levels should also be defined at this stage. The support structure arrangement should be developed in parallel with this stage of the duct arrangement.
- 5) The structural engineer selects the appropriate support types and identifies the locations to be anchored and guided. This effort must be closely coordinated with the location of the expansion joints. Thermal movements of each duct section are usually calculated at this point and used as input to the duct analysis and the expansion joint procurement.
- 6) The global and local structural analysis and design of the duct sections and their elements is performed by the structural engineer. Final arrangements and sizes for internal stiffeners, trusses, struts and flow distribution devices should be reviewed by the mechanical process engineer for their effect on flow and pressure drop.
- 7) The structural analysis and design of duct support structures and their foundations is performed by the structural engineer using the loads and eccentricities resulting from the duct analyses.

2.2 INTERFACES WITH EQUIPMENT

Ducts must interface with many different types of equipment which contribute to the combustion or pollution control process. Some equipment, such as an electrostatic precipitator or a fan, is external to the ductwork. In these cases the duct sections connect to a mating flange at the equipment inlet and outlet. Other equipment, such as a steam coil air preheater or a flue-gas conditioning system, is located inside of the ducts. This section will address the important aspects related to the interface between ducts and equipment. See Section 1.5 for a brief description of the most commonly encountered ductwork equipment.

2.2.1 Isolation of Major Equipment From the Ductwork

Generally, ductwork should be structurally isolated from major equipment such as fans and air pollution control devices. Isolation serves the following purposes.

- Isolation simplifies the structural analysis of the system by preventing the transfer of loads to and from the equipment across the isolation joint. This isolation makes the structural behavior more predictable.
- Isolation improves the ability of duct system components to expand and contract under temperature changes.
- Isolation reduces the transmission of vibrations from the equipment to the ducts.
- Isolation establishes a clear definition of responsibility between the equipment vendor and the duct supplier.

Equipment isolation is usually accomplished through the placement of an expansion joint where the duct attaches to major equipment. Non-metallic expansion joints provide the best isolation because of their very low, often negligible, stiffnesses in all directions. Metal expansion joints may be used if isolation is only required in the axial direction, although the greater stiffness of a metal joint will reduce its effectiveness as an isolator. Because of their greater stiffness, metal joints tend to transmit more vibrations, create greater thermal restraint, and develop more indeterminate load paths in the ductwork than do non-metallic joints. Therefore, the potential for transferring loads or vibrations to and from equipment should be investigated by the structural engineer when metal expansion joints are used. Non-metallic joints may transmit vibrations if they "flutter" in the flow; however, vibrations due to fluttering of non-metallic joints usually have an insignificant effect on the ductwork design. However, fluttering of any expansion joint should not be tolerated, since the joint will eventually fail if the flutter is not eliminated.

2.2.2 Fans

There are many types of fans that can be present in a ductwork system, as discussed in Section 1.5. When arranging the ductwork adjacent to a fan, the performance of the fan and the effects of the fan on the duct must be considered. The fan manufacturer may have restrictions on the minimum uninterrupted length of duct or

the shape of transition sections on either side of the fan. The fan manufacturer may also recommend minimum distances between the fan and internal duct elements such as structural trusses, struts or flow distribution devices.

In the absence of specific criteria from the fan manufacturer, the design team should consider providing a constant duct section at the fan outlet with no internal elements for a length equal to the "100% effective duct length" as defined in Section 8 of the Air Movement and Control Association, Inc. document 201-90, *Fans and Systems*. This publication sets the 100% effective duct length equal to $2\frac{1}{2}$ duct equivalent diameters for a flow of 2,500 cfm (70 cubic meters per minute) or less and adds 1 duct equivalent diameter for each additional 1,000 cfm (30 cubic meters per minute) of flow. The equivalent diameter may be taken as 1.13 times the square root of a rectangular duct's area. Internal duct elements definitely should be avoided within this length of duct. Failure to meet requirements such as this could be detrimental to the performance of the fan or could be cause for voiding of the fan warranty. Structural damage to the fan or duct from flow related vibrations may also result.

2.2.3 Equipment Removal

The layout and design of ductwork systems must often consider the ability of the owner to maintain equipment near, under, around or even within the ducts. The arrangement must ensure that the ducts and their supporting structures do not infringe on the space required to replace or maintain nearby equipment. Removable panels may need to be provided in the duct walls to allow for the removal of large pieces of equipment, such as fan wheels, or access hatches may be required to replace mechanical systems located inside the ducts, such as the catalyst bed of a selective catalytic reduction system. Trolley beams may be supported from the ducts or their supporting structures to assist with the equipment maintenance or removal. All of these factors should be reviewed by the design team and the customer prior to finalizing the ductwork system layout.

2.2.4 Dampers

Dampers are an essential part of most duct systems, since they control the flow of air or flue-gas through the ducts. Most dampers function as shut-off dampers and, in any given operating scenario, are either fully open or fully closed. Some dampers, however, are installed to modulate the gas flow and therefore function in various partially open positions.

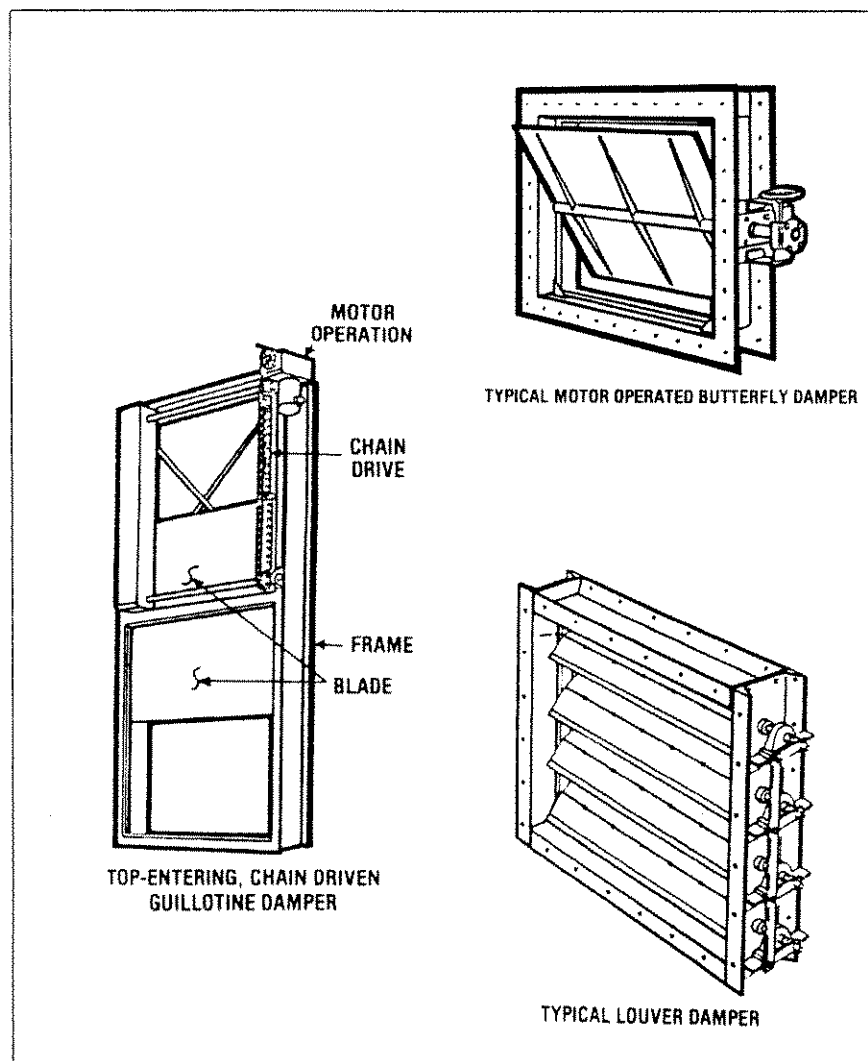


Figure 2.1
Damper Types

Figure 2.1 shows the three most common types of dampers - louver, butterfly and guillotine. There are also other types of less commonly used dampers, such as poppet dampers. Guillotine dampers usually have a single blade that slides in and out of the flow path, although some large dampers may have two opposed blades. Guillotine dampers are almost always used as shut-off dampers, and they generally function best if the blades are kept in a vertical plane. If a damper is used as a shut-off in ducts where humans may be working, a double blade guillotine damper or a single blade damper with a seal air system is usually used. Louver dampers have one or more rotating blades and may be used as either shut-off or flow-regulating dampers.

When dampers are located next to expansion joints, it is usually better to place the damper on the upstream side of the joint. As shown in Figure 2.2, this arrangement allows the internal pressure forces to cancel in the upstream duct section, thus avoiding unbalanced pressure loads on the downstream duct section. This arrangement may also increase the useful service life of the expansion joint by reducing its exposure to the flow environment. Additionally, and perhaps most important for ducts carrying air or flue-gas at elevated temperatures, in this arrangement the damper will be hotter than the downstream, inactive duct section. Placing the damper upstream of the expansion joint allows the hot damper to be structurally isolated from the cold duct, reducing the potential for high stresses in the duct and damper frame caused by the large difference in temperatures.

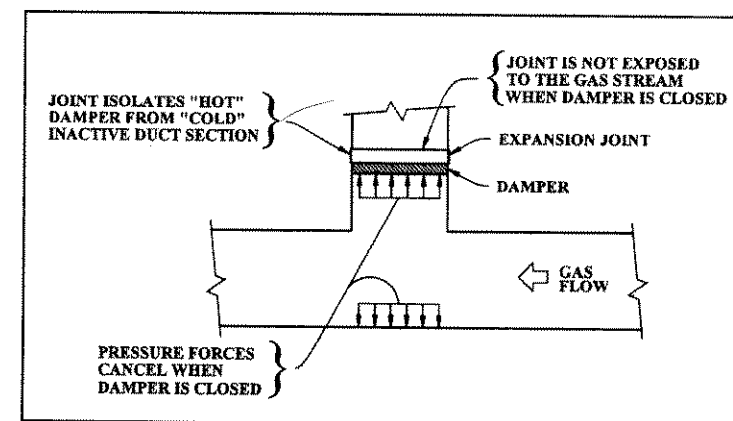


Figure 2.2
Preferred Damper Location Relative to an Expansion Joint

Dampers are usually quite heavy. The bonnets of guillotine dampers also represent large surface areas for wind load and drifting snow load. Because of these loads, the structural system will usually be most efficient if dampers are located as close to the duct supports as possible. Also, unless the damper manufacturer has been specifically instructed that the damper is to be an integral part of the structural system of the duct, the damper frame is unlikely to have enough strength or rigidity to transmit very large shears and moments. Warping of the damper frame, as it tries to transfer loads and elastically deflects with the duct, may adversely affect the ability of the damper to function properly. Therefore, dampers should be located in regions of low stress, such as adjacent to expansion joints. For similar reasons, ductwork should not be supported from dampers. Whenever a damper is located adjacent to an expansion joint, enough clearance must be provided so that the expansion joint material does not interfere with the damper blade movement.

In general, shut-off dampers should be located in such a way that "dead legs" are minimized. As shown in Figure 2.3, dead legs are sections of duct that are open to the flow at only one end because the damper at the other end is closed. Crossover and by-pass ducts are typical locations where dead legs are encountered. By carefully locating dampers, dead legs can be avoided or at least minimized.

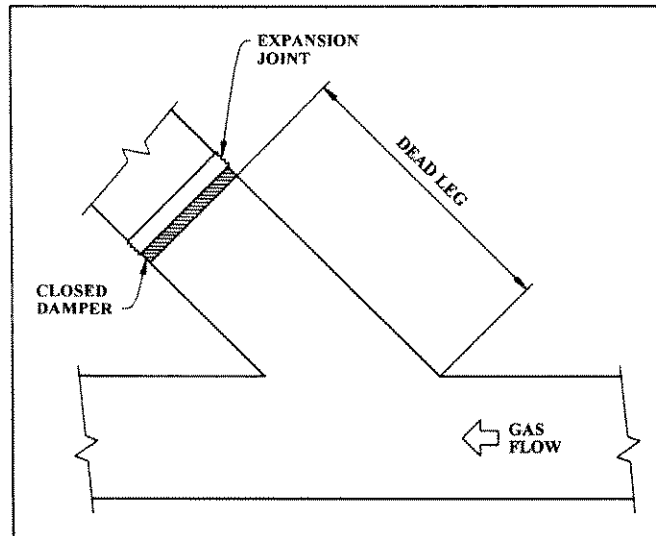


Figure 2.3
Example of a Dead Leg Duct Section

Some concerns associated with dead leg sections of flue-gas ducts follow.

- Stagnant flue-gas within the dead leg may cool off enough so that its temperature will drop below the acid dew point, resulting in an increased corrosion rate of the exposed internal duct surfaces.
- Cooling of stagnant flue-gas in the dead leg may introduce appreciable, undesirable thermal gradients into the ductwork structure. Thermal gradients are discussed in various sections of this document, including Section 2.7.
- Because the flue-gas flow is relatively stagnant in a dead leg, flyash will drop out of the flow stream. The resulting accumulation will increase the gravity load and contribute to the development of thermal gradients in the duct. This effect is discussed further in Section 2.7.
- The duct plate and internal elements in the dead leg will be exposed to the operating environment even though the duct is not conveying any flue-gas. External stiffeners will also be subjected to the operating loads and service temperatures. This exposure may result in a decreased service life when creep or corrosion are significant factors.
- During transient pressure or excursion temperature events, the dead leg may be unnecessarily exposed to adverse conditions it might otherwise be protected from.

Dead legs in air ducts are less of a concern than in flue-gas ducts due to the less severe design conditions associated with the air side of the combustion process.

Locating dampers in toggle duct sections should be avoided whenever possible. The three directions of movement of the toggle duct section could adversely affect the alignment of the damper frame and the damper actuator. In addition, the toggle duct section and its supports would be subjected to large forces from the damper. These forces would come from the damper weight, actuation forces, unbalanced pressure, and wind on the open damper blade. This additional loading is not desirable because toggle duct sections are meant to be relatively flexible and light since they are designed to move a considerable amount, as shown in Figure 1.7 and Figure 2.5.

2.2.5 Flue-Gas Monitoring Instruments

Government regulations often require the monitoring of flue-gas for levels of various pollutants. In addition, the owner may want to monitor system operating data. The instruments required to collect this data can be very sensitive to stratification of the flue-gas stream. Therefore, to ensure that representative data are collected, special criteria often must be followed regarding the placement of flow or emission monitoring equipment within the ductwork. For example, a common requirement is that an instrument must be located in a straight section of duct a certain minimum distance to bends or significant flow obstructions both upstream and downstream of the instrument. These distances are usually tied to the duct cross-sectional dimensions, such as a multiple of the equivalent duct diameter. A length of 8 equivalent duct diameters is not uncommon, but this value must be provided by the governing authority. These requirements can dictate the placement of equipment, the arrangement of certain duct sections, or the location of internal trusses and flow distribution devices. Consequently, the flue-gas monitoring systems should be defined and conceptually designed in parallel with the development of the duct arrangements.

2.2.6 Access Doors

Most ducts are provided with ports or doors for maintenance access. The number, location and type of doors required is dependent on the duct arrangement, the type of equipment and instrumentation in the duct system, the duct maintenance requirements, and the owner's preferences. The door locations should be coordinated with the layout of the duct support structure and the other access platforms provided for the plant. The doors and hardware must be designed for the duct pressures and they must be air-tight. Doors in insulated ducts should be well insulated to prevent corrosion caused by local cold spots. Section 11 contains more discussion on door insulation. Hinged doors with quick-opening latches are most convenient for examination and maintenance personnel but are more difficult to seal and insulate than removable bolted panels. A minimum size of 18 inches by 24 inches (0.45 meter by 0.60 meter) is generally recommended, but smaller doors are often used for economy. Larger doors are sometimes used because they are more convenient for plant maintenance personnel. Handholds and ladder rungs are often welded to the duct walls next to the doors to make passage easier. Depending on the location of the doors, sometimes handrails are required within the ductwork to protect personnel against accidentally falling into equipment or down a vertical duct section.

2.3 THERMAL EXPANSION

Most ducts convey heated air or flue-gas at temperatures well above ambient. Even ducts conveying combustion air are frequently exposed to elevated temperatures because preheaters are installed to heat the air to improve the efficiency of the combustion process. The structural analysis and design of ducts at elevated temperatures must consider several significant issues to accommodate the thermal expansion and contraction that will occur.

2.3.1 Expansion Joints

Expansion joints are introduced to a ductwork system to allow the ducts to expand and contract in a relatively unrestricted and controlled manner. Expansion joints allow thermal movements while limiting thermally induced stresses in the equipment, ductwork and duct support structures. They also may be used to isolate duct sections from equipment, as explained in Section 2.2.1, or to enhance the ductwork's structural determinacy, as discussed in Section 2.4.2.

Expansion joints are either made out of some sort of fabric or rubber-like material or light gauge convoluted metal. They are termed as being either non-metallic expansion joints or metal expansion joints. Because expansion joints are more flexible in their axial direction - along the duct longitudinal axis - than they are in shear, they are most efficient when they are located so that they will not be exposed to large transverse movements.

An expansion joint is limited in the amount of movement it can accommodate. A standard 12 inch (300 mm) wide non-metallic joint of a given design from a given manufacturer will only be able to accommodate a certain amount of axial and transverse deformation before the material fails. Larger deformations would require a different joint design and the joint manufacturer would have to be consulted. Metal joints will typically have more severe limitations than non-metallic joints. In addition, as discussed in Section 2.2, metal joints are much stiffer than non-metallic joints and can transmit more loads and vibrations, which should be considered in the ductwork design. It is extremely important to establish early in the ductwork layout stages the type of joint that will be used for each duct section and the deformation and temperature limits for each joint used.

Careful placement of expansion joints gives the structural engineer some control over the unbalanced pressure loads transmitted to the supporting structure as illustrated in Figure 2.4. Expansion joint placement will also affect the friction loads generated at the support points as bottom-supported ductwork expands and contracts.

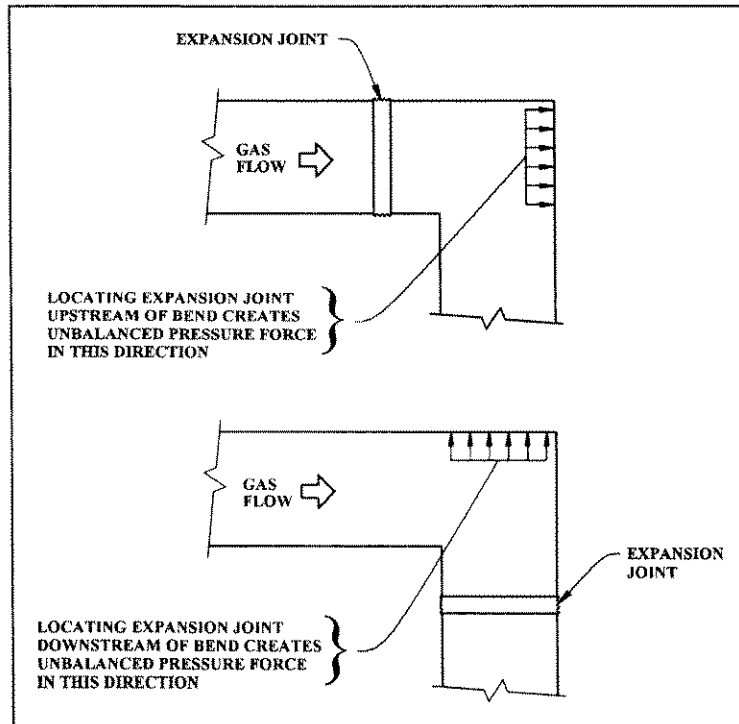


Figure 2.4

Example of the Effect of Expansion Joint Placement on Loads

Expansion joints should not be added indiscriminately to a system, but should be used only where there are clear benefits. They usually are both a high capital cost item and a high maintenance item because repair or replacement may be required every several years. They can also indirectly have a detrimental effect on the adjacent ductwork, since their need to deform makes them difficult to effectively insulate and weatherproof. This problem may lead to cold spots in the ductwork, which could increase thermal gradients or promote corrosion. This occurrence is discussed further in Section 11.6.

2.3.2 Toggle Duct Sections

Toggle duct sections are made by installing metal or non-metallic expansion joints on both ends of a short duct section in order to accommodate large differential transverse deflections between the two adjacent duct sections. The toggle duct section is usually supported from the adjacent duct sections with sliding, slotted pinned connections, or by the shear stiffness of metal expansion joints if the loads are relatively small. The expansion joints then act like sliding hinges in the duct system. Figure 1.7 and Figure 2.5 illustrate a typical toggle duct section.

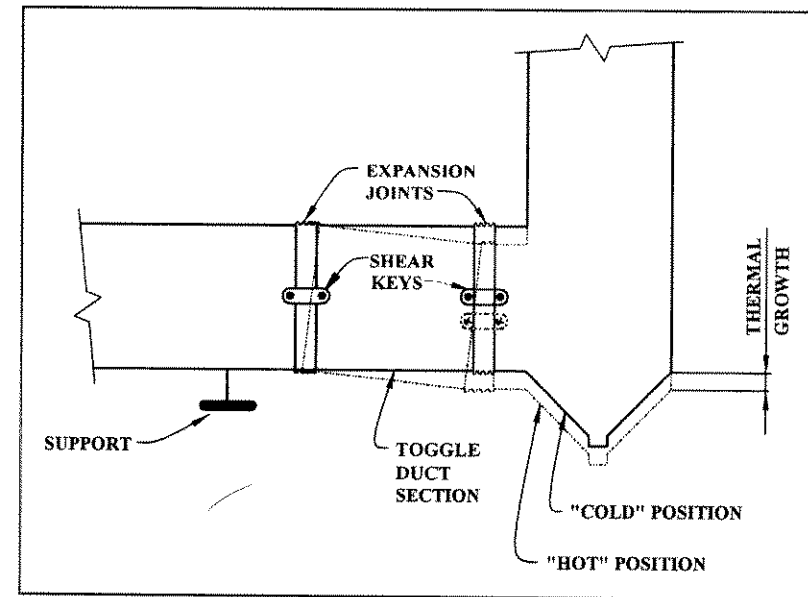


Figure 2.5

Typical Arrangement With a Toggle Duct Section

2.3.3 Location of Anchors and Guides

The supports of a duct system generally consist of gravity supports and a combination of anchors, lateral supports and guided supports. The gravity supports may be hangers or bottom supported posts. The bottom supports may be the anchor, guided supports and unguided supports. Ducts carrying air at ambient temperatures sometimes are directly attached to their support structures since thermal expansion may not need to be accommodated.

All gravity loads, externally applied loads, such as wind, and internally applied loads, such as pressure, must be resisted while still allowing the duct relatively unrestrained thermal growth. Figure 2.6 shows a typical support arrangement for a simple, bottom-supported duct section.

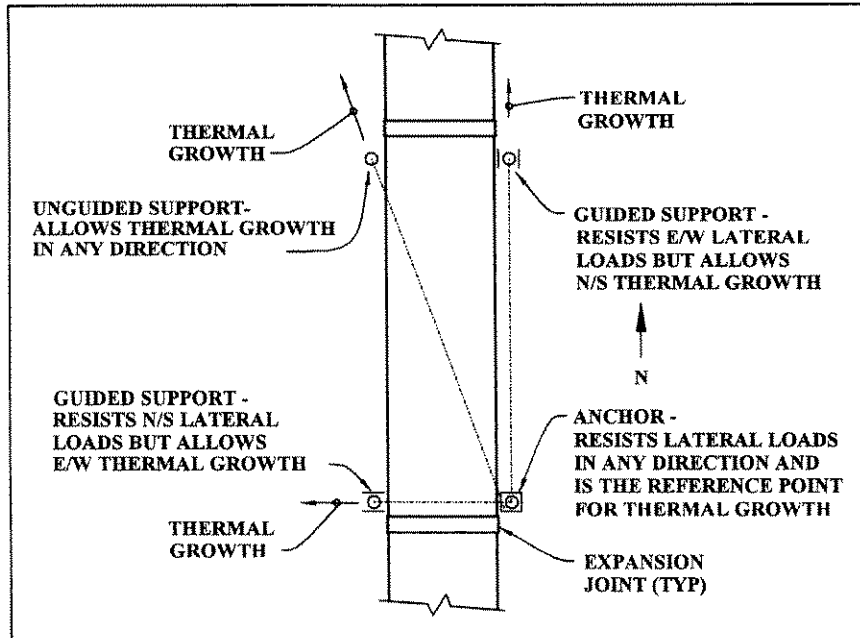


Figure 2.6
Typical Duct Anchor and Guide Arrangement

Anchors and guides should form a lateral load resisting system with the least possible restraint to thermal growth while still maintaining the structural stability of the duct section. The selection of the anchor point and the guide locations should consider the ability of the support structure and foundations to resist the duct's vertical and lateral loads; the relationship of the duct to adjacent equipment; the desired level of indeterminacy in the support system; and the effect on expansion joint deformations. The support locations need to be carefully coordinated with the support steel layout. In an efficient support structure, the duct anchors and guides are provided on the support structure's column lines. Other considerations related to duct supports are discussed in Section 2.4.

For duct sections which have multiple sets of supports, it is best to place the anchor point near the center of mass of the duct section. This will reduce the friction forces on certain duct elements, as shown in Figure 2.7.

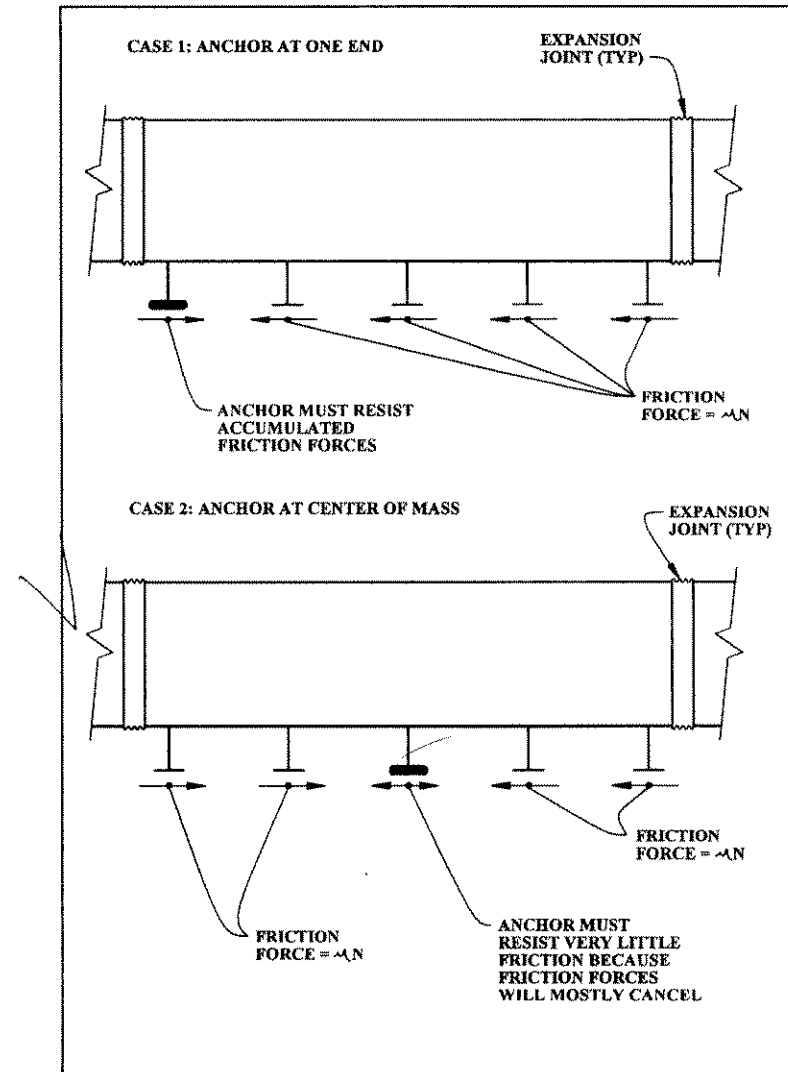


Figure 2.7
Locating the Anchor Point at the Center of Mass

Anchors are typically formed by bolting or welding the duct directly to its support structure. Guides are most often formed by installing bumpers or guide bars at duct sliding support points, as shown in

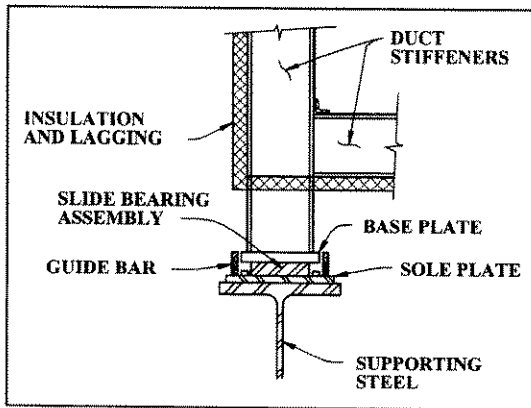


Figure 2.8
Typical Guided Bottom Support Detail

Figure 2.8, or by loosely bolting the duct to its support structure using slotted holes. Guides and slotted holes must always be oriented so that the expected thermal movement of the duct is in line with the anchor point. Sometimes there can be performance problems with slotted hole details. If they are not installed properly, the bolts may shear off and the guide detail would become ineffective. An orthogonal guide system is generally easier to fabricate and erect.

Duct guides can be arranged in such a way that a tangible anchor point is not needed. Where two lines of guides intersect, a virtual anchor location is formed even though there is no physical attachment to the support structure at this location. This arrangement is shown in Figure 2.9. When guided in this manner,

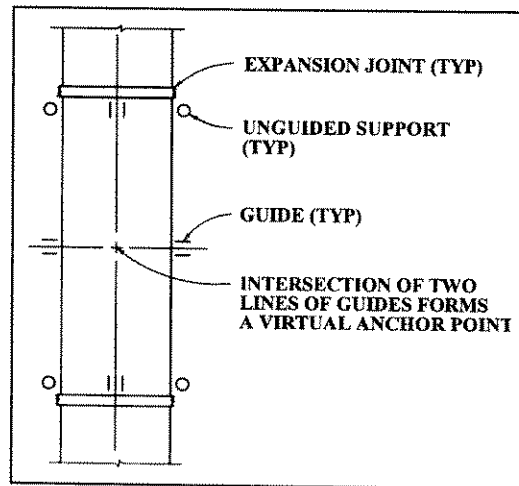


Figure 2.9
Virtual Anchor Point

the duct will expand in all directions from this virtual anchor point as if a real anchor was present. The guides must be designed for all loads considering that there is no true anchor present.

2.3.4 Slide Bearing Plates

Slide bearing plates are commonly used to reduce the frictional forces which develop between the base plates of bottom-supported ducts and the support structure as the duct expands and contracts under temperature changes. Many different types of slide bearing plates are available. Most have a maximum coefficient of friction between 0.05 and 0.15. The actual coefficient of friction varies with many factors, including the mating surface materials, the age and condition of the slide bearing plate, the service temperature, and the bearing pressure. The coefficient of friction that is assumed in the structural analysis should be based on the range of values expected over the plate's entire design life, which may not be the same as the value published for a new plate.

Two types of slide bearing plates are available - flat and spherical. Flat slide bearing plates are used when little or no relative rotation is expected at the mating surface. If appreciable rotation of one surface relative to the other is anticipated, then spherical slide bearing assemblies may be specified. As shown in Figure 2.10, a spherical assembly actually consists of two separate sliding surfaces. One is a flat surface that allows relatively free translation and the other is a spherical surface that allows relatively free rotation.

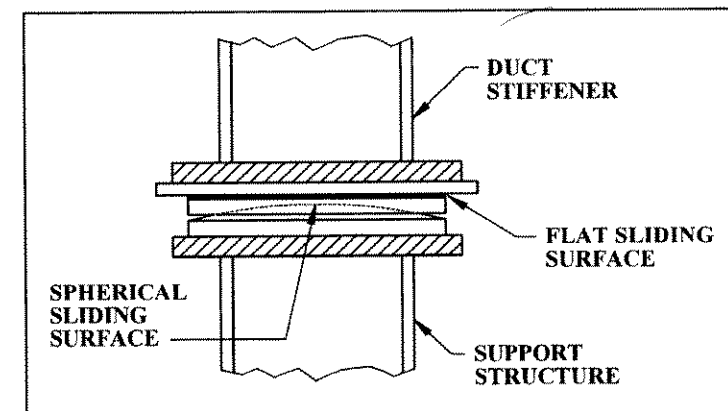


Figure 2.10
Typical Spherical Slide Bearing Plate Assembly

Roller duct supports are sometimes used in lieu of slide bearing plate assemblies. The performance of rollers is very sensitive to their orientation, since relatively unrestricted thermal movement must occur in order for the support to function properly as designed. The rigidity and hardness of the roller are very important to its design, since a roller which will deform under the duct's loads may not operate freely. Roller design details should include provisions for keeping debris out of the roller's path so that the roller is free to roll. With the current successful performance of relatively inexpensive slide bearing plate assemblies, rollers are very seldom used today under ducts.

2.3.5 Clearances

When arranging a ductwork system, the design team must always consider that ducts conveying air or flue-gas at elevated temperatures are not stationary structures. Because of thermal expansion, some points on the ducts may move several inches in all three directions between their cold and hot positions. The expected range of movements must be calculated and adequate clearances to adjacent structures and equipment must be allowed. In addition to considering thermal expansion and contraction, the calculation of clearances needs to include adequate margins for final stiffener sizes, insulation and lagging details, and fabrication and erection tolerances. Structural deflections of the ducts and their support structure may also need to be accommodated if they are expected to be significant. Usually, the structural deflection of ductwork is negligible, but often the duct's supporting structure has some flexibility. Adequate clearance for construction access to erect the ducts and install the insulation and lagging also needs to be provided. Adequate clearance is also required at duct access doors and for access platforms.

2.3.6 Support Eccentricities

As discussed above, ducts which convey air or flue-gas at elevated temperatures will experience significant thermal expansion upon unit start-up. This three dimensional expansion will result in a change in the position of all duct supports which are not anchored. At the same time, however, the support structure is at ambient temperature and thus remains stationary. As a result, the eccentricity of the duct support with respect to its support structure will change as the duct heats and cools. Significant stresses may result in both the duct and the support structure because of the moments and torsional couples induced by this eccentricity. The structural engineer needs to be

aware of this phenomenon and adequately account for it in the design of both the duct support elements and the duct support structure. A common practice to minimize the effects of eccentricities induced by thermal expansion is to initially offset the duct support point from its supporting structure by an amount equal to one-half of the expected movement at the duct's operating temperature. In this way the eccentricities in both the hot and cold conditions are roughly equal, although opposite. This arrangement is shown in Figure 2.11.

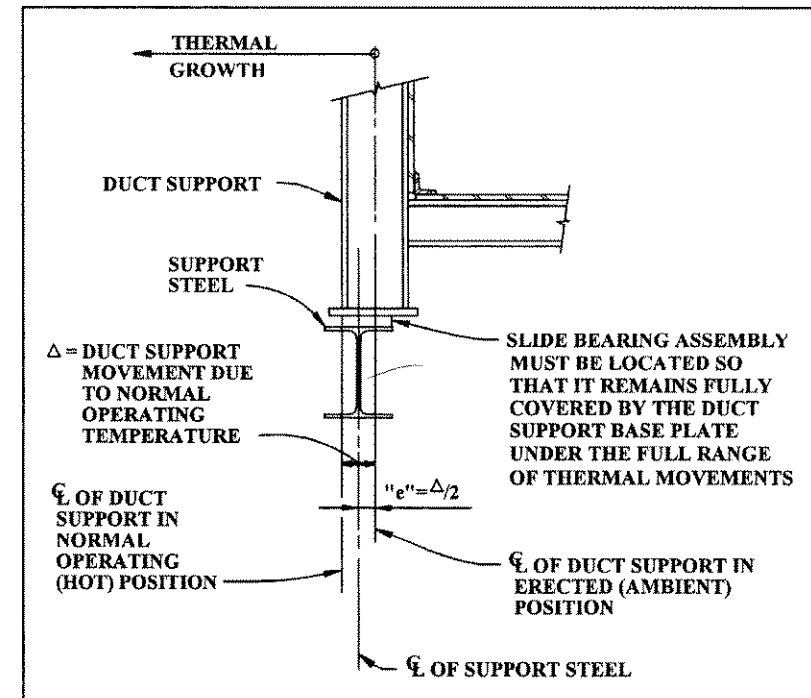


Figure 2.11
Initial Offset of Bottom Support to Reduce Eccentricity

2.3.7 Attachment of Cold Items to Ducts

A great deal of care must be taken when items such as electrical conduits, ladders and access platforms are supported from ducts conveying air or flue-gas at elevated temperatures. Details must be used that allow differential thermal expansion and contraction between these items and the hotter ducts. Otherwise, significant

forces may develop and failures may result. Elements which remain essentially at ambient temperatures should never be rigidly attached at two or more locations to ducts conveying air or flue-gas at elevated temperatures. Typically, one end will be rigidly attached to the duct, while the other end is allowed to move freely in the direction of thermal expansion.

Similarly, duct guides or bumpers, support brackets and duct support legs which extend outside a duct's insulation and lagging will be exposed to the ambient air and thus may be at a lower temperature than the duct to which they are attached. Construction details for these elements must be designed considering this temperature difference or else damage could result.

2.4 SUPPORTS

Most ductwork is supported by structural steel framing, although occasionally an arrangement will allow the ducts to be supported directly on the foundations. The duct support structure layout should be developed in conjunction with the ductwork arrangement to optimize support locations, support types, foundations and access platforms.

The design of structures supporting ductwork needs to consider the following factors, which are usually not significant in the design of typical building systems.

- Torsional effects are almost always present, in at least some parts of the structure, due to the frictional forces and support eccentricities that develop as the ducts expand and contract.
- Localized stresses, such as local flange or web bending, are often significant at duct support points, due to the large, concentrated forces and support eccentricities.
- Heat transfer from the ducts to the support structure can result in high thermal stresses in the support steel. This effect depends on the operating temperature of the duct, the geometry of the interface and the duct insulation details. This occurrence is often critical for support members framing through the crotch of hoppers in hot ducts.
- The stiffness of structures and foundations supporting indeterminate ducts can have a profound effect on the distribution of loads to the duct support structure.

- Duct support structures may have unique temporary loads due to duct construction methods or sequencing.

The following sections discuss some of the other significant issues that the structural engineer needs to address when determining how to best support the ductwork.

2.4.1 Support Locations

For the most efficient duct support structure, the duct supports should be located on support structure column lines whenever possible. This will create the most direct load paths to carry the duct loads to the foundations. The duct support locations and support structure framing should also be arranged to allow the friction and unbalanced pressure forces to cancel as directly as possible, as shown in Figure 2.12. This will avoid the need to design the support structure's bracing and foundations for these loads.

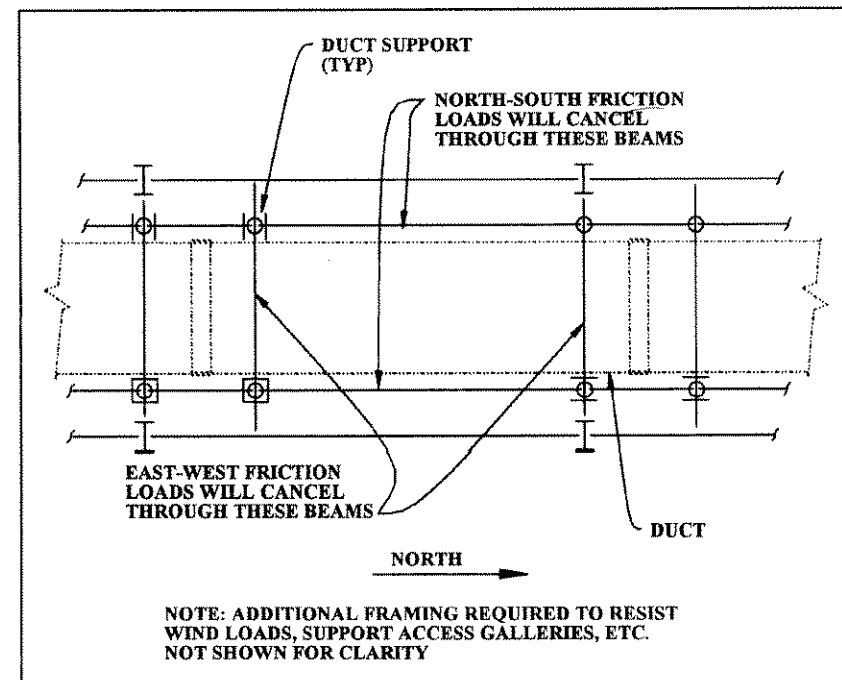


Figure 2.12
Example of Support Steel Framing Which Allows Friction Forces to Cancel

2.4.2 Structural Determinacy of Ductwork

Structures are statically determinate when the accuracy of their structural analysis is independent of the stiffness of the structure itself and its supports. In reality, since ducts are three-dimensional stiffened plate structures, very few are truly statically determinate. However, as discussed in Section 7, structural engineers commonly analyze ductwork as a system of planar structures which can each be individually classified as determinate or indeterminate. This approach is very similar to the common practice of taking a three dimensional building structure and analyzing it as a series of determinate horizontal floors and vertical frames. One of the most significant decisions to be made by the structural engineer is whether the ductwork will utilize determinate or indeterminate support systems.

Indeterminate Ducts

Indeterminate structural systems often have a lower initial cost than determinate systems because there is usually less material. If arbitrary minimum stiffener sizes or plate thicknesses do not apply, an indeterminate duct will usually be lighter, and therefore less costly, than a similar determinate duct. However, especially in hot flue-gas ductwork applications, the behavior of indeterminate ducts can be unpredictable. This unpredictability can lead to unforeseen problems with locally overstressed components, potential failures and increased maintenance. Because of these reasons, structurally determinate ductwork systems usually should be chosen whenever practical. When the use of indeterminate duct sections are unavoidable, or when indeterminate support systems are chosen for their apparent economy, the structural engineer must attempt to perform the structural analysis of the ducts and support structures as accurately as possible. This effort may result in a more rigorous analysis than a determinate system would require, since the validity of the assumptions upon which an indeterminate structural analysis is based will have a significant impact on the structural behavior. This approach is discussed in more detail in Section 7.

When indeterminate ductwork systems are used, factors such as the duct stiffness, the support structure stiffness, foundation settlement, and thermal gradients within the ductwork all have a significant impact on the distribution of forces through the structural system. These unpredictable situations often lead the structural engineer to build extra contingencies into the design of the support structure and the ducts which may negate the intended material savings of using an indeterminate system. For example, a duct with multiple sets of

supports may be designed for the full positive moment from the global analysis, $wl^2/8$, ignoring that the duct's continuity could allow a design moment as low as $wl^2/12$. Another typical example is where the support loads may be increased by some factor to account for any potential modeling inaccuracies or variables in the ductwork structural analysis. These contingencies would be a way to allow for the possibility that the actual distribution of the loads to the supports may vary from that calculated in the structural analysis. The application of such contingencies would tend to reduce the indeterminate duct system's cost advantage when compared to a determinate duct system.

A straight duct section supported at three locations (six points) along its length, as depicted in Figure 2.13, should be considered

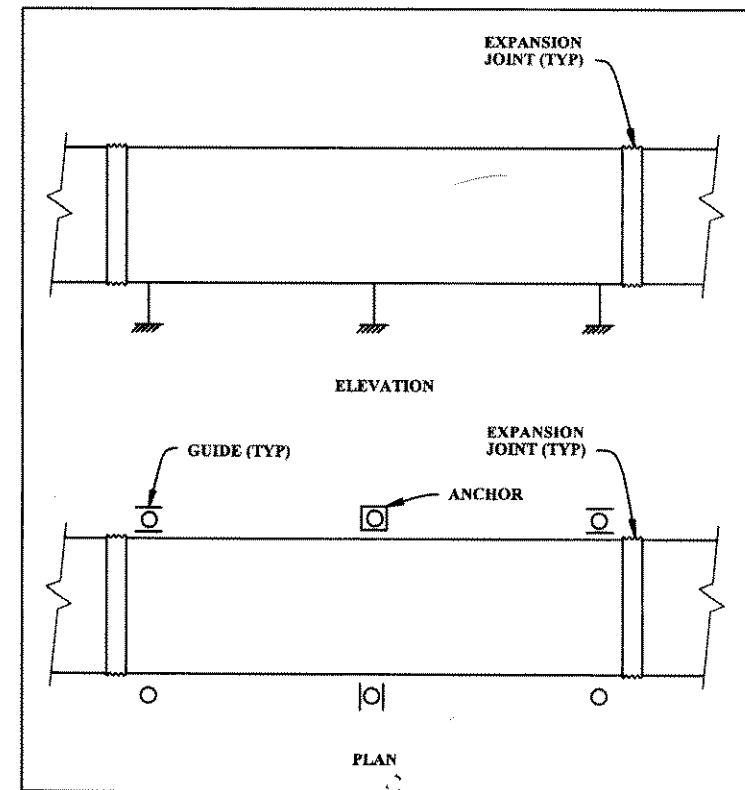


Figure 2.13
Example of an Indeterminate Duct Section

structurally indeterminate. In order to accurately analyze this duct, the structural engineer must calculate or assume the stiffnesses of both the duct and its support structure. This can be a time-consuming, iterative process. In addition, especially for foundations, the stiffness values may not be reliable. If the actual stiffnesses in the as-built structure do not match those used in the analysis, the analysis results may be invalid. Similarly, if the foundations under the supports do not settle in the same way that was assumed in the analysis, the distribution of loads to each support point will change. The accuracy of settlement calculations can be very dependent on the structural engineer's ability to accurately estimate the magnitude and duration of loads, but some of these loads, such as live load, ash weight and wind, may actually be extremely variable. If the duct is subjected to a thermal gradient, the gradient will try to bow the duct. This bowing will then cause the gravity loads to redistribute among the various supports. The construction sequence or method may also affect the dead load distribution in an indeterminate duct section, since most indeterminate ducts are erected in several pieces which are then field spliced in place after they are placed on the supports. Since all of the above factors can be present simultaneously, the inaccuracies introduced by using a structurally indeterminate duct system can become quite significant.

Determinate Ducts

If the same duct were to be supported at only two locations (four points) along its length, as shown in Figure 2.14, it can usually be considered structurally determinate. The distribution of loads to each support would be relatively unaffected by duct stiffness, support stiffness, foundation settlement, thermal gradients or construction sequencing. Although the same size duct would have to span farther than it would if it had multiple support points, the analysis results would be very reliable. Behavior of the duct section would be extremely predictable, adding contingencies to the design would be unnecessary, and the potential for overloading components would be reduced.

To summarize, although indeterminate ductwork has been used successfully in many installations in the past, statically determinate ducts exhibit more predictable behavior and are therefore less likely to experience local overloading and potential failures. For this reason, determinate systems are encouraged whenever practical. In locations where indeterminate ducts are unavoidable, the structural engineer must perform a structural analysis and design that takes all potential concerns into account.

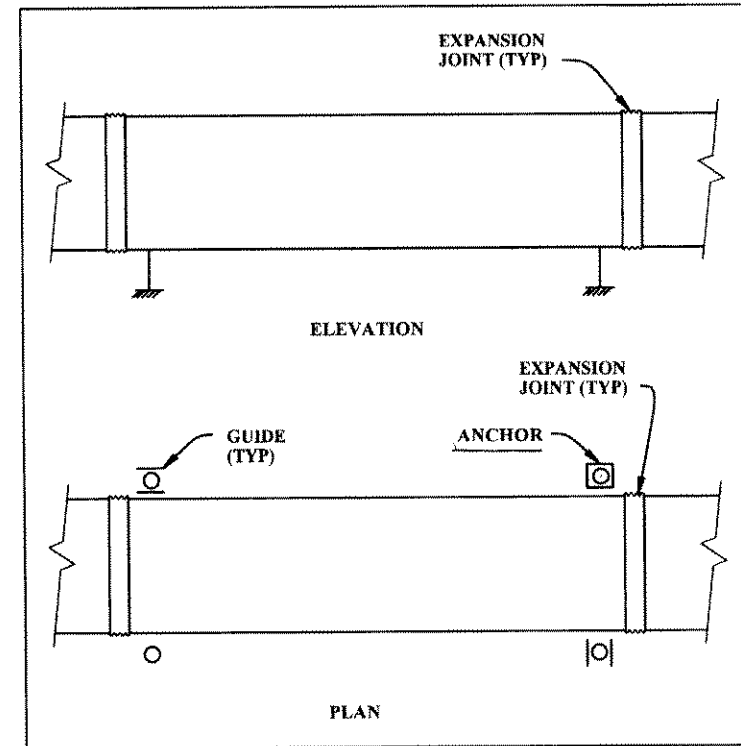


Figure 2.14
Example of a Determinate Duct Section

2.4.3 Hangers Versus Bottom Supports

Ducts may be supported in a variety of ways. The best way to support a particular duct section is dependent on many project specific factors. However, most duct sections can be classified as being either hanger supported or bottom supported. Regardless of which support type is employed, anchors and guides are needed to control thermal expansion and resist lateral loads.

Hangers

There are three basic types of hangers: rigid, variable support spring and constant support spring. Hangers are used more often in indoor applications than outdoor applications because support steel above the ducts is usually more readily available inside buildings.

Hangers have the following advantages over bottom supports.

- Hangers are efficient structural members, since they are loaded in pure tension.
- Using hangers near the top of vertical sections of ductwork may result in a more economical duct design, since the duct plate will be in tension under gravity loads.
- Hanger connections can easily be designed to allow the hanger to pivot about its ends, by using rod and clevis hangers or rocker details. This can be a simple, effective way to provide a true pinned connection and accommodate thermal expansion of the duct.
- Frictional forces are practically eliminated with hangers. Pin rotational friction is still present, but it is usually small and is typically neglected.
- The use of constant support spring hangers can help mitigate the uncertainties associated with indeterminate duct support systems.
- Hangers are usually more cost-effective than saddles for supporting circular ducts.
- Hung ductwork can usually absorb energy better than bottom supported ductwork during seismic loading, since there is typically a significant amount of damping associated with the pendulum effect as the ducts sway on their hangers. Also, it will not be catastrophic if a lateral bumper fails since the hangers will still keep the duct from permanently displacing laterally.

The following disadvantages are associated with using hangers as duct supports.

- Failures associated with hangers are likely to be severe, since tension failures are often a total fracture of an element. Once a hanger or gusset plate fractures, its total load must be redistributed to the other supports. If a progressive failure is triggered, there is often nothing to prevent the duct from dropping a significant distance and causing damage to additional areas of the plant.

- The duct support structure receives its loads at a higher elevation, which may penalize the support structure and foundation design.
- Spring hangers require periodic adjustments and maintenance. They also require careful installation.
- Hangers alone usually cannot resist horizontal loads, thus bumpers or lateral ties must be added.
- Hung ducts can be more difficult to erect than bottom supported ducts, since the supporting steel must be erected before the ducts can be hung from it. This could create access restrictions which would preclude the preassembly of large duct sections.

When hangers rotate due to thermal expansion of the duct, the hanger needs to be long enough to keep the angle of rotation relatively small. Usually, hangers rotation should be kept at an angle of less than about 5° . Also, as described in Section 2.3 for bottom supports, hangers may be installed with an offset to minimize the effects of rotation. If a hanger is allowed to rotate excessively, the angle will induce large lateral forces into the support system and the duct will try to lift up, as shown in Figure 2.15.

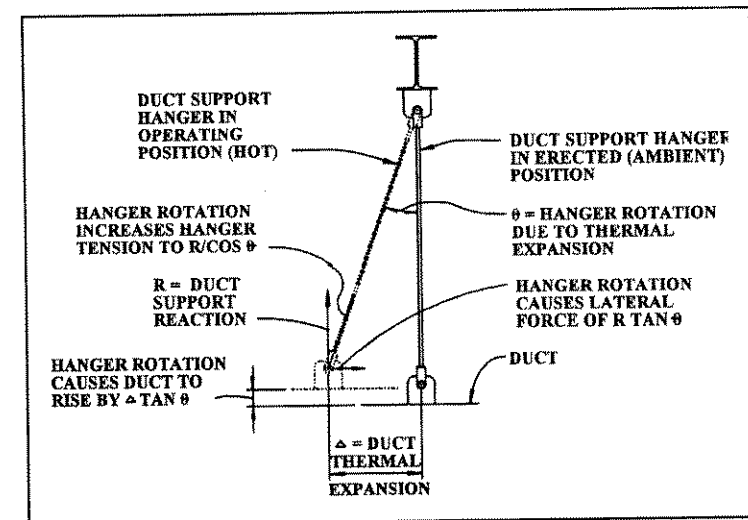


Figure 2.15
Effect of Hanger Rotation

The structural engineer should ensure that there is enough clearance in the hanger pin holes if the details are oriented such that the thermal movement of the duct is not in the same direction as the clevises would normally rotate about their support pins.

Bottom Supports

Bottom supports are generally achieved by extending selected duct side wall stiffeners past the bottom of the duct. Sometimes an independent post comes off of the stiffened duct bottom. A base plate is attached which bears on the support structure usually through a slide bearing plate assembly. This detail is shown in Figure 2.8. A system of anchors and guides is used to control thermal expansion and slide bearing plates are usually used to reduce the frictional forces at the base plates. This type of support system is discussed in Section 2.3 and is shown in Figure 2.6.

Bottom supported ducts have the following advantages over hangers.

- Failures associated with the bottom supports are unlikely to result in total loss of support for the ductwork.
- Bottom supported ducts are relatively easy to erect, since large sections can be preassembled and set directly on top of the support structure.
- The duct support structure receives its loads at a lower elevation, which may result in a more economical support structure and foundation design.
- Anchors and guides can be easily incorporated into the bottom support base plate designs without having to add bumpers or lateral ties.

The following disadvantages are associated with using bottom supports for ducts.

- Frictional forces will develop at the support points as the ducts expand and contract due to thermal expansion. Even with the use of low friction slide bearing plates, these friction forces can be sizeable.
- Bottom supports often load the support structure eccentrically because the supports move as the duct thermally expands while the duct support structure remains stationary.

- Vertical offsets are usually more difficult to accommodate in a duct section when bottom supports are used.

2.4.4 Spring Hangers Versus Rigid Hangers

Rigid hangers are usually preferred, because they require little or no maintenance and they cost less than spring hangers. However, the use of spring hangers may be beneficial under certain circumstances. The most common reason to use spring hangers is to accommodate vertical thermal movements at the support points. Constant support spring hangers may be used to alleviate the uncertainties associated with the analysis of indeterminate ductwork systems.

2.4.5 Support Elevations

Whenever possible, all supports for sections of ductwork which convey air or flue-gas at elevated temperatures should be located at a common elevation. This is the best way to accommodate thermal expansion and contraction. As a minimum, all supports must be located in the same plane. If all the supports for a duct section are not in the same plane, then one or more of the supports will try to lift off the support structure as the duct thermally expands. This lack of support contact can result in significant load redistributions.

Having all supports at the same elevation is especially important for bottom supported ducts, since slide bearing plates work best when the mating surfaces remain parallel. Relative rotation between the mating surfaces will result in uneven loading on the slide plate, which may damage the slide plate or cause it to lock up. This condition can be alleviated by installing the slide plates at an angle in line with the anchor point, as shown in Figure 2.16, or by installing spherical slide bearing plate assemblies instead of flat slide bearing plates. However, the structural engineer should consider that fabricating and installing base plate details at precise angles is difficult, slide plates installed at an angle will induce large, undesirable lateral gravity forces into the support elements, and spherical bearing assemblies cost more than flat slide plates. Using hangers instead of bottom supports could alleviate these conditions.

2.4.6 Support Structure Stiffness

The stiffness of the support structure is usually only an issue if the duct is structurally indeterminate, as discussed in Section 2.4, or if adjacent supports on opposite sides of a duct section have a vastly different stiffness, as shown in Figure 6.1. For most ducts, the

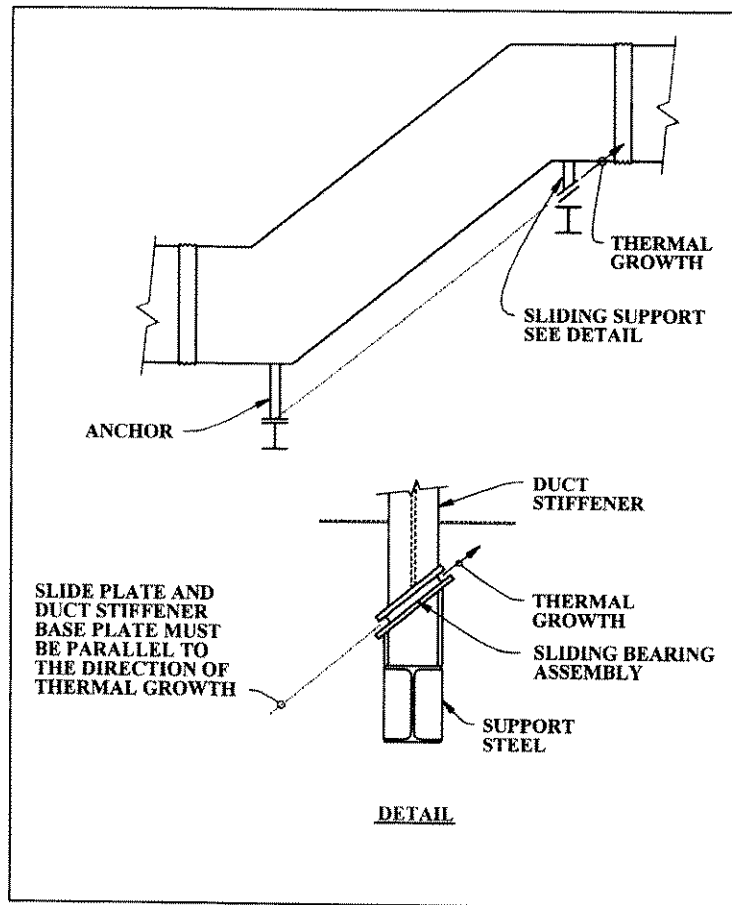


Figure 2.16
Example of the Proper Arrangement of Supports
at Different Elevations

support structure can be designed for standard building deflection criteria. When support structure stiffness is important, the stiffness of the foundations and their settlement must also be considered. Support structure stiffness may also need to be considered if the support structure is relatively flexible. For example, if a tall, slender tower is used to support a duct section, the lateral deflection of the tower under wind, seismic or unbalanced pressure loads may need to be factored into the expansion joint design or into the calculation of clearances to adjacent structures.

2.4.7 Ductwork Stiffness

Due to their size and material thickness, ducts are by nature very stiff structures. The overall behavior of ducts is similar to that of a large box girder. Overall stiffness or deflection checks of air and flue-gas ducts are generally not required, although local checks of the plate and structural elements are sometimes necessary to avoid vibration problems. The calculation of overall deflections at expansion joints, dampers, equipment flanges or other locations where excess movement could cause problems may be prudent.

Some structural engineers choose to apply an indirect stiffness criteria to the design, such as requiring that the distance between duct supports be no more than some multiple of the duct height or width.

2.4.8 Supporting Ducts from Equipment

Ordinarily, ducts should be supported independently from equipment to simplify the interfaces, reduce the transmission of vibrations, and avoid the application of loads to the equipment which could affect performance. However, there are some instances where it makes sense to use equipment to support certain ductwork sections. For example, the transition duct sections at the inlet and outlet of a precipitator are commonly supplied with and supported by the precipitator. Whenever equipment is used to support ductwork, the ductwork arrangement and loading information must be communicated to the equipment supplier to ensure the proper integration of these considerations into the equipment design and to avoid equipment warranty problems.

2.4.9 Retrofitting Ductwork

While developing the ductwork arrangement for a retrofit project, there may be several constraints created by the arrangement or by the capacity of the existing structures. The location of existing steel framing and the capability of existing foundations may dictate the location for the new duct supports, since the ability to erect new support framing or install new foundations may be severely limited. Also, crane access for the duct erection may be so limited that the construction methods become a significant factor in the ductwork arrangement and design approach. The ASCE publication *Retrofitting Fossil Plant Facilities - Structural Perspectives* provides excellent guidance in this area.

2.5 DUCT GEOMETRIES

Ductwork is generally either circular or rectangular in cross section. The exceptions to this are transition configurations. The selection of a basic cross-section should be made on the basis of its effect on flow, cost and structural behavior, while also considering external constraints such as available space, available means of support, connection to equipment and fabrication, shipping and erection limitations. This section discusses some of the ways that the duct's shape influences its behavior or cost. The process engineer should be consulted for flow considerations.

2.5.1 Basic Ductwork Configuration

The most fundamental decision regarding a duct's shape is whether it should be circular or rectangular in cross section. Circular ducts with minimal stiffeners often represent the lowest total installed cost alternative for smaller diameter ducts which can be shop fabricated and shipped in preassembled sections. For larger ducts, fabrication, shipping or erection limitations may cause a circular duct to be less economical. Also, space constraints in the area through which the duct must be routed will often preclude the use of round ducts. Shipping limits are addressed in more detail in Section 10. Where permitted by the arrangement, a square cross-section is generally preferred for rectangular ducts because it provides the most efficient section for both flow and structural considerations. Square ducts also sometimes offer economies related to repetitive detailing and fabrication for all four sides. There are many varied plate and stiffener configurations possible in duct design. Both good references and sound structural engineering judgement should be used as each problem presents itself.

Following are some of the significant items that affect the overall cost of the ductwork, and should be reviewed when making these basic decisions.

- The effect on the plate thickness of various stiffener spacings and sizes - perhaps even a design with no stiffeners.
- The amount of welding required for a given stiffener arrangement.
- The transportation mode, the extent of temporary bracing required for shipping and erection, and the maximum shipping piece size.

- The available methods for supporting the ductwork, either below or above the duct.
- The relative cost of shop labor versus field labor, including the fabrication and erection of the duct and its support structure, and the application of insulation and lagging.

2.5.2 Rectangular Ducts

Ducts with rectangular cross-sections, as shown in Figure 2.17, are commonly used in utility and large industrial boiler applications. Duct panels are typically fabricated from flat plate with rolled steel shapes welded to the exterior or interior at periodic intervals to stiffen and support the plate. The corners are often reinforced with angles or bent plates and internal trusses may be used to maintain the squareness of the duct, transmit pressure forces and transfer loads to the support structure. The completed duct sections behave like large box girders, so they have excellent strength and stiffness characteristics. For additional information on the behavior, analysis and design of rectangular ducts, refer to Sections 6 and 7.

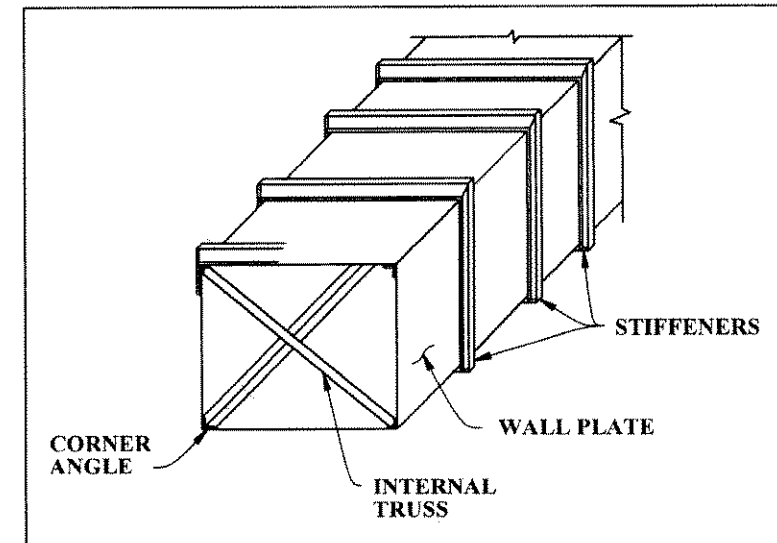


Figure 2.17
Typical Rectangular Duct Construction

Rounded corners are often suggested as a means of reducing pressure drop at bends in the ductwork. Typically, the mechanical process engineer might want both the inside and outside corners at duct elbows to be rounded. However, rounded corners are more difficult to analyze, design, fabricate and erect than are square corners. Therefore, their use should be limited to areas where flow-related benefits are significant and justifiable. *NOT FOR US*

2.5.3 Circular Ducts

Circular ducts are most often used when the outside diameter is 12 feet (3.6 meters) or less, although circular ducts with larger diameters are sometimes used. The maximum diameter for a cost-effective design is influenced heavily by space, fabrication, shipping and erection limitations. This is all discussed in more detail in Section 10. Here are some of the advantages in using circular ductwork.

- Circular ducts are very efficient in resisting internal pressure loads. This efficiency may allow the use of a thinner wall plate than would be needed for a rectangular duct.
- Circular ducts usually require fewer and smaller stiffeners than rectangular ducts. Depending on the loading, duct diameter and wall thickness, stiffeners may even be eliminated altogether.
- For a given cross-sectional area, a circular duct will have a smaller perimeter than a rectangular duct, which may reduce the duct weight and the insulation and lagging cost. The reduced weight should result in a less costly duct; it may also reduce the support structure requirements.
- Circular ducts usually have better internal flow characteristics than rectangular ducts and, thus, lower pressure drop.
- The better shape factor of a circular duct should result in smaller wind loads as compared to a rectangular duct with an equivalent projected area, although the projected area of a circular duct may be larger than that of a rectangular duct to obtain the same internal flow area. This lower wind load may allow for a more economical overall duct or support structure design.

- Circular ducts will not retain as much snow as rectangular ducts of the same width, which may allow for a reduction in the design snow load. Again, this may result in a slightly more economical duct design and a lighter duct support structure.
- Rain water and snow melt will drain off of a circular duct much better than off of a flat or slightly sloped rectangular duct. This means that there is generally less chance of water related damage to the insulation and to the duct plate with circular ducts.

On the negative side, transitions from a circular shape to a rectangular shape or to a rectangular equipment flange can often be difficult to design, fabricate and erect. Also, in order to maintain the same cross-sectional area for flow, a circular duct must be approximately 13% wider internally than a square duct. This wider duct could cause layout constraints and erection problems.

Stiffeners for circular ducts are typically fabricated from plate or relatively small rolled shapes. Additional information regarding the cost and structural design of circular ducts is discussed in Section 6.

2.5.4 Hoppers

Hoppers are often inserted into the duct system where ash is expected to drop out of the flow. Hoppers are usually either conical or pyramidal and may have ash removal equipment suspended from their outlets. Hoppers may also be fitted with rappers, air cannons or other devices to help the collected material flow better during removal.

2.5.5 Transition Duct Sections *! MAY APPLY ON FGD*

Unusually shaped duct sections are often required to provide a relatively gradual transition between ductwork and equipment or between two duct sections with different cross-sections. Abrupt transitions should be avoided because of the potential adverse effects on flow and pressure drop. For a discussion regarding ductwork transitions at large fans, refer to Section 2.2. Transition duct sections at the inlet and outlet of precipitators are usually so unusual that they are sometimes not even considered as being ducts. The structural analysis and design of these unusual duct sections should be performed by a structural engineer very experience in working with them.

2.6 INTERNAL TRUSSES AND STRUTS

Ductwork internal trusses and struts are used to transfer loads between various components of the duct. They are also used to maintain the squareness or roundness of the duct. This section addresses some of the issues to be considered when locating and arranging internal trusses and struts. The structural design of truss members and struts is covered in Section 8. Other internal elements, such as turning vanes, perforated plates and other flow distribution devices, are typically laid out by the mechanical process engineer, often with the aid of flow model tests. However, the structural engineer should have input as to their locations especially when they are to be located in areas near internal trusses and struts. The structural design of flow distribution devices is discussed in Section 9.

2.6.1 Location and Layout

Truss diagonal members and struts are typically fabricated from pipe sections in order to minimize disruption of the air or flue-gas flow. Sometimes angle shapes are used with the heel of the angle facing upstream. This orientation provides a better shape factor for flow resistance. The arrangement of internal trusses and struts should be closely coordinated with the arrangement of flow distribution devices to avoid interferences.

The structural engineer should always attempt to minimize disruption of the flow when laying out internal trusses and struts. Members and their connections should present the smallest projected area possible.

Trusses are typically, but not always, used in the following locations.

- At each pair of duct supports to maintain squareness and transfer the reactions from the duct to the supports.
- Wherever else squareness is important, such as at connections to equipment or metal expansion joints. However, as discussed in Section 2.2 and Section 2.7, trusses should normally be avoided at major fan inlets and outlets.
- At branches of a ductwork system where the opening for the adjoining duct creates a structural discontinuity in the duct wall. This arrangement is shown in Figure 2.18.

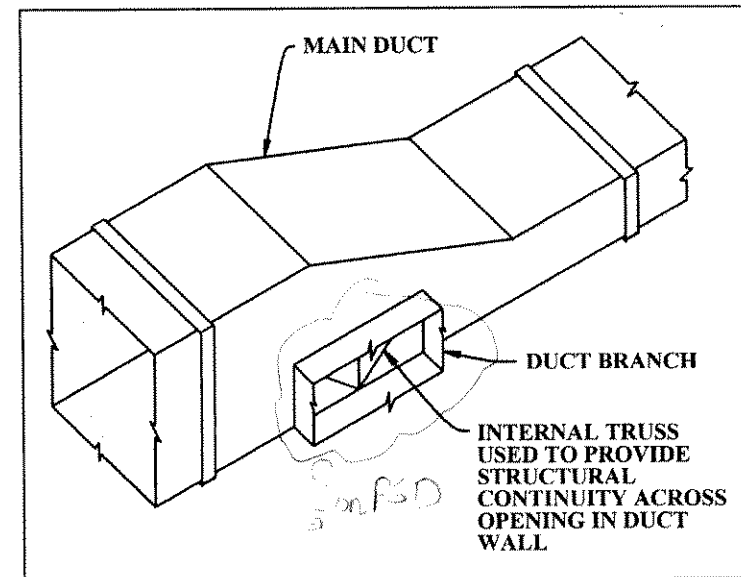


Figure 2.18
Internal Truss at a Duct Branch

- Along the centerline of a very large duct section, to reduce the span of the stiffeners and to help transfer the loads to the supports. This arrangement may be valuable when there are restrictions on stiffener depths due to limited clearance around the duct.
- Inside of ducts with complex geometry due to limited space or due to having to retrofit new ducts into existing plants. In these cases, trusses are often helpful to transfer loads around corners and through transitions.

Internal struts are often used to cancel pressure loads applied to the two opposite sides of a duct, to reduce the span of the duct stiffeners, or to allow stiffeners on opposite sides of a duct to share in resisting loads applied to only one side. This arrangement is shown in Figure 2.19. Used in this manner, the cost of the struts is usually more than offset by a corresponding reduction in stiffener sizes. Internal struts are also commonly used in circular ducts at periodic intervals or at support locations to prevent ovaling. As with trusses, internal struts should be avoided at the inlets and outlets of major fans.

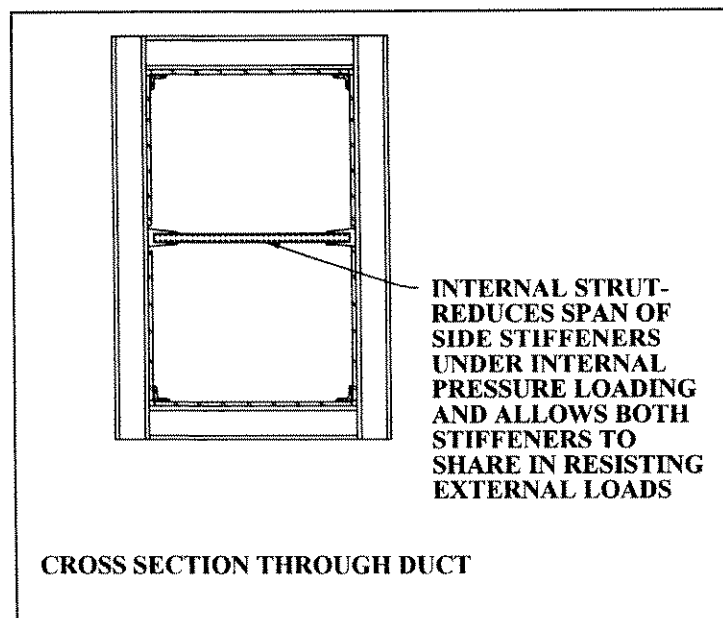


Figure 2.19
Internal Strut

Truss arrangements should also provide some flexibility under potential thermal gradient conditions. Some common examples of flexible and inflexible truss arrangements are shown in Figure 2.20. Workpoints should be located to achieve symmetry or should be located at points of concentrated loads. Workpoints at the duct walls should be located either at the centerline of the stiffeners or in the plane of the plate, depending on the assumed load path and the resultant eccentricities. Workpoints should also be placed at abrupt changes in the contour of the duct wall, such as corners or changes in slope. If loads are predominantly in one direction, the arrangement should put as many of the internal members in tension as possible, not just for structural economy but also to minimize the flow disruption, since tension members tend to be smaller than compression members. Additionally, as with any truss, extremely small angles (less than 30°) between members should be avoided, since the connections become less compact and more difficult to design and build.

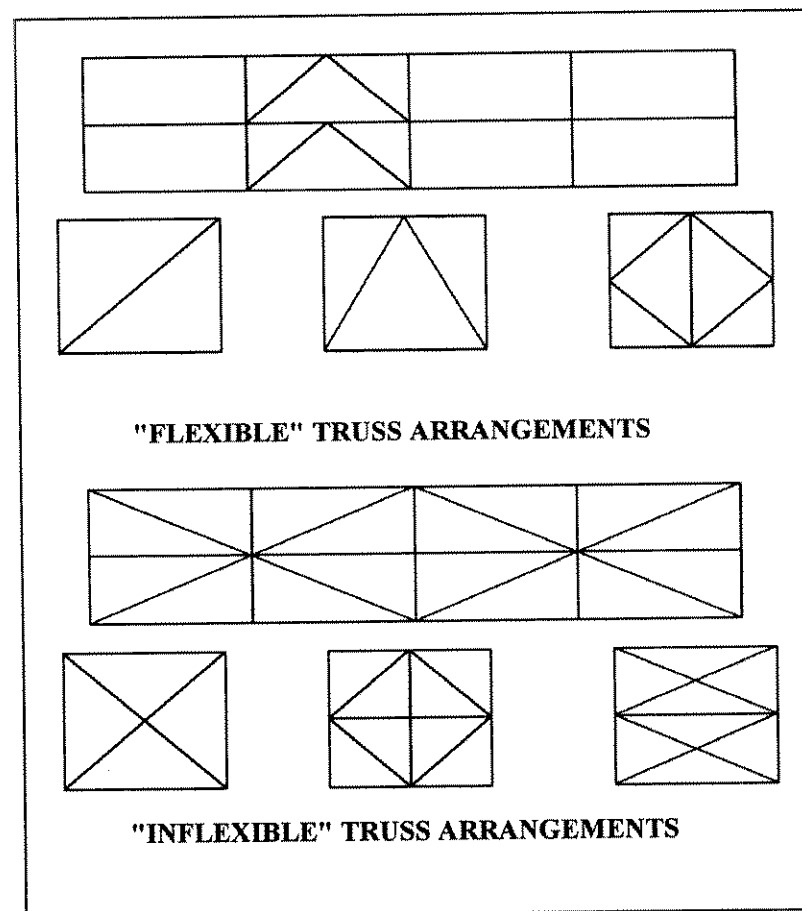


Figure 2.20
Typical Flexible and Inflexible Truss Arrangements

Because trusses and struts may affect the flow and pressure drop, their benefits should be weighed carefully before the project team makes the final decisions on their use. The mechanical process engineer should be notified of any planned internal bracing so that the effect on the flow performance of the system can be assessed. Also, the structural engineer should decide whether the service environment inside the ducts is so poor so as to limit the use of internal components such as trusses and struts. For example, it may be prudent to limit the use of internal trusses and struts in a flue-gas desulfurization system outlet duct because the internal members

would have to be fabricated from very expensive corrosion resistant alloys or encapsulated in some sort of protective material in order to survive in the harsh chemical environment.

Possible alternatives to internal trusses and struts include designing stiffener frames as moment resistant frames, designing openings in duct walls as Vierendeel Trusses, and using larger stiffeners that can span the full width of the duct. These alternatives will usually make the ductwork's initial cost higher because the increased weight of the stiffeners and increased field welding at the frame moment connections will have a bigger cost impact than the elimination of the trusses. These alternatives will also reduce the overall stiffness of the duct, which may be an important factor in certain applications.

2.6.2 Vibration Considerations

Another factor to be considered in the design of internal trusses and struts is their susceptibility to flow-induced vibrations. This topic is covered in more detail in Section 8. To reduce the potential for vibrations, the use of internal trusses or struts should be avoided immediately upstream or downstream of large fans. The exact requirements should be requested from the fan manufacturer. When the fan manufacturer does not furnish this information, Section 8 of the Air Movement and Control Association (AMCA) document 201-90, *Fans and Systems*, provides excellent guidance. This is discussed in more detail in Section 2.2. Where internal trusses or struts cannot be eliminated near large fans, their natural frequencies should be checked to avoid resonance with the fan and the fan manufacturer should be consulted for any other possible adverse effects.

2.7 EFFECTS OF THE ARRANGEMENT ON LOADS

The ductwork arrangement will affect some of the loads that the duct and the support structure experience. These effects are discussed here. For more detailed information on the definition, determination and application of loads, refer to Section 4. Section 5 outlines typical loading combinations and their associated allowable stresses.

2.7.1 Static Pressure

Static internal pressures are present in all ducts because of the fans which force the air or flue-gas through the system. Depending on the overall arrangement of the system and the location of the

particular duct section within the system, these pressures may be positive or negative and will vary from duct section to duct section. Pressures will also vary under different operating modes.

Whenever a section of duct has an expansion joint located so that there is a duct wall that does not have another duct wall directly across from it, an unbalanced pressure occurs in that duct section. When this arrangement occurs, the resulting unbalanced pressure force must be transferred through the duct to its support structure. If no mechanism is available to resist the unbalanced pressure force, the duct section may move off of its supports, which could cause considerable damage to the duct, the support structure, and nearby structures and equipment. Unbalanced pressure forces will only occur opposite openings or expansion joints directly upstream or downstream of bends or transitions. The structural engineer may often be able to exercise some level of control over these forces through judiciously orienting openings, improving the geometry of transition sections, keeping the duct runs as straight as possible, and ensuring the proper placement of dampers and expansion joints. This arrangement is illustrated in Figure 2.4.

2.7.2 Dynamic Pressure

As air or flue-gas flows through the ductwork, it possesses momentum. The duct must exert a force to redirect that momentum at each bend in the duct. The magnitude of these forces is dependent on the velocity and density of the air or flue-gas and the angle of the bend. Most of the time these forces are not significant compared to the other forces present, but it is the structural engineer's responsibility to determine if this is true with the particular duct section being designed. If the dynamic pressure loads are significant, they must be included in the design of the duct and its support structure.

Dynamic pressure forces are also developed as the air or flue-gas moves past internal flow distribution devices such as turning vanes, perforated plates or silencers. For additional information on dynamic pressure loads, refer to Sections 4, 8 and 9.

2.7.3 Vibrations

Vibrations in ductwork may result from interaction with the equipment or may be induced by flow-related phenomena. Usually only steady vibrations are a concern.

The large fans in the duct system are the most common sources of equipment related vibrations. The direct transmission of vibrations to the adjacent ducts from fan housings or other equipment can usually be avoided by isolating the equipment from the duct with expansion joints.

Flow-related vibrations can be caused by vortex shedding, gas pulsations or resonance. Vortex shedding affects internal duct components such as internal truss members and struts. Flow pulsations may occur close to fans or at the boiler outlet, where the duct may experience boiler induced pulses. Flow pulsations will be synchronous with the fan blade tip frequencies and boiler combustion pulses. Isolating the duct with expansion joints will not alleviate flow-related vibrations.

Another potential source of vibration is ash collection hoppers. The flow of collected material through the hoppers can cause intermittent vibrations. The presence of devices installed to help the material flow, such as rappers or air cannons, can also cause vibrations. These intermittent hopper vibrations are usually not a major concern.

In order to avoid vibration related problems, flow distribution devices, internal trusses and struts should be avoided immediately upstream and downstream of major fans. This is discussed further in Section 2.6. If installing these items within the duct cannot be avoided, the natural frequencies of the elements should be checked to avoid resonance. As discussed in Sections 6 and 8, the spacing and sizing of stiffeners near major fans should also be carefully performed to reduce or eliminate vibration concerns. For additional information on designing flow distribution devices for vibrations refer to Section 9.

2.7.4 Ash Deposition

Ash particles will drop out of the flow stream when the flue-gas velocity drops below a certain minimum value. The exact velocity at which this will occur depends on the particulate size, shape and density. Experience and flow model tests have shown that for most fossil fuel ashes, drop-out should be within acceptable limits if the flue-gas velocity is kept above 40 feet per second (12 meters per second). Even when the velocity is kept well above 40 feet per second (12 meters per second), it is common to find deposits of ash in the following locations: the corners of ducts, especially at duct turns; at transitions from smaller ducts to larger ducts; and in front

of obstacles to the flow, such as gusset plates for internal trusses. Ash deposition is also a potential concern in dead legs. The flue-gas is likely to become relatively stagnant in the dead leg, making particulate drop-out much more severe. Also, quite often flyash is carried over from the flue-gas ducts to the air ducts through the air preheaters. When this is anticipated, the air ducts must be designed for the expected ash accumulation.

Ash deposition affects the structural design of ducts in two ways. First, the ducts must be designed for the dead load of the ash. In addition, if the ash accumulation is excessive, it will act as an insulator, which may contribute to increased thermal gradients in the ducts. For more information on designing for ash deposition, refer to Section 2.7.6 and Section 4. Thermal gradients are discussed in various locations in this ASCE Special Publication.

Ash accumulations in expansion joints can harden and reduce the joints' effectiveness. Packed ash can also contribute to premature degradation of the joint material. The expansion joint manufacturer should be consulted regarding any design features which may be available to alleviate these concerns.

2.7.5 Metal Expansion Joints

If metal expansion joints are used in the duct system, they will affect the distribution of loads within and between duct sections and the equipment. This is because metal expansion joints have appreciable stiffnesses in all directions and can therefore transmit sizeable forces across the joints to the ducts on either side of the joints. A metal expansion joint's stiffness is dependent on the joint size, material and design configuration and should be obtained directly from the joint manufacturer.

2.7.6 Thermal Gradients

Thermal gradients across a section of ductwork or across an individual duct structural element can develop in any system, however, they are usually structurally significant only in hot ducts. Thermal gradients are typically most severe during unit start-up and shutdown conditions. If the temperature differentials are very large, or if the ductwork is indeterminate, the gradients may introduce large stresses into the ducts and may cause a redistribution of all loads among the supports. In severe cases, the gradients can actually warp a duct section enough to cause some of its supports to lift up off of the support structure. The uplifted supports are thus

rendered non-functional and the remaining supports and the support structure can become severely distressed as the loads redistribute.

The overall arrangement of the ductwork system can have a great influence on whether or not significant thermal gradients are likely to develop. Flow model testing can help identify problem areas and give indicators that can help predict where thermal gradients are likely to develop. The preferred approach should be to avoid thermal gradients rather than to try to design for them.

Addressing the following items is important for minimizing thermal gradients, especially in hot ducts.

- As discussed in Section 2.2.3, dead legs should be minimized to the greatest extent practical.
- As discussed in Section 2.7.4, the flue-gas velocity should be maintained above 40 feet per second (12 meters per second) to minimize ash deposition, since excessive ash will act as an insulator.
- False floors, walls, or ceilings should be avoided, because dead zones behind the falsework are created which are not directly exposed to the hot flue-gas. The exposed walls will heat up or cool off faster during start-up or shutdown than the hidden walls will. The dead air space may also act as an insulator, creating a gradient even during steady-state operating conditions.
- Members which are directly within the path of the flue-gas stream, such as internal truss members, may heat up or cool off faster than the duct walls during unit start-up or shutdown. Truss arrangements which can accommodate the resulting thermal stresses should be used wherever possible, as discussed in Section 2.6.
- Poor flow distribution or stratification can create problems by exposing some portions of the ducts to flow streams of differing characteristics. Sections of ductwork where the mixing of two distinct flow streams takes place are usually very vulnerable to stratification. Common examples include locations where ducts from two or more boilers merge into a common duct before entering a pollution control device or the chimney; where tempering air is added to a duct; and where bypass flue-gas reenters the ductwork downstream of

a scrubber. Flow model testing can often help identify arrangements which are susceptible to stratification. Flow distribution devices such as turning vanes, baffles or perforated plates may be added to alleviate the stratification.

Thermal gradients can also develop locally in duct plate, external stiffeners, expansion joint frames, duct support legs and similar components due to the insulation and lagging details used. Refer to Section 11 for further information regarding thermal gradients caused by poor insulation details.

Nagging structural problems or damage to existing ducts may be partially due to temperature differentials within the duct section. This effect can often be quantified by using thermocouples to collect temperature data from within the duct and then performing a structural analysis using these temperatures. This data collection is discussed in Section 12. Thermal analysis and design are discussed in various sections of this publication.

SECTION 3**Structural Material - Selection, Application and Properties**

	<u>Page</u>
3.1 INTRODUCTION	83
3.2 AVAILABILITY OF MATERIALS	83
3.3 MATERIAL PROPERTIES	84
3.3.1 Coefficient of Thermal Expansion	85
3.3.2 Modulus of Elasticity	85
3.3.3 Yield Strength	87
3.3.4 Ultimate Strength	87
3.3.5 Creep and Creep Rupture	88
3.3.6 Temper Embrittlement and Graphitization	91
3.4 MATERIAL SELECTION	92
3.4.1 Low and Medium Temperature Ducts	92
3.4.2 High Temperature Ducts	92
3.4.3 Wet Ducts	94
3.5 BOLTS	95
3.6 WELDING ELECTRODES	95
3.7 DUCTWORK PROTECTION	96
3.7.1 Corrosion Allowances	96
3.7.2 Coatings	97
3.7.3 Liners	98
3.8 HANGER ELEMENTS	99

SECTION 3

Structural Material - Selection, Application and Properties

3.1 INTRODUCTION

The structural design of air and gas ductwork requires that the appropriate material be selected for the anticipated operating and exposure conditions. The entire contents of this ASCE Special Publication on the structural design of ducts assumes that some type of steel will be used for the ducts and all of their structural elements. The selection of the proper steel is the responsibility of the structural engineer designing the ductwork.

The steel design stresses are expected to be proportioned in accordance with the design procedures detailed in Sections 5, 6, 7, 8 and 9 of this publication.

The remainder of this section makes reference to a number of American Society of Testing Materials (ASTM) material specifications for steels that are commonly used in ductwork construction. Such references are not intended to preclude the use of other steels, but rather to represent the materials currently most commonly used for ducts.

3.2 AVAILABILITY OF MATERIALS

The steels most commonly used for the fabrication of ductwork are widely available. The structural engineer should, however, verify the availability of the steel to be used in the design and adjust the design approach accordingly if necessary. Limitations exist on the available sizes of certain steels such as ASTM A242, which is usually limited to 1/2 inch (12 mm) maximum thickness, and ASTM A36, which is not generally available in thicknesses less than 3/16 inch (5 mm). Rolled shapes are also not available for some thicknesses and grades of certain steels, necessitating the use of built-up sections. Special consideration must also be given to the lead time required for purchasing some rolled shapes.

Another potential concern for the structural engineer is the availability and lead time of certain alloys that are used for wet scrubber ducts, particularly when the material is used in small quantities. These alloys are discussed in Section 3.4.3.

3.3 MATERIAL PROPERTIES

The structural design of ductwork must properly account for changes in the physical properties of the steel during the anticipated operating and exposure conditions. For ductwork in power plant and industrial boiler applications, the exposure condition that has the greatest impact on the material properties is usually the exposure temperature. Ductwork will typically be exposed to a wide, but predictable, range of temperature. Over its life, a duct will normally be exposed to approximately the same operating temperature range for the majority of the time. The upper end of this temperature range is typically used as the design temperature for the duct and the steel's allowable stresses should be based on this temperature for all normal operating loading combinations as explained in detail in Section 5.

The material properties of steel vary significantly with temperature. The structural engineer must determine the appropriate design values based on these reduced properties. The properties of primary interest with regard to structural design are the coefficient of thermal expansion, the modulus of elasticity, the yield strength and the ultimate strength. Depending on the type of steel, consideration should also be given to creep, temper embrittlement and graphitization when the steel is exposed to very high temperatures, above 750°F (400°C), is anticipated. Everything presented in this document assumes that the structural engineer understands basic steel behavior and the proper application of the terms and values presented herein.

The values presented in the following subsections typify values that are often used by structural engineers in designing ductwork exposed to temperatures above ambient. The values presented in this Section have been obtained from information published by the American Society for Testing and Materials (ASTM), the United States Steel Corporation and the American Society of Mechanical Engineers (ASME). These values should be assumed to be guidelines. The exact values are a function of the actual chemistry of the steel used. They should be obtained by the structural engineer from one of the following sources: proprietary data, material test results, American Institute of Steel Construction (AISC) published values, ASME published values, ASTM published values, or from the steel supplier.

3.3.1 Coefficient of Thermal Expansion

The coefficient of thermal expansion of steel, ϵ , increases slightly with increasing steel temperature. Figure 3.1 shows the effect of temperature on the coefficient of thermal expansion for some of the steels commonly used in ductwork applications. The coefficient of thermal expansion indicated in the figure is the mean coefficient of thermal expansion (inches/inch/°F) as the steel temperature increases from 70°F (20°C) to the indicated temperature.

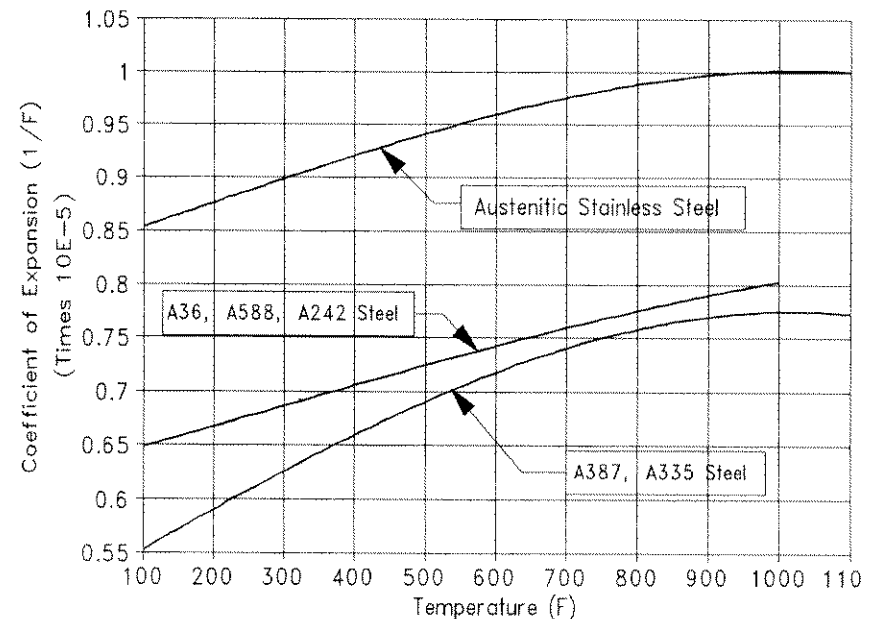


Figure 3.1
Coefficient of Thermal Expansion Versus Temperature

3.3.2 Modulus of Elasticity

The modulus of elasticity, E , is the ratio of stress to strain in the steel's elastic range. The modulus of elasticity for steel decreases with increasing steel temperature. Figure 3.2 shows the effect of increased temperature on the modulus of elasticity for some of the steels commonly used in ductwork applications. There are temperature limits commonly imposed for the practical structural application of some of the steels shown on this graph. These limitations are discussed in Section 3.4.2.

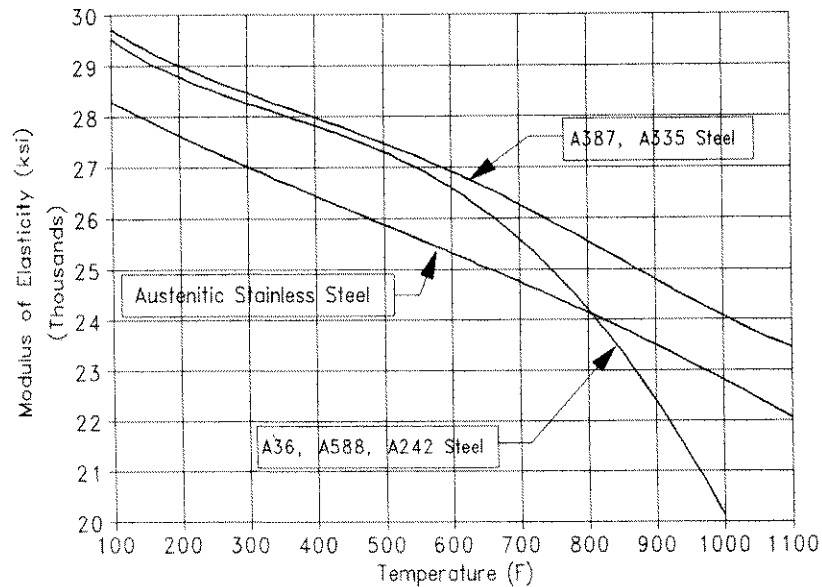


Figure 3.2

Modulus of Elasticity Versus Temperature

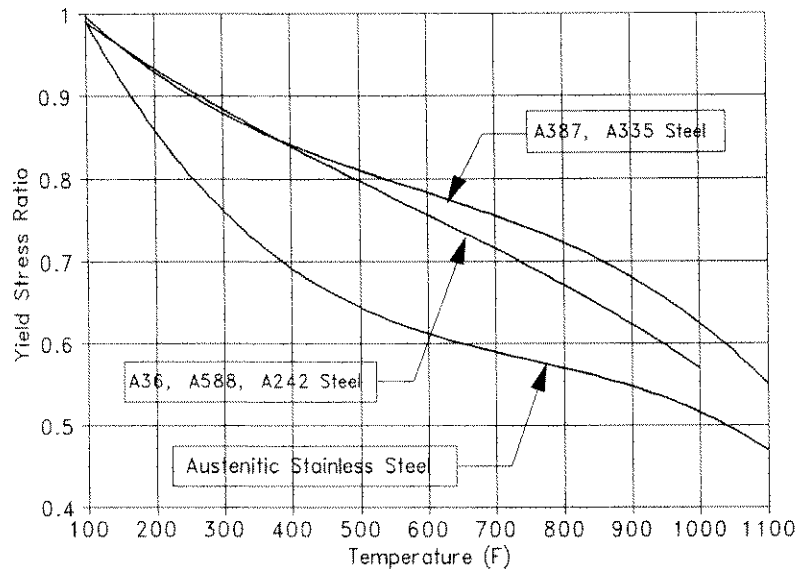


Figure 3.3

Yield Strength Ratio Versus Temperature

3.3.3 Yield Strength

The yield strength of steel, F_y , also decreases with increasing steel temperature. A steel's yield strength may be quantified by the ratio of the elevated-temperature yield strength to the ambient temperature yield strength, which is the value presented in the ASTM specifications. The effect of temperature on the yield strength ratio for some of the steels commonly used in ductwork applications is shown in Figure 3.3. The design yield strength is arrived at by multiplying the ASTM published ambient value by the yield strength ratio.

The variation of yield strength with temperature is somewhat different for various grades and types of steel because of differences in their chemistry and microstructure. Steels having relatively high percentages of Carbon will exhibit strain aging in the range of 300°F to 700°F (150°C to 370°C). This may result in a higher yield strength than that shown in Figure 3.3 with an associated decrease in ductility. There are temperature limits commonly imposed for the practical structural application of some of the steels shown on this graph. These limitations are discussed in Section 3.4.2.

3.3.4 Ultimate Strength

The ultimate strength of steel, F_u , also decreases with increasing steel temperature. The ultimate strength depends on the type of steel used, but may be quantified by the ratio of the elevated-temperature ultimate strength to the ambient temperature ultimate strength. The effect of temperature on this ultimate strength ratio for some of the steels commonly used in ductwork applications is shown in Figure 3.4. The design ultimate strength is arrived at by multiplying the ASTM published ambient value by the ultimate strength ratio.

The variation of ultimate strength with temperature is also somewhat different for various grades and types of steel because of differences in their chemistry and microstructure. Additionally, steels having relatively high percentages of Carbon will exhibit strain aging in the range of 300°F to 700°F (150°C to 370°C), also producing somewhat higher ultimate strengths than those shown in Figure 3.4. There are temperature limits commonly imposed for the practical structural application of some of the steels shown on this graph. These limitations are discussed in Section 3.4.2.

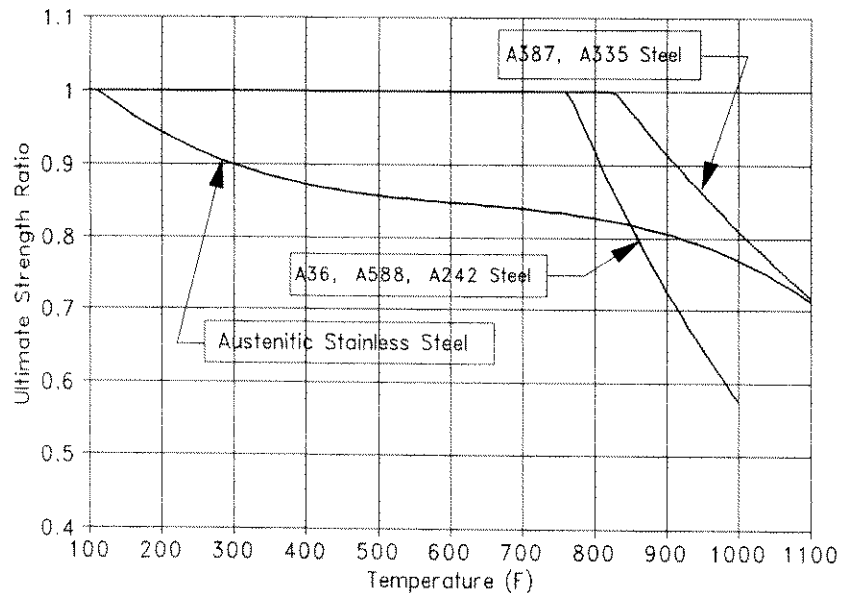


Figure 3.4
Ultimate Strength Ratio Versus Temperature

3.3.5 Creep and Creep-Rupture

At exposure to very high temperatures, steel experiences creep and its strength becomes strain-rate dependent. At very high temperature with a constant stress, the steel strain will increase (creep) continuously as time progresses. Considerable strain and an eventual failure may occur at stresses well below the yield strength as measured in the typical ASTM short-duration test. This type of eventual failure is termed a creep-rupture failure and the stress that causes a creep-rupture failure in a given time at a given temperature is defined as the creep-rupture strength of the material, sometimes also referred to as the stress-for-rupture. The time period required to cause rupture is known as the time-to-failure. Depending on the stress level, the exact steel chemistry and the exposure temperature, this time can be a matter of hours or years. For relatively low stresses in normal design ranges, this time is usually thousands of hours. Creep is distinguished from fatigue and fracture in that creep takes place within the grain boundaries while fatigue is an intergranular occurrence.

For long-term high-temperature service, especially when the temperature is above 750°F (400°C), the creep-rupture strength of the steel becomes a primary factor in determining the allowable design stresses. In addition, a limiting creep rate should be considered in establishing the allowable design stresses. Creep and creep-rupture strength vary inversely with temperature and with the time duration of the exposure to the temperature.

Creep and creep-rupture are also very dependent upon the exact chemistry of the steel. Some steels, such as ASTM A7 and ASTM A36, are very susceptible to creep and creep rupture while others are almost creep resistant. While the ASTM specification to which a steel conforms helps to qualify its susceptibility to creep and rupture, the exact chemical composition of the steel is necessary to quantify its creep and creep rupture properties.

The design creep life should be selected by the structural engineer based upon design criteria consistent with the expected service life and service conditions. Design for creep is typically based on creep and rupture properties corresponding to a creep life of 100,000 hours. This creep design life is the duration presented in the *ASME Boiler and Pressure Vessel Code* as explained below. A shorter or longer creep design life may be appropriate depending on the operating mode and the expected service life of the ductwork. Because of their nature, allowable creep stresses are only used to limit stresses from loading combinations which will be sustained at elevated temperatures. The stresses arising from such load combinations must be below the allowable creep stress. See Section 5 for more information on the use of allowable creep stresses with certain loading combinations with sustained loads. The maximum allowable creep design stress, or limiting creep stress, as taken from the *ASME Boiler and Pressure Vessel Code, Section I - Rules for Construction of Power Boilers*, should not exceed the lowest of the following two values:

- 1) the average stress to produce a creep rate of 1% in 100,000 hours with a factor of safety of 1.0,
- 2) the average stress to cause creep rupture at the end of 100,000 hours with a factor of safety of 1.5.

Selected allowable creep stresses for various steels are presented in Table 3.1. The values presented in this table represent the governing allowable creep stress collected from various sources and determined as described above. Creep and rupture properties are highly dependent upon the exact chemical composition of the steel.

Allowable Creep Stresses (in ksi) (1)								
Type of Steel (2)	Temperature (°F)							
	750	800	850	900	950	1000	1050	1100
A36 (5) A53 Gd B (5)	14.3 (3)	† 10.3(3)	*	*	*	*	*	*
A242 Type 1 (6) A618 Gd 1 (6)	--	12-17	8-13	5-9	‡	‡	*	*
A588 Gd A (6) A588 Gd B (6)	--	12-17	‡ 8-13	‡ 5-9	‡	‡	*	*
A387 Gd 11 (7) A335 Gd P11 (7)	--	--	--	15.7 (3)	10.7 (3)	7.1 (4)	4.4 (4)	2.7 (4)
A387 Gd 12 (7) A335 Gd P12 (7)	--	--	--	18.0 (3)	11.3 (3)	7.3 (3)	4.5 (4)	2.5 (4)

-- Indicates that the creep value does not govern - normal allowable stresses based on F_y govern.
 * Indicates that the use of this steel is not recommended at this temperature.
 ‡ Indicates that the use of this steel at this temperature is only recommended for non-critical applications.
 () Indicates reference to notes.

NOTES:

- 1) The values presented in this table are **allowable stresses** based on the criteria presented in Section 3.3.5 with a design life of 100,000 hours. The appropriated factor of safety has been incorporated in these values.
- 2) Creep and rupture properties are highly dependent upon the exact chemical composition of the steel. The values indicated in the table are intended to be used only as a reference. Values used in design should be obtained from test data reflecting the precise chemical composition of the steel to be used in the ductwork fabrication.
- 3) The allowable stress value at this temperature is governed by the creep rupture strength.
- 4) The allowable stress value at this temperature is governed by the creep rate.
- 5) Creep and rupture properties for this steel are derived from ASTM DS-11S1.
- 6) Creep and rupture properties for this steel are derived from various United States Steel Corporation publication, including *Steels for Elevated Temperature Service*.
- 7) Creep and rupture properties for this steel are derived from ASTM DS-50. These values differ from some of the ASME values because ASME limits the allowable stress to $0.25F_y$, which is a limitation for boilers - not ducts.
- 8) A range of values is presented for A242, A588 and A618 steels because of the potentially large variation in chemistry which can drastically effect the steel's properties. The lower bound value should be used unless test data indicates otherwise.

Table 3.1
Typical Allowable Creep Stresses (ksi)
for Steels Common To Ductwork Applications

This dependency is especially true for the family of ASTM A242 and A588 steels. The values indicated in Table 3.1 are intended to be used only as a reference. Values used in design should be obtained from test data reflecting the precise chemical composition of the steel to be used in the ductwork fabrication. If steels other than those presented in Table 3.1 are used at high creep susceptible temperatures, the structural is responsible for determining the steel's creep and creep rupture strength.

3.3.6 Temper Embrittlement and Graphitization

Steel also experiences other metallurgical changes at high temperatures that affect the mechanical properties, producing brittle characteristics that should be considered in the structural design. Those of importance in the structural design of ductwork include temper embrittlement and graphitization.

Temper Embrittlement

Temper embrittlement occurs when certain steels are isothermally aged in the temperature range of 700°F to 1,100°F (370°C to 600°C). It is attributed to the segregation of impurities to the grain boundaries and is retarded by the presence of Molybdenum which tends to inhibit such segregation. Steels with relatively high percentages of Phosphorus and traces of certain uncontrolled impurity elements such as Tin, Arsenic and Antimony, are very susceptible to temper embrittlement. When the steel becomes temper embrittled, it loses its toughness and easily cracks when stressed or impact loaded in the presence of a flaw, such as at a weld. Temper embrittlement raises the steel's nil ductility temperature from approximately -60°F to 0°F (-50°C to -20°C) to as much as +250°F (+120°C). This increase in the NDT causes the steel to be extremely susceptible to brittle fracture at ambient temperatures or during unit start-up and shutdown. Temper embrittlement effects can only be mitigated by specifying a steel chemistry that is not susceptible to temper embrittlement when it is to be exposed to these high temperatures.

Graphitization

Graphitization, sometimes called carbon migration, occurs in steels containing a relatively high amount of carbon. In this process graphite forms at the grain boundaries while the steel is exposed to temperatures exceeding 750°F (400°C) for a prolonged period of time. Graphitization effects are reduced by lowering the carbon content of the steel and by adding Chromium. Graphitization causes the steel to prematurely fail at the weakened grain boundaries.

3.4 MATERIAL SELECTION

The selection of the type of steel to be used for a duct section must take into consideration the service conditions to which the material will be exposed. The following subsections identify and discuss materials commonly used for various ductwork exposure conditions. The ASTM specifications discussed in this section are generally those for which plate, structural shapes and bar products are available. Similar ASTM specifications exist for the thinner sheet and strip products. For example, ASTM A570 is the sheet and strip counterpart to ASTM A36 plate. Similarly, ASTM A606 is the sheet and strip counterpart to ASTM A242 and A588 plate.

3.4.1 Low and Medium Temperature Ducts

This subsection addresses material for ducts having an operating temperature of less than 750°F (400°C). Carbon steel is typically used for duct plates, stiffeners, and other rolled shapes in this temperature range. ASTM A36 and ASTM A572 are the most common steels used for this temperature range, although high-strength low-alloy steels such as ASTM A588 Grade A or B or ASTM A242 Type 1 may be used to provide improved resistance to corrosion. ASTM A572, ASTM A588 and ASTM A242 are higher strength steels, so their use would provide added strength, typically less overall weight and perhaps added economy.

Internal bracing for this temperature range will generally be carbon steel as well. Typically, either ASTM A53 Grade B, ASTM A500, ASTM A501 or ASTM A618 Grade 1 pipe sections are used for the internal brace members. Connection material is usually made from the same steel as the duct plate.

The material properties for steel in this category must be adjusted from the published design values, as indicated in Figures 3.1, 3.2, 3.3 and 3.4, when the ductwork is exposed to operating temperatures exceeding approximately 100°F (40°C).

3.4.2 High Temperature Ducts

This subsection addresses material for ducts having an operating temperature greater than 750°F (400°C) but less than 1,100°F (600°C). Within this temperature range, many steels reach a temperature limit where alternative steels become more attractive. The selection of a material for a given temperature requires judgement and is normally based upon prior experience or the

interpretation of available material test results. The following guidelines reflect the current industry practice and are intended to assist in the selection of a high temperature material for ductwork plates and shapes.

ASTM A36 steel has very limited uses at temperatures above 750°F (400°C). Creep and graphitization become more predominant above this temperature. The use of ASTM A36 steel above 800°F (430°C) is definitely not recommended.

ASTM A242 Type 1 steel has very limited uses between 900°F and 1,000°F (480°C and 540°C). When the steel's temperature exceeds 900°F (480°C), there is a significant drop-off in the creep-rupture strength. Therefore, above 900°F (480°C) the use of ASTM A242 steel is not recommended in structural applications unless the structural engineer takes steps to alleviate these concerns. At temperatures above 900°F (480°C), the structural engineer should investigate a better performing material having higher creep-rupture capacities and less susceptibility to temper embrittlement. This steel is very susceptible to temper embrittlement when exposed to very high temperatures. More stringent control of the chemistry of this steel can dramatically improve its creep-rupture capacities but, can increase its susceptibility to temper embrittlement. The use of this steel above 1,000°F (540°C) is not recommended.

ASTM A588 Grades A and B have exhibited relatively high elevated-temperature strength, but very low creep-rupture ductility above 800°F (430°C). For this reason, this steel is normally not used in structural applications above this temperature. This steel may be used above 800°F (430°C) by carefully controlling and refining its relatively broad ASTM chemical composition range. The use of this steel above 1,000°F (540°C) is definitely not recommended.

ASTM A335 and ASTM A387 can economically be used in various grades for exposure temperatures between 750°F and 1,100°F (400°C and 600°C).

Some of the ferritic and austenitic stainless steels have also been used and continue to be used in hot duct applications. Stainless steel has been very successfully used for floating liners in combustion turbine exhaust ducts.

Internal bracing in high temperature ductwork is generally made from ASTM A335 Grade P11 pipe section. The connection material will generally match the duct plate, but ASTM A387 may be used.

The material properties for these steels, and any others, must be adjusted from the published design values, as indicated in Figures 3.1, 3.2, 3.3 and 3.4. Additionally, other considerations for high temperature phenomena discussed in Section 3.3 must be considered when using some of these steels.

All steels will exhibit oxidation and scaling when continuously exposed to temperatures above 950°F (510°C). Because of this effect, a corrosion allowance may be prudently included in the design of duct steel above this temperature.

3.4.3 Wet Ducts

This subsection addresses low temperature ductwork which will be exposed to wet conditions such as encountered in the presence of a wet flue-gas desulfurization system (scrubber). Hot flue-gas typically enters the inlet of a scrubber in the 250°F to 450°F (120°C to 230°C) temperature range and is cooled to 120°F to 140°F (50°C to 60°C) after passing through the scrubber. Some systems utilize a reheat process to raise the flue-gas temperature to around 200°F (95°C) so that condensation should not occur and corrosion of the duct should not result. Protected or unprotected ASTM A36 carbon steel is commonly used in applications where a biomass fuel with no Sulfur content, such as wood or peanut hulls, is used.

High-strength low-alloy steels such as ASTM A588 and ASTM A242 are not recommended for use in wet ducts because the surface oxidizing properties of these steels cause the material to erode and corrode rather quickly.

High-alloy liners or special coatings are typically used when municipal or hazardous waste or coal with very high chlorides is used for fuel. Austenitic stainless steels are commonly used in systems fueled with petroleum or coal where chloride concentrations are very low. These austenitic stainless steels include types 316L, 317L and 317N per ASTM A240 and 904L per ASTM B673.

In addition to temperature considerations, the material selected is highly dependent upon the expected chemical composition of the scrubbed or unscrubbed flue-gas. Important corrosion factors to consider are the flue-gas acid concentrations, the presence of chlorides or other corrosive chemicals, and the presence of solid corrosive deposits on the duct floor. ASTM G-48, *Standard Specification for Test Method for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by the Use of Ferric*

Chloride Solutions, presents the testing procedures for determining the lowest temperature at which corrosion occurs in the material. The mechanical process engineer should be consulted when determining the material to be used for wet ducts in a relatively cool, corrosive environment.

In highly corrosive areas where chlorides or acids exist, high-alloy material is usually used. Nickel-based alloys with significant Chromium and Molybdenum added for resistance to pitting and crevice corrosion include: ASTM B564 Alloy 625 and ASTM B575 Alloys C-22 and C-276. These materials are used as solid plate, as part of a clad plate, and in thin liner applications. The economics of solid alloy plate versus alloy-lined carbon steel should be considered when selecting the material for wet ducts. Before making any decision, the material suppliers should always be contacted regarding availability and costs.

3.5 BOLTS

Typical ductwork construction utilizes welding to produce an air tight product capable of pressurization. Bolts will therefore have only limited applications. Where bolts are used for structural connections in ducts with operating temperatures less than 750°F (400°C), they typically will be ASTM A325 Type 1 with ASTM A563 Grade C nuts and ASTM F436 hardened steel washers. For structural connections in ducts with operating temperatures in excess of 750°F (400°C), ASTM A193 Grade B7 or other appropriate stainless steel bolts typically are used with ASTM A194 nuts. As with the duct steel, consideration must be given to the reduction in bolt strength due to the high temperatures.

ASTM A307 bolts are generally specified for ductwork applications which are not subjected to high temperatures or significant loading. They are sometimes used as expansion joint frame connection bolts or erection fit-up bolts for welded field splices.

The use of galvanized bolts is not uncommon for ductwork external applications at low temperatures.

3.6 WELDING ELECTRODES

AWS D1.1 - Structural Welding Code, Steel, is usually specified for ductwork structural welding. Sometimes the *ASME Boiler and Pressure Vessel Code, Section IX - Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators*, is specified. The use

of these codes and other welding information is discussed further in Section 10.3.

Welding electrodes with a minimum tensile strength of 70 ksi are commonly specified for carbon steel applications in ductwork construction. For high-temperature applications, above 750°F (400°C), 80 ksi electrodes are typically specified. Alloy steels, such as ASTM A335 and ASTM A387, generally utilize E8018-B2L electrodes with welding conforming to AWS D10.8 - *Recommended Practice for Welding of Chromium-Molybdenum Steel Piping and Tubing*. The appropriate electrodes must be selected when welds are made between dissimilar metals. The type of rod specified should be based on the higher grade material being welded.

Due consideration must also be given to the reduction in weld metal strength when exposed to high temperatures. The temperature based strength reductions for weld metal are usually assumed to be the same as that for the base metal.

3.7 DUCTWORK PROTECTION

The exposed surfaces of a duct section are likely to be subjected to atmospheric conditions at various times during its service life. Many factors impact the selection of an appropriate surface protection system. The selection should include consideration of the susceptibility of the ductwork steel to corrode. Factors to consider are the flue-gas composition, operating temperature and time of exposure to corrosive elements. The protection system chosen may consist of simply including a corrosion thickness allowance for the duct steel, or it may involve coating or placing a lining on the inside surface of the duct.

3.7.1 Corrosion Allowances

Ductwork composed of carbon steel frequently includes a corrosion allowance as a means of corrosion protection. This is done by providing thicker material than required by design. Additionally, the use of such corrosion resistant steels as ASTM A588 or A242 may provide improved resistance over that of ASTM A36 steel. High temperature ductwork, comprised of alloy material, may require no further consideration for corrosion. The use of insulation and lagging usually may be considered to afford sufficient protection against external corrosion. See Section 11 for more information regarding insulation and lagging.

3.7.2 Coatings

External

Selection of a painting system for external ductwork surfaces requires careful evaluation of the anticipated environment and the long term goal of the painting system. Painting of ductwork will fall into one of two categories: protection for the life of the ductwork and protection during shipment, storage and construction.

will be If the ductwork is expected to have low surface temperatures and will not be insulated and lagged, the exposed surfaces would typically be painted with the same coating system used for the adjacent structural steel. If the ductwork will be insulated and lagged, painting might be used to protect the surfaces during shipment, storage and construction. If so, the appropriate primer would be an inexpensive shop primer, which could be classified as the manufacturer's standard. Sometimes a weldable primer is used. This primer would most likely burn off during operation, but the surfaces would remain protected by the insulation and lagging. In the rare case that ductwork is designed with elevated surface temperatures but is not insulated and lagged, a high temperature coating would be required. In any case, the compatibility of coating systems with the expected environment must always be investigated.

Consideration must be given to test ports, support legs and other exposed items which penetrate the insulation and lagging. Penetrations can bring the temperature at their duct plate connections to corrosive flue-gas dew point levels. This is discussed further in Section 11.2. These items may experience elevated temperatures and should be treated with an appropriate heat resistant coating system or else they should be fabricated from corrosion resistant materials. If the duct support legs are uncoated weathering steel, such as ASTM A242 or ASTM A588, the coated support steel will become stained or discolored from the "bleeding" of the weathering steel. This unsightly problem can be alleviated by coating the exposed weathering steel.

Internal

Some flue-gas desulfurization absorber outlet ducts are coated with a system designed to protect the duct steel from the harsh chemical environment. This system would be in lieu of a liner as discussed in Section 3.7.3. The discussion of these types of internal coatings is beyond the scope of this publication.

3.7.3 Liners

Ductwork liners are used to protect structural ductwork components from corrosion and erosion on the interior surfaces of the duct. Inside surfaces of ductwork are exposed to the flue-gas carried by the duct and, depending upon the composition of the flue-gas, can be exposed to abrasive particulate and corrosive condensate, particularly as the temperature on the inside surface of the ductwork decreases below the dew point temperature of the flue-gas. The selection of a liner should include consideration of such factors as the flue-gas composition, operating temperature, and time of exposure to corrosive or erosive elements. The use of a liner results in a more expensive design and should therefore be limited to applications with harsh exposure conditions. Liner materials that are commonly used include: brick, mortar, castable refractories, rubber, and various steel and high-nickel alloys.

— Metal liners may be stainless steels or high-nickel alloys. These liners are made from thin sheet metal which is placed like wallpaper on the interior surfaces of the ductwork. The liners may be welded to the underlying steel or attached through a bonding process to form a clad plate. They are usually welded. When liners are used, special care and detailing is required to insure complete envelopment of the flue-gas by the corrosion and erosion resistant liner material, particularly at welds, splices, corners, internal bracing and flow distribution device connections, and other breaks in continuity of the ductwork interior. A key factor in the successful installation of a metal liner is the welding. The welding electrode filler metal must correctly match the alloy base metal in corrosion resistance and mechanical properties. Special care must be taken during fabrication, shipment and installation to avoid contamination of the liner material by carbon steel, especially at the welds between the carbon steel and the liner. Consideration must also be given to differences in the coefficients of expansion and flexibility that may exist between the liner material and the underlying duct steel. More information about surface preparation, installation and weld sequencing for thin metallic alloy "wallpaper" linings can be found in the National Association of Corrosion Engineers (NACE) document RP 0296, *Installation of Thin Metallic Wallpaper Lining in Air Pollution Control and Other Process Equipment*. Liners are generally not considered to contribute to the duct's load carrying capability in the stress calculations except when absolutely necessary in retrofit applications.

When an alloy liner material is to be used, consideration might be given to fabricating the entire duct section from the material specified for the liner. This will generally be more expensive, but, depending upon the construction circumstances, may be an attractive alternative.

Internal gutters, downspouts and other liquid flow collection devices are sometimes used in ducts where the flue-gas temperature is below its acid dew point and excessive internal liquid condensation is expected. When this is the case, internal drains must be installed in the ducts to take the flow to a proper repository. Because of the corrosive nature of this liquid, these liquid flow collection devices and drains must be made from the same material as the duct liner.

Hot gas ducts for gas-turbine exhaust applications utilize a thin "fish scale" type lining placed over internal duct insulation which protects the structural outer shell plate from high temperatures.

3.8 HANGER ELEMENTS

Ductwork is frequently supported by hangers comprised of hanger rods, clevises and turnbuckles. Where these hanger elements are exposed to temperatures of less than 750°F (400°C), carbon steel rods such as ASTM A36 are typically used with forged steel clevises and turnbuckles. Where exposed to higher temperatures of up to 1,100°F (600°C), alloy steel rods, clevises and turnbuckles conforming to ASTM A182 Grade F11 are typically used.

SECTION 4

Service Conditions and Design Loads

	<u>Page</u>
4.1 SERVICE CONDITIONS	103
4.1.1 Site Location	103
4.1.2 Indoor Versus Outdoor Service	103
4.1.3 Mechanical Performance Considerations	103
4.1.4 Nature of the Media Flowing Through Ducts	104
4.1.5 Operating Conditions	104
4.1.6 Excursion and Transient Conditions	108
4.1.7 Insulation and Lagging Requirements	108
4.1.8 Corrosion and Erosion Allowances	109
4.2 DESIGN LOADS	109
4.2.1 Dead Loads	109
4.2.2 Live Loads	110
4.2.3 Environmental Loads	110
4.2.4 Operating Loads	111
4.2.5 System Related Loads	114
4.2.6 Thermal Gradient Loads	117
4.2.7 Construction Loads	118

SECTION 4

Service Conditions and Design Loads

4.1 SERVICE CONDITIONS

Before beginning the structural analysis and design of ductwork and its support structure, the structural engineer should obtain certain pertinent information regarding the service conditions to which the ductwork will be subjected. Collecting the following information is imperative.

4.1.1 Site Location

The structural engineer must always be provided with the location where the ductwork system is to be located. This information should include the country, state, region and municipality. The proximity to coastal areas is also very important. This information will be used to determine the applicable wind and seismic zones and to ascertain which design codes may be applicable.

4.1.2 Indoor Versus Outdoor Service

The structural engineer should always know if the ductwork is to be located indoors or outdoors. When ductwork is indoors, wind and snow loads may be ignored except when addressing construction loading conditions. The owner shall always be informed if the ductwork was not designed for these loads in case conditions change in the future. Lagging requirements may also change if the ducts are indoors.

4.1.3 Mechanical Performance Considerations

Prior to arranging and designing the supports for the ductwork, the structural engineer should consult with the responsible mechanical process engineers on the project. The structural engineer should obtain all of the available information regarding the desired performance of the ductwork system. This information might

include such things as the required duct size or free flow area, maximum and minimum allowable gas velocity, and, in particular, pressure drop requirements. The latter will be affected by the configuration and routing of the ducting, location and type of expansion joints and dampers selected, and the use of any internal bracing or stiffening. Flow distribution and directional devices may be decided upon as being necessary to satisfy mechanical performance requirements. Continuous consultation between both disciplines is recommended throughout the design to ensure a successful project.

4.1.4 Nature of the Media Flowing Through Ducts

Information regarding the media flowing through the ducts must be obtained by the structural engineer. For air ducts, it is important to know if contamination with ash via carryover through common equipment, such as an air preheater, is expected. For flue-gas ducts, it is important to know the chemical composition of the gas. It may be important to know if harmful chemicals such as chlorides, fluorides, ammonia and sulphides are present in the flue-gas. Additionally, it is important to know the flue-gas expected dew point and moisture content. This data will be used to determine whether a (sludge or slurry) will form at the expected flue-gas service temperatures. The expected ash quantity and bulk density in the flue-gas, as well as the velocity, will also help determine what ash loading should be used for the design.

4.1.5 Operating Conditions

The maximum expected continuous operating conditions inside the ductwork must be obtained by the structural engineer from the mechanical process engineer or another reliable source. The values provided for this condition may be somewhat larger than what is commonly called the normal operating conditions since they may occur at some imbalanced point in operation. However, they usually exist for an extended period of time and thus should be the governing criteria.

The operating conditions that are absolutely necessary to know are the maximum expected Operating Pressure and the maximum expected Operating Temperature. Because of the ductwork configuration and the equipment in the duct system, the pressure and temperature is usually different within different sections of duct. See Figure 1.5 for a typical pressure profile for a ductwork system.

For typical **EXAMPLE** pressure and temperature values see the following tables:

- For a pressurized coal-fired power plant, see Table 4.1.
- For a balanced draft coal-fired power plant, see Table 4.2.
- For pressurized and balanced draft industrial boiler systems, see Table 4.3.

Duct Section	Operating Pressure (inches H ₂ O)	Transient Pressure (inches H ₂ O)	Operating Temperature (°F)	Excursion Temperature (°F)
FD Fan to Air Preheater	+30 to +60	+60 to +90	50 to 120	100 to 150
Air Preheater to Boiler	+25 to +55	+60 to +90	300 to 700	400 to 750
Air Preheater to Pulverizer	+30 to +60	+70 to +90	250 to 700	400 to 750
Air Preheater Inlet (From the Boiler)	+10 to +25	+30 to +40	650 to 850	750 to 950
Air Preheater to Precipitator or Baghouse	+5 to +20	+30 to +40	250 to 450	350 to 750
Precipitator or Baghouse to Stack	+5 to +10	+10 to +15 0 to -10	250 to 450	350 to 750

Notes:

1. The location and closing time of dampers can greatly affect the pressures, especially the transient pressures, given in this table. This table assumes that there are dampers at the precipitator inlet.
2. The values in this table are only representative examples. They should not be used for design. The user must obtain the proper design values for the duct system under consideration from the appropriate sources.
3. The table is based on a "cold side" precipitator or baghouse.

Table 4.1
Air and Gas Duct EXAMPLE Pressures and Temperatures
for a Pressurized Coal-Fired Power Plant

Duct Section	Operating Pressure (inches H ₂ O)	Transient Pressure (inches H ₂ O)	Operating Temperature (°F)	Excursion Temperature (°F)
FD Fan to Air Preheater	+20 to +35	+25 to +35	50 to 120	100 to 150
Air Preheater to Boiler	+15 to +35	+25 to +35 -5 to -15	300 to 700	400 to 750
Air Preheater to Pulverizer	+40 to +70	+70 to +90	250 to 700	400 to 750
Air Preheater Inlet (From the Boiler)	-10 to -25	-35 to -50	650 to 850	750 to 950
Air Preheater to Precipitator or Baghouse	-20 to -35	-35 to -50	250 to 450	350 to 750
Precipitator or Baghouse to ID Fan	-30 to -50	-35 to -50	250 to 450	350 to 750
ID Fan to Scrubber	+5 to +15	+30 to +45 -5 to -15	250 to 450	350 to 750
Scrubber to Stack	+5 to +15	+10 to +25 -5 to -15	120 to 350	180 to 750

Notes:

1. The location and closing time of dampers can greatly affect the pressures, especially the transient pressures, given in this table. This table assumes that there are dampers at the precipitator inlet.
2. The values in this table are only representative examples. They should not be used for design. The user must obtain the proper design values for the duct system under consideration from the appropriate sources.
3. The table is based on a "cold side" precipitator or baghouse.

Table 4.2
Air and Gas Duct EXAMPLE Pressures and Temperatures
for a Balanced Draft Coal-Fired Power Plant

Pressurized System				
Duct Section	Operating Pressure (inches H ₂ O)	Transient Pressure (inches H ₂ O)	Operating Temperature (°F)	Excursion Temperature (°F)
FD Fan to Air Preheater	+15 to +30	+20 to +40	50 to 120	100 to 150
Air Preheater to Boiler	+10 to +25	+15 to +35	300 to 500	400 to 500
Boiler to Heat Trap (Exchanger)	+5 to +20	+10 to +25	450 to 800	500 to 850
Heat Trap to APCD	+5 to +20	+10 to +25	300 to 500	400 to 600
APCD to Stack	0 to +5	0 to +10	250 to 500	300 to 600

Balanced Draft System				
Duct Section	Operating Pressure (inches H ₂ O)	Transient Pressure (inches H ₂ O)	Operating Temperature (°F)	Excursion Temperature (°F)
FD Fan to Air Preheater	+10 to +20	+15 to +30	50 to 120	100 to 150
Air Preheater to Boiler	+5 to +15	+10 to +20	300 to 500	400 to 500
Boiler to Heat Trap (Exchanger)	-5 to -10	-10 to -15	450 to 800	500 to 850
Heat Trap to APCD	-10 to -20	-15 to -20	300 to 500	400 to 550
APCD to ID Fan	-10 to -20	-15 to -25	300 to 500	400 to 550
APCD to Stack	0 to +5	0 to +5	300 to 500	400 to 550

Notes:

1. The location and closing time of dampers can greatly affect the pressures, especially the transient pressures, given in this table. This table assumes that there are dampers at the Air Pollution Control Device (APCD) inlet.
2. The values in these tables are only representative examples. They should not be used for design. The user must obtain the proper design values for the duct system under consideration from the appropriate sources.

Table 4.3
Air and Gas Duct EXAMPLE Pressures and Temperatures
for Pressurized and Balanced Draft Industrial Boilers

The values in these tables are only representative **EXAMPLES**. They should not be used for design. The user must obtain the proper design values for the duct system under consideration from the appropriate sources.

4.1.6 Excursion and Transient Conditions

The maximum expected excursion and transient conditions that will occur inside the ductwork must also be obtained from the mechanical process engineer or another reliable source. These conditions will occur at some imbalance point in the operation and exist only for a relatively short period of time. Depending on the event, this could be several seconds, minutes, or maybe even hours.

The short term conditions that are absolutely necessary to know are the **maximum expected Transient Pressure** and the **maximum expected Excursion Temperature**. As with the operating conditions, these short term values will usually be different within different sections of duct. The minimum design pressure requirement given in chapters 4 and 5 of the National Fire Protection Association (NFPA) documents NFPA 85C, *Standard for the Prevention of Furnace Explosion/Implosions in Multiple Burner Boiler-Furnaces*, NFPA 8504, *Standard on Atmospheric Fluidized-Bed Boiler Operation*, and NFPA 8505, *Recommended Practice for Stoker Operation*, may be applicable. Pressures may be negative or positive values. These transient pressures may occur during boiler implosions, flame basket collapse, main fuel trips, failure of dampers to open or close, accidental damper actuation, air preheater failure or emergency shutdowns.

See Tables 4.1, 4.2 and 4.3 for typical **EXAMPLE** values of transient pressures and excursion temperatures.

4.1.7 Insulation and Lagging Requirements

The structural engineer must be able to determine or conservatively estimate the weight of the insulation and lagging which will ultimately be attached to the ductwork. The insulation may be inside or outside of the duct. Refractory may be used as internal insulation and for corrosion protection. The thickness and type of insulation is often determined based on the customer's specification or building code requirements. The thickness and type of lagging is also often specified by the customer or may be chosen by the necessity to walk on it. In any event, the structural engineer needs to know enough to be able to obtain a weight for these items. It is

acceptable to make conservative estimates for these weights except in the case of spring supported systems or where uplift loading is critical. In these cases a more accurate weight determination is essential for proper load analysis. More information regarding insulation and lagging can be found in Section 11.

4.1.8 Corrosion and Erosion Allowances

Sometimes the customer may specify a desired corrosion or erosion allowance for the duct plate and internal element. If no allowance is specified, the structural engineer may wish to add one if certain severe conditions exist. Usually, this is in the form of a thickness allowance. See Section 4.1.4 for a discussion on the possible damaging elements carried within ducts. Special coatings or linings can also be used in lieu of a thickness allowance in cases of severe conditions as described in Section 3. If significant, the added weight of these should be considered in the design. In no case should a corrosion or erosion allowance be considered as part of the structure for strength calculations. If a corrosion or erosion allowance is used, the structural engineer should calculate the stresses based on the reduced thickness of plates or shapes but dead loading should be based on full thickness.

4.2 DESIGN LOADS

Design loads can be categorized as either primary loads or secondary loads. Primary loads are those loads which do not decrease no matter how much the structure deforms. Dead load and pressure load are good examples of primary loads. These loads are independent of structural deformation and the structure will continue to deform until failure occurs. Secondary loads are self-limiting loads which are strain controlled. Thermal loads are an example of secondary loads. With thermal load, the driving force (thermal expansion) will only be imposed up to the point where the imposed strain ceases to increase. The majority of loads considered in duct structural analysis are primary loads.

The ductwork should be designed for the following minimum loads and combinations thereof. Loading combinations and appropriate allowable design stresses are presented in Section 5.

4.2.1 Dead Loads - DL

The dead load to be used in the structural analysis should consist of the weight of all duct components and any other materials permanently fastened thereto.

Steelwork dead load includes duct plate, stiffeners, trusswork, turning vanes, platforms, ladders, dampers, hoppers and any other steel permanently attached. Other materials may include insulation, refractories, lagging, linings, instrumentation, expansion joints, or any other equipment supported by or within the duct.

4.2.2 Live Loads - LL

Live loads are herein defined as those produced by the occupancy or use of the ductwork for temporary laydown or storage. Live loads may be uniformly distributed loads, as in the case of a platform supported from the ductwork, or they may be a concentrated load such as a person walking on top of the duct. The top of a duct may be utilized for equipment laydown or storage. If this is expected, the top of the duct must be designed for this uniform live load.

Platform loads are typically a minimum of 75 lb/ft² (3,600 N/m²). This may be greater if heavier equipment is expected to be transported across the platform. The minimum concentrated load for a man walking on a duct is usually 250 lbs (1,100 N).

4.2.3 Environmental Loads - EL

Environmental loads are typically defined by local and state building codes or as presented in the ASCE Standard ASCE 7-93, *Minimum Design Loads for Building and Other Structures*.

Environmental loads are:

Wind Loads - EL_w

Snow Loads - EL_s

Seismic Loads - EL_E

Ductwork is ordinarily considered by structural engineers as Category I structures for wind and snow loads and as in Seismic Hazard Exposure Group I or II structures for seismic analysis as defined in ASCE Standard 7-93.

Wind and snow loads should be based on the exterior dimensions of the ductwork, which must include the insulation and lagging. Seismic loads are usually based on dead load and full design ash loads. Also, some codes require portions of the snow load to be included in the seismic analysis if the ground snow load exceeds some value, usually 30 psf (1,450 N/m²).

If the ductwork is indoors, wind and snow loads may be neglected except when designing for construction loading conditions. If the ducts are not designed for wind or snow loads, the structural engineer should advise the owner and the erector, especially if snow or wind loads are expected to be significant during construction. See Section 4.2.7 for more discussion on construction loads.

4.2.4 Operating Loads - OL

Operating loads are herein defined as loads resulting from the operation of the ductwork system. These loads may result from steady state or short-term conditions.

Operating loads include the following.

Operating Pressure - OL_{OP}

The operating pressure is defined as the expected maximum operating air or flue-gas pressure continuously acting on the walls of the ductwork over an extended period of time.

Transient Pressure - OL_{TP}

The transient pressure is defined as the maximum expected air or flue-gas pressure acting on the walls of the ductwork for a relatively short duration of time; several seconds, minutes or hours. Transient pressure is usually considered as an accident condition.

Ash Loads - OL_A

When flyash is entrained in flue-gas, ash fallout onto the duct floor should be expected. Because of this fallout, ash loading should be considered in the design of the flue-gas ductwork. See Figure 4.1 for typical locations of ash accumulation. Note that there may even be ash deposits on the duct floor downstream of a precipitator or fabric filter. In some instances even air ducts can be contaminated with ash via carryover through equipment such as an air preheater.

Because ash loading can be significant, ^{FGD} affecting the cost of the ductwork and its supporting structure, flow model studies are often used to more accurately predict ash fallout. These studies can be costly and time consuming, so the engineer and the owner must weigh the benefits derived from the flow model against their cost and overall schedule requirements. Flow models are also useful in determining flow distribution and pressure drop and often are more accurate in the determination of these effects than analytical methods. All of this should be taken into account in the decision process.

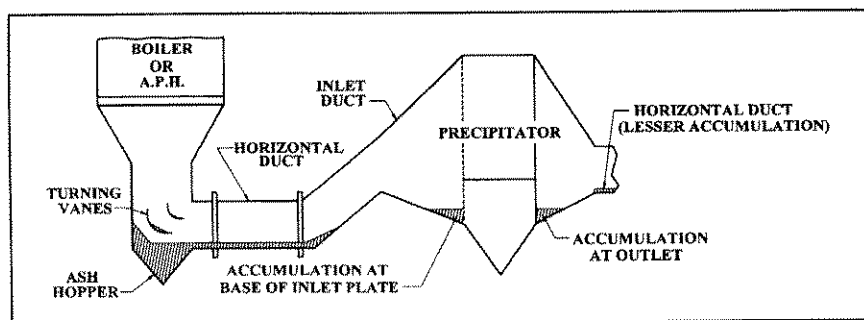


Figure 4.1
Typical Locations of Ash Accumulation

Ash densities vary depending upon the type of fuel burned, the flue-gas temperature and humidity, the method of combustion, and the wetness of the ash. A minimum pulverized coal ash density of 75 lb/ft³ (1,300 kg/m³) is recommended as acceptable, but the use of a higher value may be necessary depending on the exact type of coal or lignite and the plant operating conditions. Different values may be used for the ash density from burning oil, wood, bark, bagasse, black liquor, and municipal waste fuels. Table 4.4 presents typical ash density ranges for these different fuels.

FUEL	Density (lbs/ft ³)
Coal or Lignite	75 - 120
Oil	10 - 40
Wood, dry	10 - 30
Bark, Bimodal Sand	100 - 120
Bark, Char	10 - 30
Bark, Combination	40 - 80
Bagasse	30 - 50
Black Liquor	10 - 20
Municipal Waste	30 - 60

Table 4.4
Flyash Density Ranges

Ash depths can be as high as 5 or 8 feet (1.5 or 2.5 meters) under the most unfavorable conditions. Typical design depths vary from 6 inches (150 mm) to 25% of the duct height. The amount of ash to be considered in the analysis and design of the ducts is dependent on several factors.

- **Type of Fuel Being Burned:**

Ash is more predominant on coal, black liquor and solid fuel fired units as compared to oil or gas fired units where it is often neglected.

PGD
18 m/sec

- **Flow Velocity:**

Flyash is likely to settle out in ducts where the velocity is less than 40 feet/sec (12 meters/sec). Bypass or crossover ducts which have no flow through them during many modes of operation are particularly prone to accumulating large amounts of ash.

- **Location Relative to the Ash Collection Equipment:**

Ducts upstream of ash collection equipment such as mechanical dust collectors, precipitators, baghouses and scrubbers will have higher accumulation of ash than ducts downstream of the equipment. However, it is also very common to have very large accumulations of ash on the floor of the duct at the outlet of the ash collection equipment. Flow distribution baffles placed at the inlet of ash collection equipment often catch ash and have a fairly large accumulation at their base.

- **Increase in Cross-Sectional Area:**

When the cross sectional area of a duct greatly increases, the velocity greatly decreases and there is a strong likelihood that a large amount of ash will fallout onto the duct floor.

- **Changes in Flow Direction (Duct Corners):**

Ash is more apt to settle out at locations where the ductwork abruptly changes direction. One example of this is where a horizontal duct takes a 90° turn. Other examples are where ductwork goes from vertically down to horizontal or horizontal to vertically up. At these locations hoppers are often provided. Hoppers at these locations should be designed to be completely full of ash to the bend line. In some situations where the reliability of the ash removal system is suspect, it may be prudent to design for even a higher level.

- **Long Horizontal or Slightly Inclined Ducts:**

These ducts are also susceptible to ash accumulation. A minimum of 6 inches (150 mm) of ash should be anticipated.

- **Turning Vanes:**

Some turning vanes act as a ledge and tend to collect ash. They should be designed accordingly. See Section 9 for additional information on turning vane loadings.

Sludge Loads - OL_s

Downstream of wet and dry scrubbers and condensing heat exchangers, moisture can result as the flue-gas temperature drops below its dew point. The carry-over from this process often results in the creation of a sludge on the interior surfaces of the duct. Where coal sludge deposits are expected, a minimum density of 125 lb/ft³ (2,000 kg/m³) is typical, but the use of a higher value may be necessary depending on the type of fuel, the flue-gas moisture content and other operating conditions. It is not uncommon to find 6 to 12 inches (150 mm to 300 mm) of sludge buildup on the walls and ceiling of scrubber outlet ducts. Much larger amounts have been known to accumulate depending on the frequency of cleaning and removal. A discussion with the owner regarding the latter may be appropriate. More sludge may be present on the duct floor and on turning vanes as compared to the duct walls.

4.2.5 System Related Loads - SL

System loads are herein defined as loads that are created or result from decisions made during the design and layout process. They become real loads on the system.

Unbalanced Pressure Forces - SL_{UP}

Expansion joints are added to the ductwork system to absorb and control thermal expansion. Whenever a section of duct has an expansion joint located so that there is a duct wall that does not have another duct wall directly across from it, an unbalanced pressure occurs in that duct section. Unbalanced pressure forces will only occur opposite openings or expansion joints directly upstream or downstream of bends or transitions. When this arrangement occurs, the resulting unbalanced pressure force and any associated moments must be transferred through the duct to its support structure. The line of action of this force is along the centerline axis of the expansion joint perpendicular to the opening. The magnitude of the force is calculated by multiplying the area of the opening by the internal pressure; either operating or transient depending on the loading condition being considered. In actuality, the flow in ducts obeys Bernoulli's equations for mass flow of a compressible fluid; but because the mass velocity term is relatively small compared to the pressure and area term, the former can

usually be ignored. See Figure 4.2 for an example of the effects on a duct section from unbalanced pressure. For further detailed discussions on unbalanced pressure, see Section 2.7.

Dynamic Unbalanced Pressure Forces - SL_{DP}

Whenever turns, elbows or flow distribution devices, such as turning vanes, splitter plates or perforated baffle plates, are added to the system to distribute flow or reduce pressure drop, an unbalanced dynamic pressure force is created. The structural engineer must determine whether these forces are small enough so as to be neglected or large enough to be included in the design. In the case of turning vanes and perforated baffle plates it usually must be considered. See Section 9 for the procedure to calculate dynamic unbalanced pressure forces and the structural design of flow distribution devices.

Expansion Joint Actuation Forces - SL_{EJ}

In order for an expansion joint to operate - open and close - as intended, a force must be applied to it. If a joint is very flexible, as is the case with many non-metallic expansion joints, this load is very small and may be ignored. If, however, relatively stiff metal joints are used, this force may be large and needs to be considered when resolving loads to the external support system. The spring constant of the joint is usually available from the joint manufacturer and this stiffness factor "k", along with the anticipated movement, can be used to determine the force that results. If the duct sections undergo rotation along with axial movement, a global moment will be exerted on the duct sections. Formulas for determining these forces and moments are given in the *Standards of the Expansion Joint Manufacturers Association*, Section C-8.

Spring Loads - SL_s

If, because of anticipated thermal movement, the structural engineer needs to use spring supports at a particular location, these springs must be treated as loads when resolving the forces to the remaining duct supports for all loading combinations. When analyzing a duct section with spring supports, reverse loads that tug on the duct should be applied at the spring locations. The springs should not be modeled as supports.

There is only one cold setting and one hot setting to which a variable spring can be set. Additionally, in the case of a constant support spring, there is an inertial force of between 3% and 5% of the set load required to drive the spring which must be taken into account.

**SOLVING FOR THE DUCTWORK OPERATING
PRESSURE LOADS TO THE SUPPORT STEEL
(POSITIVE PRESSURE USED IN THIS EXAMPLE)**

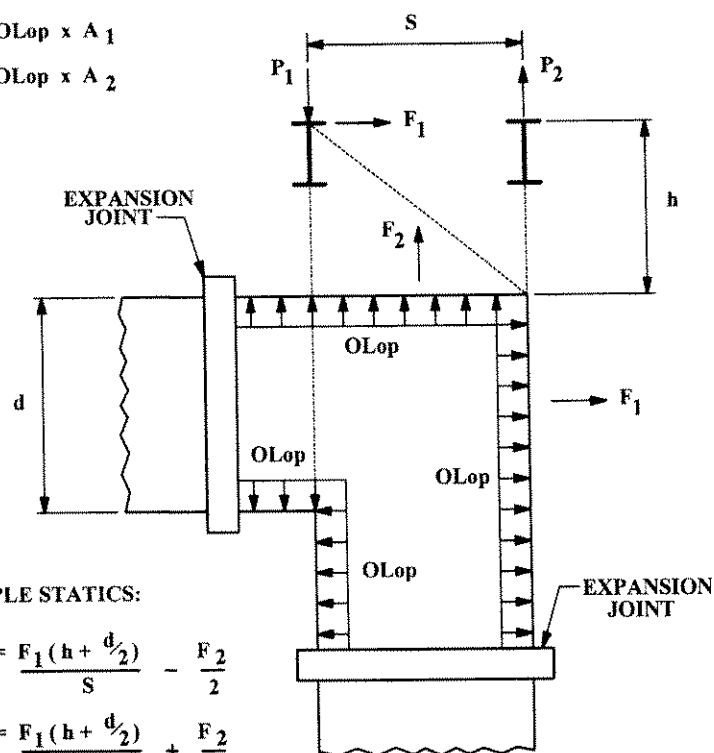
$OLop = \text{OPERATING PRESSURE (psf)} = 5.2 \times (\text{INCHES OF } H_2O)$

$A_1 = \text{CROSS SECTIONAL AREA OF DUCT
AT VERTICAL EXPANSION JOINT}$

$A_2 = \text{CROSS SECTIONAL AREA OF DUCT
AT HORIZONTAL EXPANSION JOINT}$

$F_1 = OLop \times A_1$

$F_2 = OLop \times A_2$



BY SIMPLE STATICS:

$$P_1 = \frac{F_1 (h + \frac{d}{2})}{S} - \frac{F_2}{2}$$

$$P_2 = \frac{F_1 (h + \frac{d}{2})}{S} + \frac{F_2}{2}$$

Figure 4.2
Effect of Unbalanced Pressure Forces
on Ductwork and Its External Supports

Friction Forces - SL_F

When a duct section is base supported, a sliding detail to facilitate thermal growth is required at all base supports except at the duct section's anchor or fixed point. The sliding may take place between two steel surfaces or between one steel surface and a reduced friction slide bearing plate. Slide bearing plates are relatively inexpensive and are frequently used. Rollers are also used in some applications. The anticipated frictional forces must be taken into the duct system and resolved to the fixed supports. The coefficient of friction that is assumed in the structural analysis should be based on the expected value towards the end of the plate's design life, not the new plate published value. It is not uncommon to use a coefficient of friction of between 0.05 and 0.15 for new designs. Additionally, if guide bars are used to transfer lateral loads due to wind, seismic, unbalanced pressure, etc. to the support system, lateral friction forces on the guide bars can occur and may need to be considered in the design.

4.2.6 Thermal Gradient Loads - TL

The air or flue-gas temperature within any section of ductwork is not always uniform across its cross section. For this reason, the steel exposed to the air or gas is not always at the same temperature. This leads to temperature differentials across the ductwork structure. Also, some of the ductwork elements may be exposed to hot air or gas on one side and ambient air on another side, even if insulated. This leads to a temperature differential across the individual element as well as somewhat of an overall temperature differential across the ductwork structure. Local failures of the insulation system cause these conditions to be accentuated.

The deposition of flyash in ductwork can also create thermal gradient loads. This is because the ash acts as an insulator. Therefore, during unit start-up a condition can occur when the top section of a duct is hot while the bottom is cold, creating a thermal gradient load in the ducts. Of course the reverse gradient could occur during a unit shut down.

Temperature differentials across an individual member or across a complex structural system can cause thermal stresses that are secondary in nature. If the temperature differential is very high, the developed stresses can be very high and local failures can result.

Usually, these types of thermal loads are ignored when analyzing and designing ducts. This is because the temperature differentials

and their associated stresses are usually very small, the duct structural system is usually flexible enough so that these secondary stresses are easily relieved, and most often temperature differentials are not anticipated.

If significant temperature differentials are expected, they must be considered in the structural analysis and design.

4.2.7 Construction Loads - CL

It is the erector's responsibility to secure the ductwork against all expected and unexpected loadings during construction until the ductwork is fully assembled and supported. This is in accordance with the *AISC Code of Standard Practice*. This includes the determination, supply and installation of shipping bracing, lifting lugs, temporary supports, temporary erection bracing, temporary guys, falsework, cribbing and anything else required. The erector should be strongly encouraged to consult with the ductwork structural design engineer if he has any doubts as to how this is to be accomplished. This practice especially applies to knock-down type construction.

However, when ductwork is to be supplied to the field in large shop assembled sections, the structural engineer should be more involved in this process as discussed in Section 10. In these instances, the structural engineer should select lift points and may design lifting lugs and frames. A lifting diagram may also be required, showing how the piece is to be handled during various phases as it travels from the fabrication shop to its final installation position. This must take into account the mode of transportation. The structural engineer may have to consult with the fabricator and erector as to the lifting equipment to be used. When designing these lifting lugs or frames, an impact factor of 1.5 should be applied to the lifted loads. Lifting loads must also be given to the structural steel design engineer. Since the number of lifting points are often less than the number of final support points, the structural steel in the area must be designed accordingly.

Circular ducts have a special sensitivity to transportation and handling when they are shipped in one piece as a cylinder because of their potential for buckling as explained in Section 6. Provisions for analyzing and designing these ducts for impact due to shipping and handling should be considered. See Section 10 for more detailed discussions on bracing for shipping and all of the other construction related topics mentioned above.

SECTION 5

Loading Combinations and Associated Design Stresses

	<u>Page</u>
5.1 DESIGN STRESS CONSIDERATIONS	121
5.1.1 Normal Allowable Stress	121
5.1.2 Yield Stress	122
5.1.3 Creep Stress	122
5.1.4 Fatigue and Fracture Stress	123
5.2 RECOMMENDED ANALYSIS AND DESIGN APPROACH ..	124
5.3 LOAD DEFINITIONS AND CONSIDERATIONS	124
5.4 LOADING COMBINATIONS	125
5.4.1 Off-line Loading Combinations at Ambient Temperature	125
5.4.2 Operating Loading Combination at Operating Temperature ..	125
5.4.3 Environmental Loading Combinations at Operating Temperature	126
5.4.4 Sustained Loading Combination at High Creep-Susceptible Temperatures	126
5.4.5 Transient Loading Combination at Operating Temperature ..	126
5.4.6 Thermal Gradient Loading Combination at Operating Temperature	126
5.4.7 Operating Loading Combination at Excursion Temperature ..	127

SECTION 5

Loading Combinations and Associated Design Stresses

5.1 DESIGN STRESS CONSIDERATIONS

Air and gas ducts are unique structures which are subjected to a wide variety of loads and loading combinations. The loads are discussed in detail in Section 4 and the loading combinations are discussed here in Section 5. These loadings occur or exist over long or short periods of time while the ductwork is exposed to different temperatures. Application of these loads are discussed in Sections 6, 7, 8 and 9. The structural engineer must design ductwork which will be reliable, operate safely and not fail under all of the anticipated conditions for the design life of the duct. To do this, the structural engineer must determine the stresses in the various duct components and limit them to certain acceptable or allowable values. These limiting values are presented here. See Section 3 for additional discussions on allowable stresses.

5.1.1 Normal Allowable Stress

Normal allowable stresses for steels in tension, bending, shear, compression, and all other states of stresses are traditionally defined in the *AISC Specification for Structural Steel Buildings - Allowable Stress Design and Plastic Design (ASD)* presented in the *AISC Manual of Steel Construction - Allowable Stress Design (AISC-ASD)*. The formulas given therein are expressed as a function of F_u , the ultimate strength, F_y , the yield strength, and E , the Modulus of Elasticity of the material. These AISC formulas are primarily empirical and are based on data attained through testing steel at room temperature. For elevated temperatures, the accepted practice in the ductwork industry has been to use these same formulas but substituting values for F_y , F_u and E obtained from testing performed at elevated steel temperatures. For common steels, this approach is valid up to a temperature of 750°F (400°C). Above this temperature a phenomena known as creep rupture may occur when

400°C

the steel is exposed to sustained stresses. Ductwork allowable stresses are discussed further in Section 3.3 and Section 5.1.3.

5.1.2 Yield Stress

The yield stress of a steel is that stress at which there is a marked increase in strain without an increase in stress. Below this stress level the strain is directly proportional to the stress applied. Additionally, when the load or stress is removed, the material returns to its original shape. Below its yield stress the material is elastic. As the steel temperature increases above about 100°F (40°C), its yield point decreases. See Section 3 for more discussion on yield stresses. Steel suppliers have performed tests and published values for the various structural steels used in ductwork design.

The basis for limiting stresses from transient or excursion loading combinations and thermal loading combinations is usually 95% of these high temperature reduced F_Y values or 1.6 times the normal allowable stresses. 95% of the yield stress may be used to limit tension or bending stresses, but $0.55F_Y$ should be used to limit shear stresses from transient loading combinations. Compression stresses from transient loading combinations should not exceed 95% of Euler's buckling capacity or 1.6 times the normal allowable stresses, both based on the temperature reduced values for F_Y and E . However, in structural systems where large deflections may cause large secondary stresses, a more conservative allowable stress value may be warranted.

Yield stress based values may also be used to limit stresses from transient loading combinations even when the service temperature places the materials in the creep range. However, if the stresses are sustained above the steel's creep susceptible temperature, the life of the material will be shortened due to temperature related creep and creep rupture as discussed below.

5.1.3 Creep Stress

When exposed to elevated temperatures, steel encounters a phenomenon called creep. This temperature is about 750°F (400°C) and is dependent on the exact chemistry of the steel. At very high temperature, even at a constant stress, the steel strain will increase (creep) as time progresses. Considerable strain and an eventual failure may occur at stresses well below the yield strength of the material. The deformation will continue over time until rupture occurs. This time period is known as the time-to-failure. Depending

on the stress, steel chemistry and temperature, this time can be a matter of hours or years. Creep is usually measured as a function of time. At a certain stress level, the steel will deform a certain percent in a certain time. For relatively low stresses in normal design ranges, this time is usually thousands of hours.

At operating temperatures above 750°F (400°C), creep and stress rupture begin to govern the design. The temperature at which creep governs is dependent on the material selected and, even more so, the exact chemistry of the material. The maximum allowable creep design stress, or the limiting creep stress, as taken from the *ASME Boiler and Pressure Vessel Code, Section I - Rules for Construction of Power Boilers*, should not exceed the lowest of the following two values:

- 100% of the average stress to produce a creep rate of 1% in 100,000 hours
- 67% of the average stress to cause rupture at the end of 100,000 hours

The creep rate and creep rupture values for carbon and low alloy steels can be obtained from publications of the American Society for Testing and Materials (ASTM) as well as from certain steel manufacturers. Many boiler manufacturers have also developed their own data from laboratory testing and the ASME also publishes values. See Section 3 for additional information on creep and a presentation of creep limiting stresses. Again, because of their nature, creep restricting stresses are only used to limit tensile stresses from sustained loading combinations.

5.1.4 Fatigue and Fracture Stress

There are two modes of failure in steel structures that are different in nature to those commonly considered in conventional allowable stress design. These are fatigue and fracture. Fatigue is the result of the application of stress reversal over many repeated cycles. With a high number of cycles, a member may fail at a stress level below its normal allowable stress. Fracture is failure caused by the brittle behavior of the material under certain adverse conditions of temperature and environment. Both of these types of failures are known to occur in ductwork. Because of their complicated technical nature, fatigue and fracture analysis are beyond the scope of this document. However, the structural engineer must address these failure modes when they are expected to occur, especially when the duct steel is below its nil-ductility temperature.

The experienced ductwork structural engineer's most common approach for controlling these phenomena is to incorporate design controls so that these problems are not a concern. This can be done by selecting the proper material for the expected conditions, by keeping some structural elements stiff and others flexible, and by arranging the structural system and elements in manners to reduce high local stresses and stress concentrations, minimize vibrations and minimize cyclic loadings. There are guidelines throughout this document for designing ductwork so that these problems should not occur.

5.2 RECOMMENDED ANALYSIS AND DESIGN APPROACH

In order to design the ductwork properly, the structural engineer must consider the loads outlined in Section 4 and evaluate the probability of their simultaneous occurrence. Additionally, the structural engineer must determine whether the loadings are sustained or short term and the maximum temperature under which they are likely to exist. The stresses resulting from the selected load combinations should then be compared to an appropriate limiting stress value. Unfortunately, this is often a time consuming and cumbersome task that cannot be simplified by using conventional load factor analysis because the factors would have to vary with temperature, type of material, and whether the loads or the loading combinations are sustained or short term.

Therefore, the use of actual loads and allowable stresses is recommended as the design approach, which is called allowable stress design or ASD. This design method is outlined in the *AISC Specification for Structural Steel Buildings - Allowable Stress Design and Plastic Design (AISC-ASD)* presented in the *AISC Manual of Steel Construction - Allowable Stress Design (ASD)*.

5.3 LOAD DEFINITIONS AND CONSIDERATIONS

The design loads listed below are more extensively defined and explained in Section 4.2. The load symbols used in this publication are:

DL Dead Loads

LL Live Loads

EL Environmental Loads

EL_W Wind Loads

EL_S Snow Loads

EL_E Seismic Loads

TL Thermal Gradient Loads

CL Construction Loads

OL Operating Loads

OL_{OP} Operating Pressure

OL_{TP} Transient Pressure

OL_A Ash Loads

OL_S Sludge Loads

SL System Related Loads

ΣSL_X Summation of System Loads which act simultaneously and may include:

SL_{UP} Unbalanced Pressure Forces

SL_{DP} Dynamic Unbalanced Pressure Forces

SL_{EJ} Expansion Joint Actuation Forces

SL_S Spring Loads

SL_T Friction Forces

5.4 LOADING COMBINATIONS

The structural engineer must investigate each element and component of the ductwork structural system for the applicable loading combinations outlined below. The most critical shall govern the design of that element or component. If a higher stress is calculated by eliminating any particular load and that event is possible, then that load must be left out of the loading combination. For calculating net uplift or tension stresses, 75% of the dead load should be considered along with no other load that would counteract the tension or uplift.

In the following sections is a listing of loading combinations that are to be investigated. These loading combinations consider the temperature, the type of loading and the duration of loading, and presents the recommended associated limiting stresses to be used.

5.4.1 Off-line Loading Combinations at Ambient Temperature

The following loading combinations are limited to off-line conditions at ambient temperature. Normal allowable stress shall apply.

DL + LL + EL_S + (OL_A or OL_S)

DL + CL

5.4.2 Operating Loading Combination at Operating Temperature

The following loading combination is limited to operating conditions at the operating temperature. Normal allowable stress, reduced for the temperature effects, shall apply.

DL + LL + OL_{OP} + (OL_A or OL_S) + ΣSL_X (operating values)

5.4.3 Environmental Loading Combinations at Operating Temperature

The following loading combinations are limited to environmental loading conditions at the operating temperature. Normal allowable stress increased by a factor of 1.33, then reduced for the temperature effects, shall apply.

The loading combination from Section 5.4.2 + EL_w

The loading combination from Section 5.4.2 + EL_T

5.4.4 Sustained Loading Combination at High Creep-Susceptible Temperatures

The following loading combination is limited to loading conditions with only sustained loads at the operating temperature. A limiting creep stress, with the appropriate factor of safety, should be used.

The loading combination from Section 5.4.2, but with only sustained loads.

5.4.5 Transient Loading Combination at Operating Temperature

The following loading combination is limited to transient conditions at the operating temperature. Normal allowable stress increased by a factor of 1.6, then reduced for the temperature effects, shall apply. If increasing the allowable stress by the 1.6 factor causes the allowable stress to go above $0.95F_Y$ for tension, $0.95P_{CR}$ for buckling or $0.55F_Y$ for shear, the allowable stress shall be limited to either $0.95F_Y$, $0.95P_{CR}$ or $0.55F_Y$ as appropriate.

$DL + LL + OL_{TP} + (OL_A \text{ or } OL_S) + \Sigma SL_X$ (transient values)

5.4.6 Thermal Gradient Loading Combination at Operating Temperature

The following loading combination is limited to thermal loading conditions at the operating temperature. This loading combination is usually considered only if the structural engineer expects significant thermal loads. Normal allowable stress increased by a factor of 1.6, then reduced for the temperature effects, shall apply. If increasing the allowable stress by the 1.6 factor causes the allowable stress to go above $0.95F_Y$ for tension, $0.95P_{CR}$ for buckling or $0.55F_Y$ for shear, the allowable stress shall be limited to either $0.95F_Y$, $0.95P_{CR}$ or $0.55F_Y$ as appropriate.

$DL + LL + OL_{OP} + (OL_A \text{ or } OL_S) + TL + \Sigma SL_X$ (operating values)

5.4.7 Operating Loading Combination at Excursion Temperature

The following loading combination is limited to operating conditions at the excursion temperature. Normal allowable stress increased by a factor of 1.6, then reduced for the temperature effects, shall apply. If increasing the allowable stress by the 1.6 factor causes the allowable stress to go above $0.95F_Y$ for tension, $0.95P_{CR}$ for buckling or $0.55F_Y$ for shear, the allowable stress shall be limited to either $0.95F_Y$, $0.95P_{CR}$ or $0.55F_Y$ as appropriate.

$DL + LL + OL_{OP} + (OL_A \text{ or } OL_S) + TL + \Sigma SL_X$ (operating values)

SECTION 6**Plate Design and Stiffener Location Considerations**

	<u>Page</u>
6.1 INTRODUCTION	131
6.1.1 Effects of the Types of Loads on the Preliminary Design	131
6.1.2 Effects of the Duct Support Scheme on Plate Stresses	132
6.2 RECTANGULAR DUCT PLATE DESIGN	132
6.2.1 Stiffener Contributory Areas and Plate Analysis	134
6.2.2 Typical Plate Thickness and Stiffener Spacing	134
6.2.3 Plate Analysis Deflection Theories	136
6.2.4 Secondary Versus Primary Stresses	137
6.2.5 Combined Stresses	139
6.3 PLATE AND STIFFENER COMPOSITE ACTION.....	140
6.3.1 Composite Properties and Stiffener Deflection	140
6.3.2 Corner Configurations	141
6.4 CIRCULAR DUCTWORK PLATE DESIGN	142
6.4.1 Designing for Buckling and Handling	142
6.4.2 Meridional Stress	142
6.4.3 Shell Hoop Stress	143
6.4.4 Tangential Shear Stress	145
6.4.5 Factors of Safety	145
6.5 OTHER CONSIDERATIONS.....	145
6.5.1 Fatigue, Endurance Limits and Crack Control	146
6.5.2 Solutions to Problems	147

SECTION 6

Plate Design and Stiffener Location Considerations

6.1 INTRODUCTION

There are many varied possible duct plate configurations. Duct plate can have different support conditions, stiffener positioning and edge distance constraints which affect the plate design. Both good references and sound *engineering judgement should be used by the ductwork structural engineer as each design decision presents itself. Cost should always be considered* when making decisions regarding the basic duct shape, plate thickness and stiffener arrangement.

Both rectangular and circular duct design are addressed in this section. Because of the interaction between the duct plate and its stiffeners, the material presented in this section should be used concurrently with the information presented in Section 8.

6.1.1 Effects of the Types of Loads on the Preliminary Design

Sections 4 and 5 present the types of loads, loading combinations and associated allowable design stresses that are to be used for ductwork panel design. These loads and loading combinations are used to calculate duct plate stress, deflection and dynamic response. Conceptual approaches that may be used in developing engineering calculations for these items are also addressed in this Section.

A preliminary duct panel design should anticipate the results from the structural global and local analysis. For example, circular ductwork is more cost effective when the internal pressures are very high. The alternative would probably be heavier rectangular ductwork with thicker plate. An environment with excessive thermal loading or dynamic considerations will dictate the stiffener framing arrangement and the plate design and will tend to minimize internal members.

Planned transportation and erection modularization procedures may create loading conditions which should also be considered in the panel design. The overall duct and local stiffening arrangement necessary to serve such potential schemes may control some stiffener spacings and possibly the duct plate thicknesses. As an example, if a duct section must span a very long distance over a road or a building, the erection procedure may involve lifting the entire assembly in one piece or it may be erected in two or three large pieces with temporary supports. This is similar to the methods of constructing a large span bridge. These two procedures would impose different dead load stresses on the duct structure and thus the duct plate.

6.1.2 Effects of the Duct Support Scheme on Plate Stresses

Duct plate stresses can often be dependant on the stiffness of the structural steel or foundations supporting the ductwork. Figure 6.1 shows an example of a poor duct support arrangement that should be avoided. With the conditions shown, significant torsional stresses would be developed in the duct plate because of the differences in the support stiffnesses; two supports are rigid hangers, one is off of a rigid column, and the fourth is near the middle of a relatively flexible beam. When distortion-induced effects like this are not addressed in the analysis and design, the actual primary load paths will NOT be those that were assumed or determined by the structural engineer in the analysis. Because of this one soft support, very significant secondary stresses can develop in the duct plate as the duct composite structure struggles to carry the primary loads to the three hard supports. This behavior is possible because of the relatively high stiffness of the duct itself. Stresses induced as described above are best avoided by revising the support conditions rather than including these differential support stiffness conditions in the analysis by modelling each support with a different spring force. Effects of differential support movement might also be minimized by effective positioning of an expansion joint as described in Section 2.

6.2 RECTANGULAR DUCT PLATE DESIGN

In rectangular ducts, the plate acts in conjunction with other structural elements to balance the pressure forces and carry the gravity and external loads to the supports. The plate is probably the most important structural element in the duct, but it could not economically function without its stiffeners and internal trusses or moment frames.

When the duct stiffeners are in a parallel configuration, which is the usual case, a strip of plate is assumed to span between and be supported by two stiffeners. The stiffeners may be oriented perpendicular or parallel to the flow depending on the stiffener framing philosophy of the company performing the structural design. Banded stiffeners orientated perpendicular to the flow are supported at the duct corners by the mating stiffener or the duct plate and sometimes by internal trusses or struts. Alternatively, the stiffeners may span transverse to the flow and be supported by internal trusses, struts or moment frames. These framing concepts are presented in Figure 6.1.

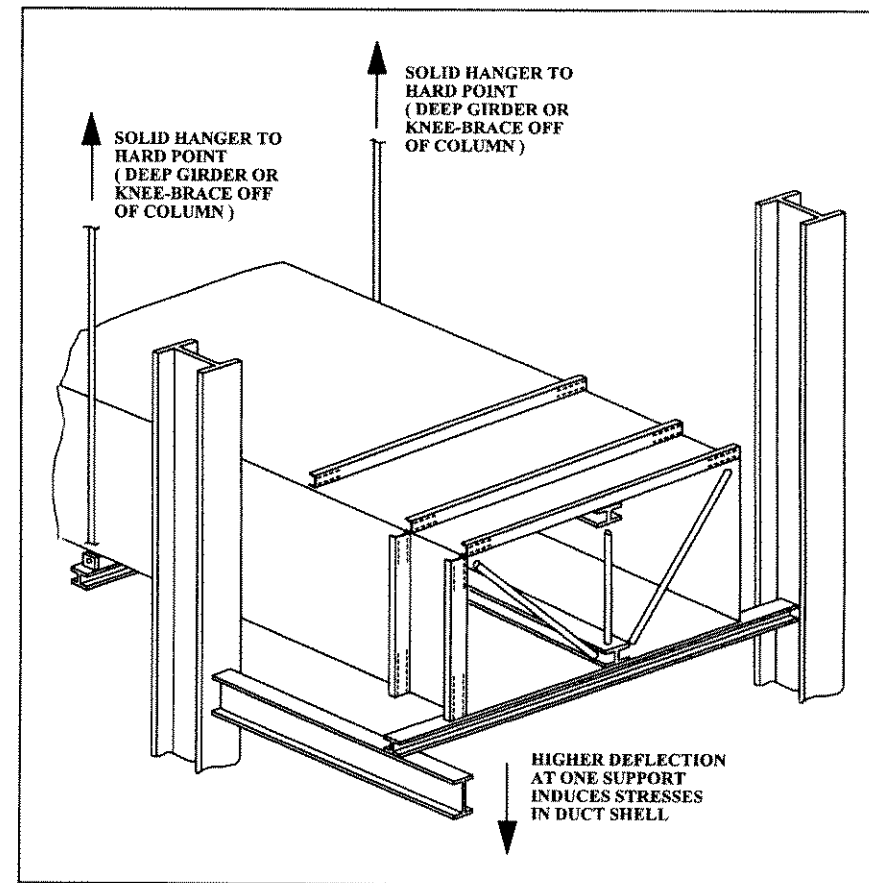


Figure 6.1
Example of Poor Duct Support Arrangement

Other basic stiffener arrangements include "waffle" framing or similar arrangements that do not utilize the duct plate to perform any significant work at all. The waffle framing concept reduces concerns about the lateral support of the compression flange of stiffeners and usually simplifies insulation installation cost. However, this framing concept involves additional pieces and more welding, which is more labor intensive and often offsets the other savings. Where a complicated waffle type grid of stiffeners is used, a computer structural analysis usually must be performed.

6.2.1 Stiffener Contributory Areas and Plate Analysis

When arranging the structural system of a duct section, the structural engineer must first develop consistent load paths in the form of contiguous element stiffnesses. The plate analysis assumptions must be based on this arrangement. As the stiffener framing and truss arrangements vary, so will the portion of panel loads picked up by a given stiffener element. Depending on the plate and stiffener configuration, the structural engineer can assume that the duct plate either spans simply between two stiffeners or continuously over many stiffeners. In the example shown in Figure 6.2, longitudinal strips "X" and "Y" are assumed to be supported by banded panel stiffeners at "Z" spacing. Plate bending calculations can then be performed for a given plate strip using conventional beam theory. The load carrying capacity of the plate then determines the plate thickness or the stiffener spacings. Additional calculations should be developed where plate stresses are applied orthogonally, such as at Point 1 or Point 2. At these locations, girder action shear combined with normal stress may greatly affect the plate and weld designs. Combining stresses is discussed in Section 6.2.5.

Many other stiffener framing patterns are encountered which are not so simple. This is especially true in transition sections of ductwork. In these unusual and difficult cases, similar assumptions can be made to simplify the analysis.

6.2.2 Typical Plate Thickness and Stiffener Spacing

Duct panels for power plant ductwork are typically fabricated from steel plate with a minimum thickness of 3/16 inch (5 mm). (For lighter industrial ducts, the minimum may be 10 gauge (3.5 mm) sheet.) The plate thickness may increase as stiffeners are eliminated as a cost reduction strategy or it may increase because it is required to support heavy loading, such as ash load. For typical plate thicknesses of between 3/16 and 3/8 inch (5 and 10 mm), ductwork

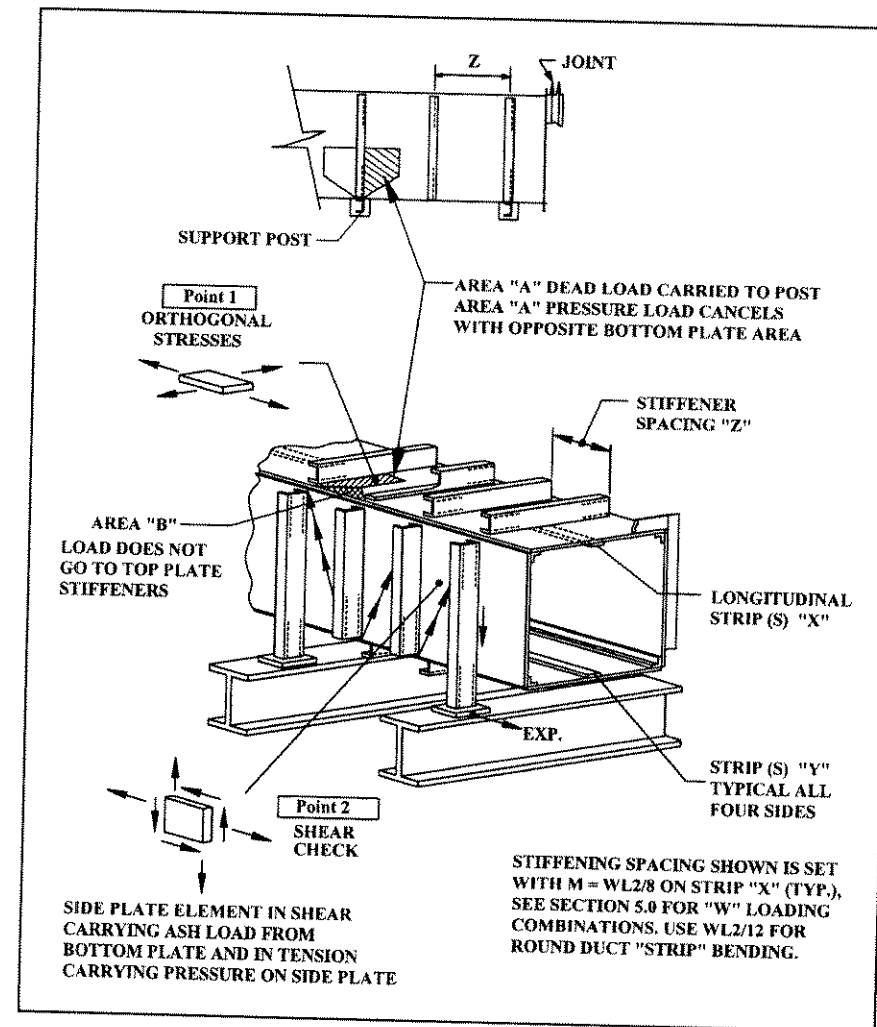


Figure 6.2
Sample Rectangular Duct Stiffener Framing

stiffener spacing usually will vary from 2 to 4 feet (0.6 to 1.2 meters). However, in locations of very low stress and no dynamic concerns, the spacing may be 5 feet (1.5 meters) or more. The stiffener spacing will vary depending on the loading, material, temperature, analysis method and stress contribution from the duct global analysis. The stiffener spacing may also be a function of

practical panel shipping sizes and field splice requirements as discussed in Section 10. To guard against a highly erosive ash or an aggressive gas environment, an erosion or corrosion allowance is sometimes considered in the plate design.

6.2.3 Plate Analysis Deflection Theories

The analysis and design of duct plate in accordance with classical flexural membrane behavior, as discussed in Section 6.2.1, is classified as small deflection theory. Small deflection analysis is the simplified norm for ductwork structural analysis and design.

If the structural engineer desires to perform a more detailed and economical design or is working on a retrofit project where an existing duct system must be investigated closely, large deflection theory analysis may be performed. Large deflection theory utilizes the membrane behavior of the duct plate to resist loading normal to the surface of the duct plate. Large deflection theory behavior is shown in Figure 6.3.

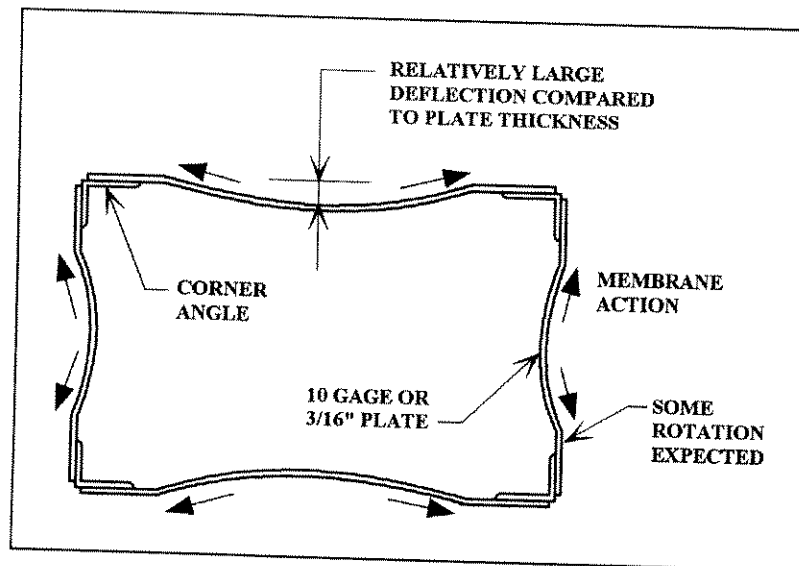


Figure 6.3
Large Deflection Theory Behavior

Large deflection theory better approximates reality in that bending stresses and membrane stresses both contribute to the total stress in the plate, usually between stiffeners. The result can be up to a 20% increase in stiffener spacing or up to a 30% increase in load carrying capacity as compared to the basic elastic strip analysis and design method. Boundary elements of the duct plate - stiffeners, corner angles and other plates - must be capable of resisting the substantial forces developed at the boundary edges of the duct plate when the large deflection theory analysis and design method is used.

In a dynamic environment with wide stress ranges which can create fatigue problems, basic elastic small deflection theory, or strip analysis, is often used over large deflection analysis. This analysis and design method is used in a dynamic environment because additional dynamic criteria must be investigated, which may govern over the large deflection theory design.

6.2.4 Secondary Versus Primary Stresses

Primary Stress

Primary stresses are stresses which do not redistribute or reduce after material yielding occurs. Primary stresses are caused by loads which are independent of structural deformations. The structure will continue to deform under primary loads until failure occurs. Examples of ductwork loads which create primary plate stresses are: dead load, live load and pressure.

Forces generated by the axial deformation of metal expansion joints as thermal expansion occurs are considered to cause primary stresses. These stresses are additive to other stresses and may be bi-directional if the metal expansion joints have been axially pre-set in their cold position. Also, toggle duct sections generate primary shear stresses at their joint flanges and in the adjacent duct plate. See Sections 1.4 and 2.3 for discussions on toggle duct sections.

Secondary Stress

Secondary stresses are caused by self-limiting strain controlled loads. Secondary stresses are caused from a driving force that only acts up to the point where the imposed strain ceases to increase. Examples of secondary plate stresses are: stresses due to constraint from the structure, stresses from friction forces due to thermal expansion, thermal stresses from the sun or differential gas temperatures, and stresses due to discontinuity effects at welds. Most of the time, secondary stresses are not necessarily calculated but are considered by the structural engineer when determining safety factors.

Two sources of thermal secondary stresses that may exist in duct plate are as follows.

- Cooling and shrinking of welds can create residual stresses and plate warping. This effect is especially prevalent with continuous welds.
- Thermal gradients, or differences in temperature from one area of a duct to another, can cause large plate stresses as differential thermal expansion occurs. Depending on the exact stiffnesses, a large thermal gradient can cause either the hotter section of plate to buckle in compression or the cooler section of plate to tear or crack from tension as the plate tries to achieve equilibrium or strain compatibility. These thermal gradients are often caused by deep ash deposits, gas stratification or water intrusion. Due to a number of reasons, excursion temperature distribution within a duct section, and thus the thermal gradient, may be very different from operating temperature distribution.

Thermal loadings should definitely be considered in certain applications, such as in large structures or where the differential temperatures are very large. However, since plate thermal stresses can easily dwarf primary stresses, the structural engineer should first try to minimize the thermal effects through two possible means:

- first by process change, including adding flow control and mixing devices, and second by rearranging the stiffness of the duct structural system so that secondary stresses will be minimized. The duct element framing arrangement should generally be as flexible as possible in a strategic effort to minimize thermal plate and member stresses. In cases where the secondary stresses are relatively small, consideration can also take the form of conservatively limiting the primary stress levels by either increasing the factor of safety or by using conservative operating loads.

The structural engineer should be aware that where high secondary stresses from shrinkage or thermal loadings are known and unavoidable, the American Society of Mechanical Engineer's (ASME) *Boiler and Pressure Vessel Code, Section I - Rules for Construction of Power Boilers* recommends, for boiler pressure parts, that the combination of all primary and secondary stresses over the full stress range should be limited to 2 times the material yield strength, reduced for higher temperature, to ensure shakedown to elastic action.

For ducts with operating temperatures above 150°F (65°C), dissimilar metals should not be welded together - especially if the pieces are very large and buckling could easily occur. If welding must be performed, the structural engineer must ensure that the two coefficients of expansion are not substantially different. For example, welding carbon steel plate to austenitic stainless steel plate can introduce very large thermal stress in hot situations.

6.2.5 Combined Stresses

As discussed in Sections 4 and 5, duct panels are exposed to many different types of loads and loading combinations. The structural engineer must be careful to consider locations where a plate element is stressed in two orthogonal directions. The most common example of this is under a stiffener where the plate is working compositely with the stiffener. This condition is shown as Point 1 in Figure 6.2. Of course, the plate also acts in bending as discussed in Sections 6.2.1 and 6.2.3. In this example the panel plate is also acting as a global structural element in transmitting gravity or wind loads to the duct supports, as discussed in Section 7.3.2. In these instances, the plate has the aforementioned two directions of bending stress plus the shear as the panel acts as a girder or truss to distribute the loads to the supports. This condition is shown as Point 2 in Figure 6.2. See Section 7 for additional global analysis information.

In some configurations, where there are compressive forces on panel edges in the plane of the panel, P-Δ effects may need to be considered in the plate stress calculations.

Proper combination of the multiple states of stress resulting from the duct plate's participation in multiple structural systems from all loading combinations must be performed. This technique is explained in detail in Section 5. Section 8 offers methods for performing these stress calculations for ductwork structural elements. The structural engineer should choose between the stress combination techniques which are consistent with the structural analysis techniques used for the duct plate and the global duct structure. The tensile, compressive and shear stresses must be combined by using a well established method.

Guidance on the interaction of shear and tensile stresses is provided in Chapter G of the American Institute of Steel Construction's (AISC) *Specification for Structural Steel Buildings - Allowable Stress Design and Plastic Design (ASD)*. Allowable stress limits are discussed in Sections 3 and 5.

Stress combination techniques are presented in many good textbooks. Some that are generally used by structural engineers designing ductwork include the following.

Direct Algebraic Addition

$$f_a + f_b < F_{all}$$

Allowable Stress Interaction Ratio

$$f_a/F_a + f_b/F_b < 1.0$$

Development of Principal Stresses

$$\begin{aligned}\sigma_1 &< F_{all} \\ \tau_{max} &< F_v\end{aligned}$$

Where,

- f_a = calculated axial stress
- f_b = calculated bending stress
- σ_1 = calculated principal normal stress
- τ_{max} = calculated principal shear stress
- F_a = allowable axial stress
- F_b = allowable bending stress
- F_v = allowable shear stress
- F_{all} = allowable stress

6.3 PLATE AND STIFFENER COMPOSITE ACTION

Once a duct stiffener is welded to the duct plate, the most realistic assumption is that they act together in composite action in carrying the applied loads. The effective plate width as part of a composite stiffener is specified as a function of plate thickness so that local buckling is limited when the composite area is in compression. This topic is discussed in more detail in Section 8.2.

6.3.1 Composite Properties and Stiffener Deflection

See Section 8.2 for a discussion of the analysis procedures and composite properties of ductwork plate and stiffeners.

The weld between the stiffener and the plate must be checked for horizontal shear, since this force determines the amount of weld required. There could be additional forces from the global panel analysis that also must be included when designing these welds. The

minimum intermittent welding requirements presented in *AWS D1.1 - Structural Welding Code, Steel*, are meant to preclude local buckling of the plate to maintain the composite plate/stiffener composite action. In a corrosive or dynamic environment, the structural engineer should consider the cost effectiveness of replacing intermittent welds with continuous welds to achieve a more reasonable design life.

Maximum stiffener deflection criteria, such as the typically used $L/360$, are generally not necessary or used in ductwork design. However, especially in dynamic environments or P-Δ situations, deflection can be very important and should be considered by the structural engineer.

6.3.2 Corner Configurations

Many types of structural corner configurations are utilized in rectangular ductwork. The use of an angle embedded in the corner is the most popular. Since plate edge support assumptions that are used in the structural analysis must agree with the actual construction details used, the structural engineer must be aware of these details and must understand their structural behavior. This understanding can be very important.

Stiffeners may frame around the duct corners or they may stop short at the corners. As mentioned above, duct corners usually have an angle or bent plate internally embedded in them longitudinally for erection adjustability, to serve as a portion of the flange of the wall, roof and floor panel diaphragm system, or to serve as a support seat for the duct stiffeners. The usage and structural design of corner angles is discussed in detail in Sections 7 and 8. Sometimes the corner may simply be a vertical plate panel fillet welded to a horizontal plate panel with no corner angle. Whatever the arrangement, the load path from the plate to the corner, the stiffeners to the corner, and stiffener to stiffener must be thought out thoroughly and consistently by the structural engineer so that the plate analysis approximates reality.

Generally, duct corner angles simplify the field assembly, improve the duct's overall torsional strength, improve the duct's overall ability to support itself through girder or truss action, and increase the duct section stiffness. This increased stiffness is particularly effective in a dynamic environment.

6.4 CIRCULAR DUCTWORK PLATE DESIGN

In circular ducts, the plate may be strong enough to act without stiffeners; it can actually behave like a large pipe. For circular ducts with large diameters and/or thin walls, the plate may require stiffening or internal bracing or trusswork like a rectangular duct. In a circular duct, the plate is definitely the most important structural element.

6.4.1 Designing for Buckling and Handling

Plate buckling from a combination of meridional, hoop, and radial stresses can be the controlling phenomenon for circular ducts with long spans and relatively thin shells. This is especially true for hot, large power plant circular ductwork.

Generally, maximum diameter to thickness ring flexibility ratios, D/t , are used to evaluate and restrict buckling. For reference, in larger piping design, where the pipe wall is relatively thin and the pipe has low negative pressures, a D/t ratio of approximately 300 is fairly typical. For ductwork with a D/t ratio between 300 and 500, shell buckling may control the plate design. For a D/t above 500, it is very likely that multiple bands of stiffeners will be needed. This is particularly true with a negative pressure loading. The structural engineer should consider that the costs of designing, detailing, and fabricating band after band of stiffeners may be more expensive than simply increasing the plate thickness.

Circular ducts have a special sensitivity to damage during transportation and handling because of the potential for buckling and ovaling. If a duct section is to be shipped in one piece as a cylinder, it should be analyzed and designed for impact due to shipping and handling. This would include the supports, bracing, internal elements and the plate. See Section 10 for more information on handling and for a discussion on bracing for shipping. A construction handling impact factor of 1.5 is considered appropriate. There are no established rules for a handling criteria which may control the plate thickness. A 3/16 inch (5 mm) minimum thickness is often used for diameters up to 48 inches (1.2 meters) and a 5/16 inch (8 mm) minimum thickness is common for diameters up to 90 inches (2.3 meters).

6.4.2 Meridional Stress

Meridional stress is the stress from global bending parallel to the axis of the duct cylinder. This stress is analogous to the outer fiber

stress in conventional beam bending design as indicated in Figure 6.3. Typically, for circular ducts with a low support spacing to diameter, L/d , ratio, this stress is minimal. The L/d ratio is considered to be low if it is 10 or less. This behavior is the same for rectangular ducts.

Circular duct sections with L/d ratios above 10 will develop significant meridional stresses. At the duct supports, hoop stresses in addition to those from the internal pressure are developed by the interaction between the duct support system and the duct shell. The magnitude of this hoop stress is a function of the location of the support points along the duct's perimeter. Selection of the support configuration must address the introduction of the circumferential bending stresses in the duct plate if the supports are positioned normal to the duct surface. Supports oriented tangentially to the duct plate will concentrate tangential shear stresses in the duct plate adjacent to the supports, but will minimize the circumferential bending stresses. The introduction of a stiffener ring at the support points to help resist the localized hoop stresses and collect forces for transmission to the supports will induce meridional bending stresses in the duct plate. This meridional bending stress is caused by the change in the radial stiffness of the duct and the stiffener ring at the supports. The interaction of meridional and hoop stresses, as well as tangential shear stresses, in the region of the supports must be addressed by the structural engineer. Guidance on the combination of stresses for the multiple design conditions which must be addressed is discussed in Section 6.2.5. The loading combinations are addressed in Section 5.

Figure 6.4 shows the multiple concurrent forces that must be resolved through the duct shell to the supports. The number of possible loading combinations, as presented in Section 5, and the different possible loading directions further complicates the process. In this figure, a static analysis reveals overturning moments from unbalanced pressure and expansion joint forces which leads to the undesirable potential for uplift.

6.4.3 Shell Hoop Stress

Hoop stresses are usually a minor contributor to the overall stress, even at higher pressures. This is one of the major advantages of circular ducts, because, unlike a similarly sized rectangular duct, stiffeners and their associated costs are not usually needed for pressure loading stresses.

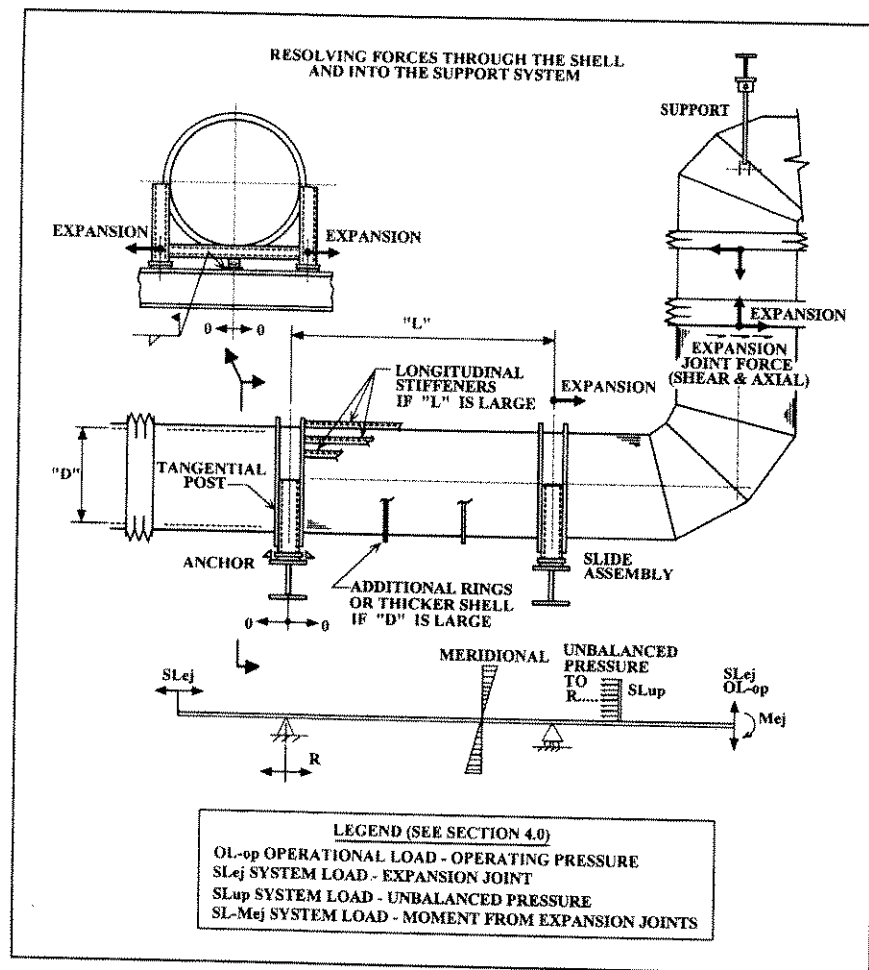


Figure 6.4
Example of Circular Duct Loading Considerations

For large circular ducts, the distribution of wind pressure about the circumference must be considered. The non-uniform distribution of normal pressure loads about the duct will induce additional circumferential bending stress in the plate which are additive to the hoop stresses. Guidance on the distribution of wind pressures about the duct's circumference can be obtained from the ASCE Task Committee on Wind Forces publication *Wind Forces on Structures*.

6.4.4 Tangential Shear Stress

When bottom support posts are aligned tangentially with the side of a circular duct, as shown in Figure 6.4, the vertical gravity loads are carried by the plate as tangential shears to the supports. The distribution of this tangential shear is a function of the location of the supports about the duct circumference and whether the duct is stiffened at the support. Locating the supports in this manner minimizes the introduction of circumferential bending stresses within the duct shell at the supports and also maximizes the overturning resistance for wind and seismic loading that the support system provides to the duct. Keeping the plate stresses low in this area will save on material and, therefore, costs.

Evaluation of tangential shear distribution through the duct section may be determined from a finite element structural analysis or by application of the analytical techniques developed for the design of horizontal cylindrical pressure vessels on saddle supports. The paper entitled *Stresses in Large Cylindrical Horizontal Vessels on Two Saddle Supports*, published by L. P. Zick in The Welding Journal Research Supplement, is a recognized approach for evaluation of stresses at support regions. The approach presented in the Zick's paper is consistent with ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 recommendations. Based on this ASME criteria, tangential shear stress is limited to 80% of S_A , where S_A is the basic material yield stress as defined in the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1. For carbon steels used in ductwork construction, such as ASTM A36, this ASME code establishes an S_A of 12.6 ksi for all temperatures up to 650°F (340°C). The resulting allowable tangential shear stress is 10 ksi. This allowable stress will be different for different types of steel and temperatures higher than 650°F (340°C).

6.4.5 Factors of Safety

When considering buckling in the duct shell, a factor of safety of 3 or 4 is usually typical. However, the structural engineer may increase it to as high as 10 under certain conditions where the quality of the fabrication and erection could be questionable.

6.5 OTHER CONSIDERATIONS

There are additional concerns other than stress and vibration that need to be considered by the structural engineer when sizing duct plate, although stress is a contributing factor in some of these additional concerns.

The most important of these concerns is crack control.

6.5.1 Fatigue, Endurance Limits and Crack Control

Although more applicable to the design of metal expansion joints, the endurance limit concept also applies to duct plate in the area of a large fan or other source of pulsating signal or forcing function.

Whether induced by pressure pulsations, sonic acoustically induced vibrations, or resonance, mechanical cycling of the plate can eventually cause a fatigue failure. To establish a reasonable cycle life, the plate stress must be kept sufficiently low so that fatigue failure will not occur. This allowable stress level is called the endurance limit. Low cycle - high stress fatigue situations should always be avoided.

The four primary parameters for fatigue are: the number of stress cycles, the stress range, the magnitude of stress concentrations and the construction details.

Design codes address fatigue in various ways, but not in a uniform, exact manner. For example, the American Society of Mechanical Engineer's (ASME) *Boiler and Pressure Vessel Code, Section I - Rules for Construction of Power Boilers*, does not address thermal fatigue failure analysis directly; it only addresses fatigue by conservatively involving the use of the Rankine Maximum Principle Stress Theory. The American Institute of Steel Construction's (AISC) *Specification for Structural Steel Buildings - Allowable Stress Design and Plastic Design (ASD)* presented in the *AISC Manual of Steel Construction - Allowable Stress Design (AISC-ASD)* uses category factors for various typical construction details to address mechanical fatigue. CICIND's *Model Codes for Concrete Chimneys and Liners* and *Model Code for Steel Chimneys* and the ASME document *STS-1-1992, Steel Stacks*, give examples for the specific situation involving vortex shedding external to circular chimneys and steel stacks. For boiler pressure parts, some duct and boiler engineering companies use maximum thickness rules to limit cyclical thermal shock cracking caused by restraint.

Fan outlet ductwork is particularly sensitive to fatigue from flow pulsations induced by internal vortex shedding and flow pulsation. The Air Movement and Control Association, Inc. document AMCA 201-90, *Fans and Systems*, describes how diffusion from the fan is controlled by specific geometric angles such that a uniform velocity profile is established 3 to 5 duct diameters downstream of the fan.

See Section 2.2.2 for the AMCA recommended criteria to calculate this distance. The use of this criteria should minimize pressure drop, improve flow conditions and may reduce fan power consumption.

While fatigue damage is closely associated with operation procedures and design conditions, a measure of crack control can be obtained in duct plate, and generally in all structures, by the implementation of the following considerations.

- The natural frequency of all ductwork structural elements should be aligned away from the fan's pulsation frequencies by some reasonable factor, such as 20%, by some method such as adjusting the stiffener spacing, the element's length, the element's stiffness, or the connection fixity.
- Plate stresses should be low and stress ranges should be minimized.
- The plate material should have an adequate toughness. The acceptable toughness should be determined by the structural engineer based on the material's lowest operating temperature. Charpy V-Notch (CVN) impact toughness tests and minimum toughness requirements can be specified for the material if required.
- Construction details, especially at connections, should minimize stress raisers.
- Plate material flaw sizes should be controlled with proper welding, fabrication, inspection and erection.
- Multiple redundant load paths should be established in the structure. Cracks tend to arrest themselves as the structure redistributes the stresses.
- The loading rate should be controlled, if possible.

6.5.2 Solutions to Problems

There are three proven considerations to help assure an acceptable duct plate design in a dynamic environment. They are: apply experience, develop and use empirical design methods and provide field adjustments.

Apply Experience

The structural engineer should interact with the mechanical process engineer and/or the customer before the start of the design to avoid conditions which could shorten the duct's design life. Examples to avoid are:

- Large fans may operate with high pressure pulsations due to poor inlet or outlet configurations.
- Large ducts that require large vortex shedding internals which can set-up standing sonic waves and pulsations.
- Ducts where the velocity is too high, which could induce vortex shedding at turns.

Many ductwork system arrangements are too complex to realistically model mathematically and accurately analyze. Hence, keeping the duct configurations as simple as possible should be a generic strategy during the conceptual and layout phases of the work.

Empirical Data Development

With experience and by extensive analysis of historical data, analysis and design rules and empirical equations can be established to calculate the dynamic response, both circumferentially and longitudinally, of the duct plate to excitations. Equations defining permissible deflections and the determination of natural frequencies can be found for some simple configurations. Tuning the element natural frequencies 20% or more from expected signal frequencies should avoid resonance, resultant rapid cycling and subsequent fatigue cracking. If this is properly done, a reasonable cycle life should be attained. There are more discussions on this topic in Sections 8 and 9.

Field Adjustments

Particularly for sonics and resonance problems, sometimes the solution approach is reactive. Following the collection of field data, minor changes can be made to significantly change natural frequencies, reduce deflections and reduce stress ranges. Examples of changes are: reframing the stiffeners in an area, revising internal truss arrangements, increasing plate thickness, reinforcing elements, adding a corner angle, and repairing damage by drilling crack ends and patching. All of these modifications change the stiffness of the individual elements and the overall duct structure. The best solution is to eliminate the source of the forcing function.

SECTION 7

Ductwork Global Structural Analysis

	<u>Page</u>
7.1 INTRODUCTION	151
7.2 GLOBAL APPROACH	152
7.2.1 Decoupling of Supports and Ductwork	152
7.2.2 Load Paths	152
7.2.3 Load Interactions	156
7.2.4 Classical Methods	157
7.2.5 Computer Models	157
7.3 STRUCTURAL MODEL CONSIDERATIONS	159
7.3.1 Support Structures	159
7.3.2 Rectangular Ductwork	160
7.3.3 Circular Ductwork	162
7.3.4 Modeling Strategy	163
7.3.5 Interface Boundary Conditions	164
7.3.6 Load Path Assessment	166
7.3.7 Load Development and Application	166
7.3.8 Model Validation	169
7.3.9 Member Forces and Reactions	169
7.3.10 Displacements	170

SECTION 7

Ductwork Global Structural Analysis

7.1 INTRODUCTION

Air and gas ducts and their support structures are major structures which require both global and local structural analysis to predict their performance and verify their structural integrity. Local structural element design and stress evaluation are discussed in Sections 6 and 8. This section discusses factors to be considered and methodologies to be used in the global analysis of ductwork and its support structure.

Many factors influence the structural design and global evaluation of a ductwork system. The structural engineer must have insight into the expected behavior of the duct and its support structure under the various operating, excursion and transient conditions. Construction issues such as erection sequence, temporary support requirements, and fabrication and erection tolerances must also be considered. The behavior of the soil and the foundation must be accounted for, as does any interaction with equipment and other structures. The structural engineer must be aware of how all these factors combine to influence the behavior of the duct and its support system.

The ductwork layout and support scheme should result in a system which possesses predictable load transfer paths. This is discussed in detail in Section 2. Once this scheme has been established, the structural analysis task is typically straightforward. A rational analytical approach is required, using a proven methodology, realistic boundary conditions, and reasonably accurate section properties. Computer analysis is not always necessary. What is required is an analysis that produces internal forces and support reactions that can be used to complete the structural design of the individual ductwork elements. In addition, displacements from thermal expansion and structural deflection are usually needed at interface points, such as expansion joints and dampers, to confirm the functionality of the ductwork and its support system.

7.2 GLOBAL APPROACH

The structural analytical approach adopted may consist of classical methods (manual calculations), computer analysis or some combination thereof. The method chosen should be dictated by the complexity of the duct or support system and the degree of accuracy appropriate for the type of structure being designed.

Sizing and routing of ductwork are typically performed by the process mechanical engineer. However, the structural engineer should participate in the early stages of ductwork layout, especially the duct support arrangement. The structural engineer's contributions would include advice on support spacing and location, early assessment of material quantities, and the structural consequences of system driven and interdisciplinary decisions. There may also be alternative arrangements that may have structural benefits not readily identified by other engineers. See Section 2 for additional discussions on duct systems sizing and arrangement.

7.2.1 Decoupling of Supports and Ductwork

The general practice within the ductwork structural engineering industry is to analyze and design the ductwork and its support structures separately. In this process, the configuration of the ductwork system is developed as described in Section 2 with emphasis on simplifying the support system while meeting the system functional requirements. The intent should be to create an arrangement that allows a determinate load path and permits decoupling of the ductwork and support system designs.

This is a fairly straightforward process when the ductwork is routed inside another structure such as a boiler building. In this situation, the structure provides support to virtually any load applied by the ductwork without significant interaction, such as deflections or settlement, that might result in load redistribution. External ductwork can usually be treated similarly, however, special considerations for interaction are discussed later in this section.

7.2.2 Load Paths

Fundamental in the analytical process is the need to verify that paths exist to transmit all external and system loads down to the foundation. Careful assessment of the structure's behavior is needed to confirm that the structure will function as designed. This is true for both the individual structural elements as well as connections between the major structural subsystems.

In the decoupled approach, the structural engineer designing the ductwork must establish various load paths within the ductwork structure that will carry all applied loads to the duct support structure. The load paths must be chosen or determined using the various ductwork structural elements described and discussed elsewhere in this ASCE Special Publication. These structural elements consist of internal trusses that stiffen the global structure and bridge between the duct supports, the plate panels, corner angles stiffeners, and duct plate stiffeners or other elements needed for this purpose.

In a similar fashion, proper load paths must be chosen or determined in the duct supporting structures so that the loads and forces make their way down into the earth.

Ductwork

Preliminary sizing of the ductwork structural elements should be based on a knowledge of the operating and transient loads and the ductwork system operating conditions. These items are discussed in Section 4. Sections 6 and 8 present discussions of typical ductwork stiffener layout and sizing considerations. While final details of the ductwork configuration are not needed at this time, some consideration of these details is needed early to assure that the analytical load paths are representative of those in the actual structure.

As indicated in Figures 7.1 and 7.2, these structural elements must be arranged to provide a load path to the support structure. Figure 7.1 shows a loading concept for resisting dead, live and gravity loads in rectangular ductwork. In this situation, the uniformly distributed vertical loads on the top and bottom plates must be transmitted to the side walls and then out to the supports. To accomplish this load transfer, stiffening of the top plate is necessary to transmit the loads to the walls. Then, the side panels carry the loads to the supports. In a similar fashion, other vertical loads, such as ash accumulation on the bottom plate or in a hopper or live load on the duct top, are carried to the duct supports. Where a simple span is used, the reactions are readily determined and assumed to be applied to the support structure without interaction. However, for long duct runs, the situation might benefit from a continuous duct spanning across several supports. In this case, an indeterminate classical solution would be required to determine the reactions.

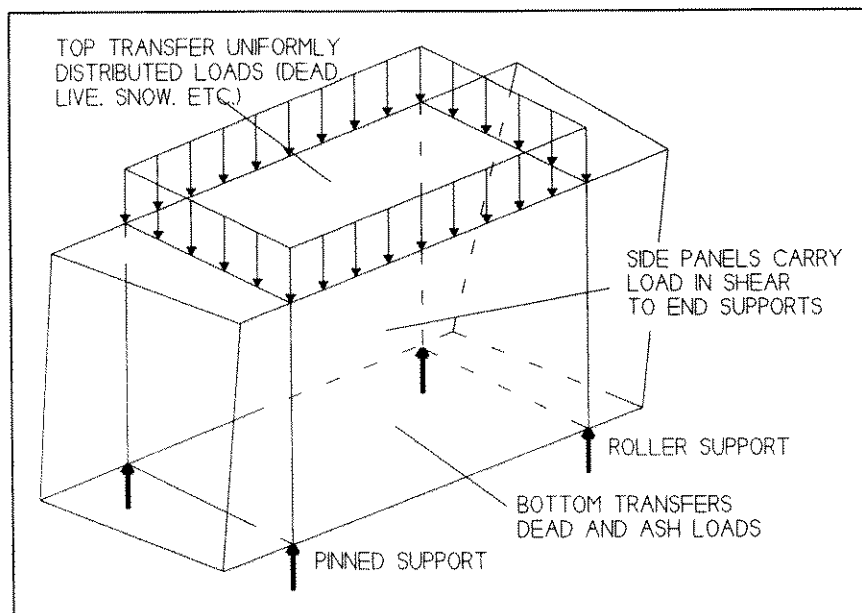


Figure 7.1
Typical Path for Dead Load

Figure 7.2 shows the typical load path for wind loads. In this case, the uniformly distributed wind loads on the stiffened sides must be carried to the top and bottom corners. From here, the top and bottom plates transfer the loads to the supports in diaphragm or truss action. Additionally, an internal truss or rigid frame is required to transfer the upper plate wind loads through the rectangular ductwork to the support structure while maintaining the ductwork configuration. In a similar fashion, other horizontal loads, such as horizontal seismic or unbalanced pressure forces, are carried to the duct supports.

In addition to these loads, system loads must also be resisted. The major system loads are the static pressure, unbalanced pressure loads, ash load and major equipment loads supported by the ductwork. See Section 4.2 for a discussion on all design loads. For each type of load, a load path must be established and utilized to transmit the loads from their origins to the support structure. For example, consider a ductwork section that cantilevers over a support and turns ninety degrees ending at an expansion joint as shown in

Figure 4.1 or Figure 6.4. In this situation, the unbalanced pressure load produces lateral loads on the support and horizontal bending in the ductwork that can result in more than one support being involved in resisting the loads. Internal trusses are usually provided to assure stability in this example.

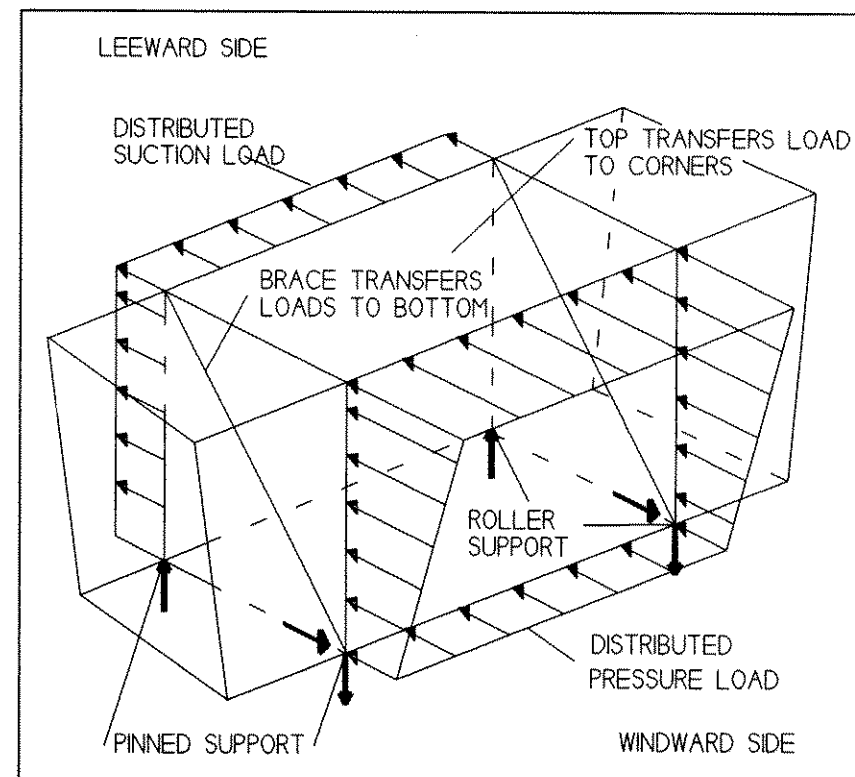


Figure 7.2
Typical Path for Wind Load

Load path identification is more straightforward in circular ductwork. Provided that the ductwork material has been properly sized as discussed in Section 6, the circular duct shape facilitates the transferring of applied loads to the support structure in an efficient manner as a single structural element. The details of the duct supports to the supporting structure, which assure the continuity of the load paths, are equally as important.

Supporting Structures

With the ductwork and its support structures decoupled, the support analysis and design is straightforward. With the framing geometry previously established, preliminary member sizing can be performed using simple approximations. A reasonable approach to perform preliminary member sizing for the support structures is to: estimate the dead, live and wind loads; calculate preliminary column loads; perform a decoupled analysis as described above; and estimate the member sizes using the *AISC Manual of Steel Construction - Allowable Stress Design (AISC-ASD)*.

An example of a simple duct support structure is shown in Figure 7.3. Since braces and struts are normally considered to have pinned connections, columns, braces and struts can be easily sized as pure compression members. If the ductwork is within a large structure, such as a boiler room, sufficient load paths usually exist. However, the addition of local bracing might be necessary.

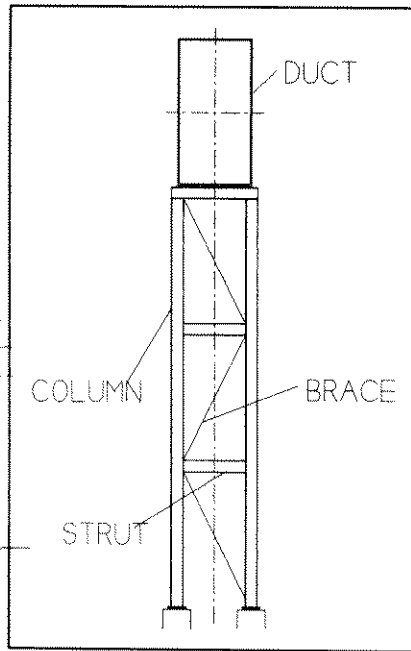


Figure 7.3
Typical External Support Structure

7.2.3 Load Interactions

From the preceding discussion, it should be obvious that structural elements in ductwork perform more than one function simultaneously. For example, stiffeners used to transfer ash dead load across the bottom plate to the side wall trusses might also be used as part of a truss system to carry horizontal wind or seismic loads to the supports. Similarly, the bottom chord of a side wall Vierendeel Truss will also participate in horizontal load transfers. The structural engineer must be familiar with the multiple functions that many structural elements perform in ductwork design and must assure that the proper strength is provided in the design.

For determinate structures, stiffness does not play an important role in load path determination. The loads will be carried as assumed because any redundant capacity will be a secondary effect. Of course, this is not true for indeterminate structures. In that situation, a more sophisticated approach may be appropriate in evaluating ductwork load paths.

7.2.4 Classical Methods

Classical methods as discussed here are manual or hand calculations using traditional structural analysis methods. When the ductwork and its support structures are decoupled, or treated as two separate structures in the structural analysis, classical methods of analysis will usually prove to be sufficient. A classical approach can be used to determine all structural element forces when the structures are determinate. Trusses can be solved using free body diagrams and the member loads will be axial with little or no moment interaction. Wall, floor and roof panels can be treated as trusses or girder webs using classical methods for calculating shears and moments.

Structures or portions of structures that are indeterminate in a single plane can also be analyzed using classical methods such as moment distribution and virtual work. These methods will produce moments, shears, and reactions that must be considered in the design.

In the preliminary stages of design, classical methods can also be used to provide the structural engineer with a better understanding of the important characteristics of a ductwork system which affect the overall structural behavior, even if computer techniques will ultimately be implemented for other reasons in the final detailed analysis and design. This provides confidence in the initial design that may prove important as the final detailed design evolves.

7.2.5 Computer Models

Physical plant constraints and system functional requirements can result in ductwork configurations which may require a more sophisticated analytical approach. This is particularly true where the assumption that the ductwork and its supports can be analyzed separately may not be valid. In these cases, computer modelling and analysis may be beneficial and prudent. Examples of cases where computer analysis may be performed are:

- When the configuration of the system is such that stability is a major concern or when the ductwork or the support system is statically indeterminate.
- When there are intermediate phases in the construction sequence where an alternative load path is needed or when exposure to severe environmental loads on the partially completed structure is significant.
- When unusual foundation related restrictions have been identified that might warrant special attention during the analysis. Such a situation can arise when uplift loads must be limited because of difficult soil conditions that limit pile capacity or when significant differential settlement is expected and unavoidable.
- When physical constraints imposed by the need for strength and stability result in undesirable behavior because of operating or excursion differential temperatures within the duct.
- When local codes or customer specifications require a response spectra analysis for a seismic event.
- When a complex, redundantly supported ductwork design is being used or when the relative stiffness of structural elements results in load redistribution under some load combinations, such as when the lateral stiffness of the ductwork is adequate to transfer loads to interfacing equipment rather than allowing it to be resisted by the supporting structure.

The presence of these factors could indicate that computer modeling and analysis of the ductwork and its support system is the most efficient method to develop the information needed for the design. Further, while classical methods provide the structural engineer with sufficient information for member sizing, the need for selected deflection data to assure functionality at critical interfaces, along with other issues discussed earlier, may compel the structural engineer to use computer solutions. Used within their known limitations, computer analyses and designs can provide a more efficient evaluation and design.

7.3 STRUCTURAL MODEL CONSIDERATIONS

Independent of the analytical approach, the structural engineer must conceptualize and create a structural model, or free body diagram, of the ductwork and support structure that is to be analyzed. This model must be an accurate approximation of the actual structure and it must represent the structure's functional capabilities. The methods used to develop critical elements of the model and the application of the loads are discussed in the following sections.

7.3.1 Support Structures

Modeling the supporting structures for a ductwork system is straightforward. A realistic two or three dimensional model, such as that shown in Figure 7.4, should be developed. The truss elements, braces and struts should have three degrees of freedom per node. Columns should be represented by continuous beam elements to account for the continuity bending moments and for a proper stability assessment. The details of geometry, member orientation, member properties and work points require close attention.

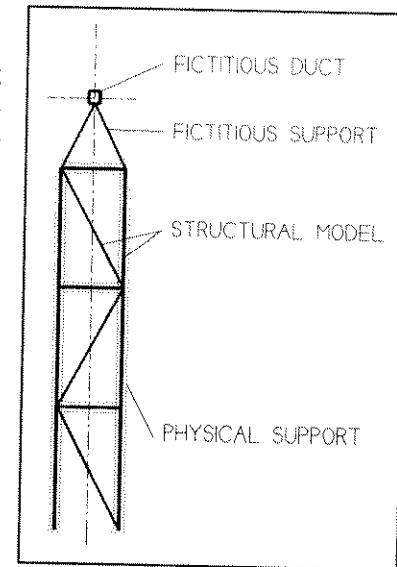


Figure 7.4
Typical Support Model

Computer models should not include connection details; connections are typically represented in the model by member end conditions. Connections are assumed to be fixed, to be free to rotate, or to have a rotation spring stiffness that must be included in the model. Connection angles, flange restraints and member stiffeners need not be modeled.

During creation of the model, consideration should also be given to how the loads will be applied. For example, early decisions should be made regarding which loads should be applied as uniform loads on surfaces, line loads on members or point loads on members or at joints.

7.3.2 Rectangular Ductwork

Special care must be taken when creating the ductwork structural model. Provision must be made to position loads correctly so that support forces are accurately determined. Care also must be taken to assure that proper continuity is maintained in the ductwork structure model. The modeling techniques described here may allow unrealistic flexibility in the longitudinal direction that can result in faulty load distribution in the analysis. Furthermore, the presence of internal bracing, longitudinal stiffeners or fixed-end transverse stiffeners may substantially increase the ductwork's assumed sectional properties.

As with the support structure model, the ductwork analysis model should not specifically include details such as stiffeners, connections, or internal flow distribution devices. The design of these items is covered in Sections 9. Their inclusion usually will not affect the results of the global analysis. Furthermore, the design of these items can only be completed after the analytical results are available.

Axial and Flexural Considerations

In rectangular ducts, because of the plate's high width to thickness, b/t ratio, the stiffness of the duct is usually less than that of a typical box beam. As a consequence of this, only a portion of the ductwork should be considered when calculating ductwork stiffness in resisting bending loads. For this purpose, the effective section is usually initially based on a plate width of $16t$ from the edge of any corner stiffening, as shown in Figure 7.5. There are several rationales that can be used to choose an effective width of

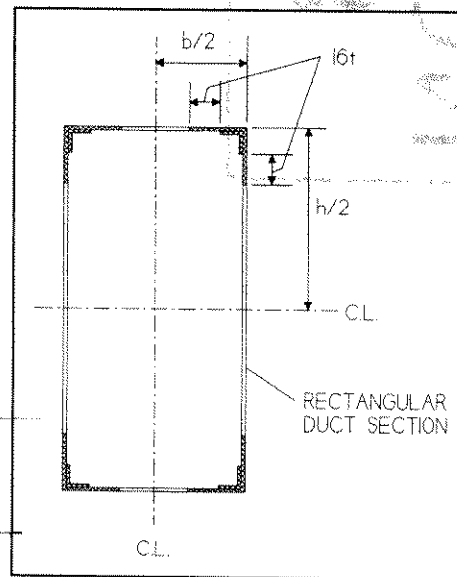


Figure 7.5
Effective Area Considered
for Duct Stiffness

duct plate. *Design of Welded Structures*, by Blodgett, recommends a value of $12t$ off to either side of the corner angle edge. The United States Steel Corporation publication, *Steel Design Manual*, uses $190t/\sqrt{F_Y}$, which is $32t$ for $F_Y = 36.0$ ksi; $16t$ on either side of the angle leg. If the limits set for uniformly compressed stiffened elements given in the American Institute of Steel Construction's *Specification for Structural Steel Buildings - Allowable Stress Design and Plastic Design (ASD)* are used, then the effective width will be $253t/\sqrt{F_Y}$, which is $42t$ for $F_Y = 36.0$ ksi; $21t$ on either side of the angle leg. Note that even though F_Y decreases as the temperature increases, the ambient temperature value of F_Y should conservatively be used in this application. Regardless of which criteria is used, adjacent effective plate widths should not overlap each other. Typically, a kt value of $16t$ is used in ductwork analysis as shown in Figure 7.5. Any longitudinal stiffeners and corner angles that are provided to reinforce the ductwork corners should also be included in the stiffness calculation. This effective flange and web area is then used to derive axial, flexural and torsional member properties.

The need for turning vanes or other flow distribution devices will complicate the ductwork's structural behavior. Changes in direction, where trusses and turning vanes are usually located, are often associated with a congested stiffener pattern. Therefore, these areas are quite rigid. In these locations, it is often appropriate to use the full section properties of the ductwork so that indeterminate conditions are properly considered. In situations where the course of action is unclear, it is prudent to analyze a range of properties to envelope all possible behavior.

When stresses in the duct wall theoretical webs and flanges are low, the corner elements become more effective. The assumed initial structural element values, primarily thicknesses, can be modified based on stress results in accordance with the design as discussed in Sections 3, 6 and 8.

Shear Considerations

The side walls and the top and bottom panels of a duct can be modeled in two different manners. They can be modeled as trusses with the stiffeners acting as struts and the duct plate serving as the diagonal members. The second method assumes that the duct plate is the web of a large fabricated girder with the panel stiffeners serving as the girder web stiffeners. The above discussed method can then be used to calculate the area of the truss top and bottom chords or the girder top and bottom flanges.

The decision to model a plate wall as a girder or a truss should be made based on the h/t ratio of the plate. If the h/t ratio is above 330, the girder method is usually not used.

Girder web design is based on a combination of both web shear and tension field action between the web stiffeners. Both mechanisms are assumed to contribute to the girder strength. Shear load is initially resisted directly by the plate. However, as the load increases, the plate is assumed to buckle between the stiffeners with the remaining load being resisted by tension field action. Web plate buckling is a mechanism which is dependent, among other things, upon the material's modulus of elasticity, E . With increasing temperature, the modulus of elasticity decreases as will the plate's buckling capacity. The plate's pure shear capacity is also decreased, but not directly proportionate to the buckling capacity. For this reason, the reduction in total shear capacity with increasing temperature is not linear. The actual reduction in allowable stresses for a particular configuration depends upon the aspect ratio of the stiffened panel and the slenderness of the plate. The structural engineer should refer to the theory on this subject in a textbook, such as *Steel Structures* by Salmon and Johnson, to develop an necessary plate shear capacity tables similar to those in the AISC Specification.

For long duct spans, where significant shear could accumulate in the plate near the supports, it is usually more economical to add diagonal stiffeners to the plate to carry the shear force rather than increasing the plate thickness.

7.3.3 Circular Ductwork

The cross section of circular ductwork is normally considered to be fully effective. However, depending upon that final configuration and the methods used to preclude cylinder buckling, the allowed design stresses may be quite low. This is a result of imposing high safety factors against the critical buckling stress.

For modeling purposes, it is reasonable to use the full duct cross section when determining a model's stiffness. On the assumption that the support details can be designed to accommodate the loads without local buckling, the load distributions should be fairly insensitive to subsequent changes in ductwork stiffening modifications.

7.3.4 Modeling Strategy

When a coupled analysis of the ductwork and its support structures is contemplated, the structural engineer must create a model configuration that is representative of the physical ductwork with its applied loads. In order to model the structural behavior accurately, one of the following stratagems should be adopted. The most obvious approach is to model the ductwork geometric shapes with plate or shell elements. This provides the model surfaces over which the loads can be applied. However, this poses some difficulties. First, the stiffness of a model constructed of plate elements will not be similar to that calculated by the method given above. Unless the material properties are adjusted, the model will be stiffer than the real structure. Secondly, internal load transfers, primarily from the surfaces to the supports, will be unpredictable in the model unless all of the internal ductwork structures are modeled. Thirdly, connection behavior between the ductwork and its support structure will be complicated in the model because many supports have gaps or slide bearing plates.

An alternative modeling approach is to develop a fictitious ductwork element positioned at the centroid of ductwork resistance, as shown in Figure 7.6. This ductwork element can be positioned by using fictitious rigid links to connect the ductwork element to the support structure in the model in the same manner as it is really connected.

Uniform loads can be consolidated into point or line loads for application to the simplified model. This approach also reduces the model size, which reduces post-analysis work and improves confidence in the results.

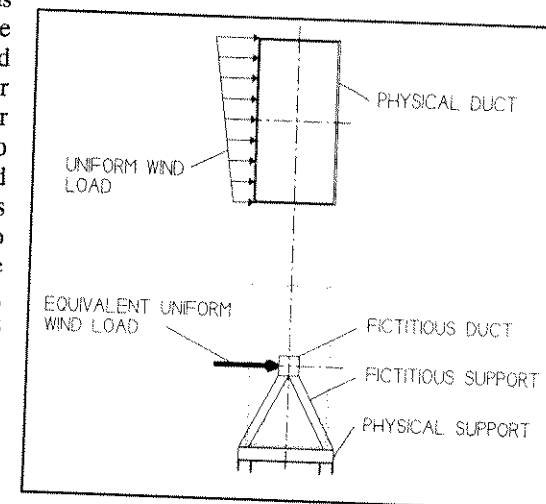


Figure 7.6
Equivalent Wind Load for Model Analysis

7.3.5 Interface Boundary Conditions

There are several interface points between the ductwork, support structure and adjacent structures where boundary conditions must be assessed for proper inclusion in the structural analysis model. Details of the connections between the components of the supporting structures, and with the ductwork itself, must be conceptualized to determine how each type of load is transferred. The goal is to represent structural functions that affect the interaction between ductwork and its support structures faithfully so that response is correctly predicted.

These interface points and typical boundary condition treatments are noted and discussed below.

Foundations

Foundations are normally considered to be rigid; they are usually not assumed to either rotate or displace under applied loads. This is usually a reasonable assumption unless site soil conditions dictate otherwise.

Differential foundation settlement of determinate structures does not normally present a problem. The structure will accommodate significant settlement with minor joint rotation. An indeterminate structure must be evaluated more closely. Ductwork that crosses several supports continuously should be considered as being indeterminate. For such structures, uneven foundation settlement will induce bending in the ductwork that could redistribute the support loads and possibly affect the ductwork design itself.

Other interactions are possible in poor soil. For example, piles placed in poor soil may have adequate vertical capacity but develop significant horizontal displacements, and thus inadequate horizontal capacity, under lateral loads. These situations should be evaluated to determine their affect on the ductwork system and its interfaces with equipment.

Interface Between the Foundation and the Duct Support Structure

The connection to the foundation for columns is normally considered to be pinned. It is not only difficult to obtain a rigid connection using anchor bolts, but it is seldom worth this effort to reduce internal forces in the support structure. Rigid connections may be of some value when the displacements of moment resisting frames are a problem or where the equipment arrangement prohibits diagonal bracing.

Interface Between the Support Structure and the Ductwork

There are many types of duct support components, as discussed in Section 2. Slide bearing plates under support posts are normally considered as theoretical 3-dimensional rollers; they are only vertical supports and are free to move in all horizontal directions. Slide bearing plates with guide bars are normally considered as rollers in the direction parallel to the guide bars and as pins in the direction perpendicular to the guide bars. Rather than attempting to perform an exact friction analysis, it is reasonable to apply estimated friction loads opposite to the direction of thermal expansion at the location of the slide bearing plates.

Hanger rods are treated as theoretical rollers in a free body diagram. Some types of hangers require special attention. For example, a constant support hanger should be modelled as a force rather than a support and a variable support hanger should be modelled as a spring. A rigid rod always act as a hard support. With hangers, mathematical instabilities will occur in the model unless lateral load transfer mechanisms, in the form of guides, bumpers or stop bars, are included.

Interface Between Duct Segments

Non-metallic expansion joints, which are used to connect sections of ductwork to equipment or other sections of ductwork, are normally considered to be a free boundary condition. This is reasonable because of the negligible stiffness and strength of the non-metallic expansion joints.

Metal expansion joints are usually modelled as springs. Metal expansion joints have an appreciable axial and rotational spring stiffness. Depending on how they are installed, they could even possibly have pre-load forces. The spring coefficients can be obtained from the joint manufacturer. The joint detail should be evaluated to determine if lock-up is possible, especially in reassessment work. In that case, the analysis should also consider the possibility of fixity at that location.

Shear keys, which are often present in toggle ductwork sections, are treated as translational restraints. Care must be taken when modeling such components due to the wide range of geometries. It is best to avoid the use of gap finite elements in this type of analysis. Non-linear analysis is unjustified in this situation. Provided that the joint functions properly, gap interactions should not affect the predicted load distribution.

The restraints at each interface can be included in the model as described above. A complete tabulation of the connection and support releases facilitates data input and later validation. It also provides an easy method of demonstrating that individual and combined loads can be accommodated.

Interface with Hoppers

The additional mass that results from the storage capacity of ash collection hoppers should be included in the structural analysis model. Distribution of this potentially large dead load can be affected by model stiffness.

In some situations, ash hoppers can impose local thermal loads to the ductwork that should be evaluated to determine if they may be significant. These arise because of both the insulating characteristics of ash during operation and its heat storage capability during shutdown.

7.3.6 Load Path Assessment

The assessment of load path performance is straight forward when the analysis is performed manually for decoupled systems as described in Section 7.2.2. Decisions are made regarding the load path and analysis proceeds on that basis. Faults seldom occur because the assumed load path is created as part of the preliminary design. On the other hand, when computer modelling is used, there exists a potential to introduce inconsistencies since the load path in an analytical model is sometimes difficult to verify. This emphasizes the need for an inherent understanding by the structural engineer of the basic structural system and all subsystems.

7.3.7 Load Development and Application

When classical methods are used for structural analysis, the development of loads requires no special provisions. The loads are applied directly to the structural elements as the various parts are evaluated.

When performing a computer structural analysis using an analytical model that approximates the structure as described in this section, attention must be given as to how the loads are applied. Specifically, the following are loads that may require special treatment.

Ductwork Dead Load

When the ductwork is structurally modeled as described in this section as a fictitious member with calculated properties positioned at the centroid of the ductwork shape, rather than a prismatic section, automatic self-weight determination performed by a computer program will not be correct. Modification of the material density may be the best method to include the total weight of the actual duct and all of its attachments. Flow distribution devices and other ductwork accessories and attachments are best treated as an applied concentrated load.

It is normal practice to overestimate the dead weight of a structure somewhat to provide some margin in the design. However, in situations when uplift or net tension controls the design, an overestimation of dead load may not be conservative. In these cases, loading combinations should use a reduced dead load, generally taken as only 75% of the calculated value. For uplift conditions, this effect will result in a reasonable factor of safety against overturning.

Ash Load

In a detailed model, ash loads can be applied to the bottom ductwork plate as it is expected to occur in the real structure. Load transfer would be accomplished by the plate elements. Using the fictitious element approach to position the ductwork element will cause all ash loads to be applied at the point where the rigid links connect to the support structure. In both cases this is not exactly representative of the real structure. An assessment must be made to determine how the ash load will be transferred to and carried by the support structure. Details regarding the load distribution at the local level are provided in Sections 6 and 8.

Since it is common practice to suspend hoppers from ductwork, it is also necessary to include the ash load from a full hopper in the loadings. On the other hand, if a separate support arrangement is provided for hoppers, unbalanced pressure load effects should be investigated.

Wind Load

Wind loads are normally applied over the entire ductwork projected area. However, this may be simplified for the support structure by applying wind as joint loads. The wind load derivation must be based on the projected area of the ductwork with insulation and lagging.

Temperature Differentials

Thermal differential loads typically only apply to the ductwork. The support structure is not normally subjected to this loading unless the ductwork is indeterminate and the support conditions are such that equal and opposite reactions are developed. The normal strategy is to provide support and interface conditions that allow thermal movements to take place unimpeded.

Thermal gradients can arise from the insulated properties of ash, as it collects on the bottom of ductwork and in hoppers. There have been situations where thermal gradients have imposed significant loads, and corresponding deflections, in structures. The structural engineer should be alert to this possibility as the model is developed and evaluated.

One way to apply thermal loads to an integrated computer analytical model is to let the support structure material have the coefficient of thermal expansion specified as zero while the ductwork has the correct value for the materials being used. Thermal gradients within a duct structure are handled by assigning the expected absolute temperature to each individual element, including all of the plate elements.

Seismic Loads

For outside ductwork, the environmental loading combination with wind loading normally controls over the loading combination with seismic loading. However, recent code revisions have re-emphasized the importance of seismic loads. In situations where the ash loading is large, seismic inertial forces can have important consequences to structural integrity. In high seismic zones, response spectra analysis may be specified for code compliance, or chosen by the structural engineer to reduce forces that result from simplified approaches such as pseudo-static analysis. This will require special modeling and dynamic analysis beyond the scope of this document. Inside buildings, ductwork seismic loads can contribute significantly to the support structure's design requirements.

Unbalanced Pressure

Pressure loads on closed sections of ductwork are internal forces that cancel out and, as such, need not be included in the overall structural analysis. However, opposite expansion joints in open sections of ductwork or at the connections to equipment the internal pressure produces an external force between duct sections that can be significant and must be considered in the ductwork and support structure design.

7.3.8 Model Validation

Before proceeding with the final design of the individual structural elements, it is prudent to assess the accuracy of the analytical results. The results must be validated for correctness. Conformity with the expected performance must also be assessed. For a computer model, this begins with the obvious first task of verifying the accuracy of the model input, boundary conditions and loading information. Graphical displays allow viewing of the model and some software may also display graphical boundary conditions and loads. Otherwise, the text input must be checked.

For indeterminate structures that may possibly have external constraints, it is useful to begin the analysis with a simplified structure. These results then can be used to baseline the final configuration analysis. This approach provides a good approximate check of the final results and, if the constraints are applied sequentially rather than all at once, offers a method for debugging the computer model.

7.3.9 Member Forces and Reactions

Member internal forces and moments are needed to perform the final member sizing and to design connections. These should be calculated or obtained at intervals along the members that will assure that maximum component combinations have been enveloped. The accuracy of automated member sizing depends upon this.

Support reactions must be evaluated from several viewpoints. First, the sum of the reactions must approximately equal the sum of the known loads for each loading combination. This simple check is fundamental to assure model accuracy and to ensure that the loads have been properly considered. While input loads and reactions can be compared upon request by some computer software, this is not an independent check and it cannot assure that fictitious or erroneous multiple loads have not been introduced. This automated method also will not determine if loads were incorrectly entered in the model when it was created. Secondly, the resulting reactions must be evaluated to determine that they are within the capacity of the foundations. Mismatches at this stage in the analysis and design effort must be corrected prior to proceeding with final member sizing. Finally, overturning and sliding of the structure should be evaluated. It is prudent, at this point, to check the results of all loading combinations for situations that result in net uplift at

supports. This should be done using 75% of the dead load and no live load in these particular loading combinations.

Net uplift is usually the result of cantilevered type ductwork configurations or overturning moments from lateral loads such as unbalanced pressure, seismic, wind and friction. A cantilevered arrangement that results in permanent dead load driven uplift or lateral forces should be avoided where practical. It is always a good practice to modify the support scheme to eliminate net uplift, if possible, before proceeding further with the design.

7.3.10 Displacements

Large unexpected calculated displacements indicated in the computer analysis output are clear indications that the model is not correct. These must be resolved before proceeding. Most often they are the result of an extraneous member release, excessive load or incorrect member property.

However, a more disciplined displacement evaluation of the computer output should be undertaken in indeterminate structures with potentially redundant load paths to identify more subtle potential model errors. For example, an inadvertent release at one support leg could require the ductwork model to redistribute loads to other supports. This could cause locally undersized members and erroneous loads being applied to the support structure. In addition, ductwork forces elsewhere could be significantly increased.

With thermal loads included in the analysis, thermal movements should be reviewed at ductwork interfaces to assure that the behavior of connecting accessories, such as expansion joints, are not compromised. This would include an assessment of the thermal movement at the slide bearing supports to assure proper functioning. The thermal movements will also be important final details in the design of the duct support structure elements for eccentric support loadings.

SECTION 8 Structural Element Design

	<u>Page</u>
8.1 GENERAL CONSIDERATIONS	173
8.2 RECTANGULAR DUCTS	174
8.2.1 Stiffeners	174
8.2.2 Stiffener End Connections	183
8.3 INTERNAL TRUSSES AND STRUTS FOR RECTANGULAR DUCTS	185
8.3.1 Analysis Methods	187
8.3.2 Truss Element Design	187
8.3.3 Truss Member End Connections	190
8.3.4 Vertical Duct Support Elements	191
8.4 CIRCULAR DUCTS	193
8.4.1 Ring Stiffeners	193
8.4.2 Internal Struts	196
8.5 LATERAL EXTERNAL TIE ELEMENTS	197

SECTION 8

Structural Element Design

8.1 GENERAL CONSIDERATIONS

The overall structural integrity of a duct can only be as reliable as its individual elements. Its structural elements must perform their duty across a range of operating and environmental conditions for the design life of the duct. In order to meet this demand, the overall duct structure and each individual structural element must be designed by the structural engineer to meet these conditions while remaining within certain predefined allowable stresses.

In order to properly design the individual structural elements, the structural engineer must be cognizant of the many different failure modes that an element can experience. Once these failure modes are recognized, the structural engineer must investigate the different types of loading conditions the elements will face during the life of the duct. These loading combinations are presented in Section 5.

In general, ducts may be quite large. Structural engineers can take advantage of the inherent strength of these ducts by adequately reinforcing the plate material to withstand not only internal pressure loads but also membrane and bending stresses due to dead load, live load, and other operating and environmental loads. The design of structural elements entails the identification of different forces imposed on the duct and properly combining the resulting actual stresses into totals that can be compared to allowable stresses. This process may involve complex structural analyses and may be performed by hand or with the aid of computers. Either way, the structural engineer must be aware of the various, and sometimes redundant, load paths by which loads can get to the external restraints.

When performing the structural design of a duct and its various structural elements, the structural engineer's duty is to provide adequate structural integrity and to design the structural elements economically. The loads

must be safely transferred from the duct down to the foundations or, in the case of most pressure and friction loads, cancelled out within the structure. An economical structural system usually has an additional advantage in that it results in a structure that is less rigid, thus, it has lower strain controlling stresses such as those developed from thermal expansions and temperature differentials.

Ducts are inherently indeterminate structures with complex loading patterns imposed on them, thus it may be difficult to intuitively recognize the load paths that will adequately transfer the loads to the supports. A structural engineer must be able to identify the various load paths and be able to properly design each element along the paths.

8.2 RECTANGULAR DUCTS

There are two basic duct configurations: rectangular and circular. Of course there are many other possible shapes, especially duct sections that transition into major equipment. This section and Section 8.3 will discuss rectangular duct sections. Section 8.4 addresses circular ducts. Unusual duct configurations are not specifically addressed because of the infinite number of possible shapes. However, once the design of rectangular and circular duct sections is mastered, the structural engineer should be able to use judgement when designing unusual duct configurations.

8.2.1 Stiffeners

Stiffeners are attached to the duct plate to strengthen the flat panels against pressure loads, to reduce vibration of the plate and to stiffen the plate against buckling. If a duct panel height or width is greater than the allowable plate span for the design loads or for vibration considerations, then stiffeners are required to reduce the span. Stiffeners must be spaced at some convenient spacing so that the plate stress is less than the allowable stress. The design of duct plate is discussed in Section 6. Stiffeners are usually placed to make uniform panels. If the duct panel height or width is less than the allowable plate span, then theoretically the panel does not need stiffeners. However, if the duct is to be lifted and handled in one piece, then some stiffening may be necessary to maintain the duct's shape. In any case, stiffeners become an integral part of the duct's structural system. Stiffeners may also function as duct supports as well as plate reinforcement.

Composite Action

Composite action is the interaction of a stiffener element and a certain portion of the attached duct plate that act as one cross-

section to jointly resist loads. The width of this portion of duct plate is called its effective width. The position of the composite section's neutral axis reflects this continuity and it can be calculated using basic applied mechanics principals. Figure

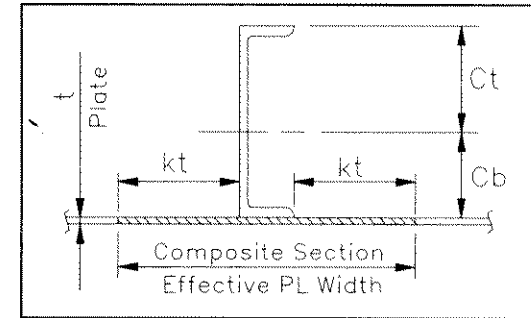


Figure 8.1
Stiffener Composite Section

8.1 illustrates a typical composite stiffener cross-section. The effective width of the plate is determined by the structural engineer and the calculation method may be somewhat arbitrary. There are several rationales that can be used to choose an effective width of duct plate. *Design of Welded Structures*, by Blodgett, recommends a value of 12 times the plate thickness, t , off to either side of the stiffener edge. The United States Steel Corporation publication, *Steel Design Manual*, uses $190t/\sqrt{F_y}$, which is $32t$ for $F_y = 36.0$ ksi; $16t$ on either side of the stiffener leg. If the limits set for uniformly compressed stiffened elements given in the American Institute of Steel Construction's (AISC) *Specification for Structural Steel Buildings - Allowable Stress Design and Plastic Design (ASD)* are used, then the effective width will be $253t/\sqrt{F_y}$, which is $42t$ for $F_y = 36.0$ ksi; $21t$ on either side of the stiffener leg. Note that even though F_y decreases as the temperature increases, the ambient temperature value of F_y should be used. Regardless of which criteria is used, adjacent effective plate widths should not overlap each other. In Figure 8.1, kt is the width off to either side of the stiffener and should not be greater than one-half of the clear distance between adjacent stiffeners. Typically, a kt value of $16t$ is used in ductwork analysis.

In order for composite action to be fully effective, the attachment between the stiffener and the plate must be strong enough to transfer horizontal shear between the two. The most typical and effective connection is made by using intermittent fillet welds that are staggered on either side of the stiffener. Intermittent welding adds less heat to the plate reducing the amount of plate warping and is more economical. This weld is typically provided continuous for 3 to 12 inches (8 to 30 mm) on both sides at both ends of the

stiffener and intermittent along the stiffener's length. If there are any discontinuities along the stiffener, the weld is usually made continuous around the discontinuity. The size and spacing of the intermittent fillet welds must be designed for the horizontal shear forces. Figure 8.2 shows typical stiffener to plate welding.

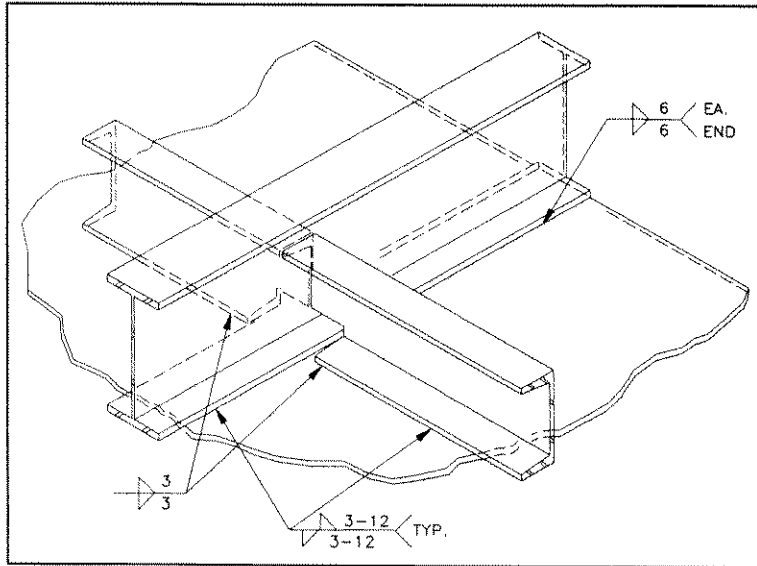


Figure 8.2
Typical Stiffener to Plate Connections

Placement and Spacing

Stiffeners are most often located on the outside of the duct. This arrangement promotes an uninhibited fluid flow resulting in reduced pressure drop. Stiffeners may also be located inside of the duct, but the effect on the pressure drop must be considered. There may be a number of acceptable stiffener arrangements, but the most economical are the ones that make use of stiffeners in more than one capacity. This concept limits the number of pieces and the amount of welding.

External stiffeners are usually oriented transverse to the flow, spanning from one edge of the panel to the other and effectively wrapping around the duct. Internal stiffeners are usually oriented longitudinal to the flow, spanning between internal trusses or perpendicular collector stiffeners. Long runs of uninterrupted duct

usually have stiffeners arranged in an orderly and uniform manner. If possible, the distances between stiffeners should be equal even if it means adding an extra stiffener or two. Equal spacings give more uniform stresses in both the plate and the stiffeners as well as making it easier to apply the insulation and lagging. An exception to this approach would be near large fans where unequal plate spans would help change the duct's fundamental natural frequency, therefore reducing plate vibrations.

Placement of stiffeners around structural discontinuities, such as access doors and flue-gas sampling probes, is not necessarily easy and must be handled on a case-by-case basis. Even though arrangements of duct systems vary greatly, they often are made up of configurations that are similar from one run of duct to another. Transition sections, rounded corners and T-sections are basic geometries except for dimensional differences. A standard set of preferred stiffener layouts should be developed so that a consistent approach is taken toward each duct section.

There can be many acceptable stiffener arrangements for a given section of duct. Even though structural engineers tend to arrange stiffeners perpendicular to the run of duct, there are times when it is necessary to orient stiffeners differently. Figure 8.3 illustrates an example of how stiffeners can be framed to form a successful design. The two main concepts when arranging stiffeners are: the plate span between stiffeners must be less than the allowable span and the ends of each stiffener must be adequately attached to a stable load carrying element, such as another stiffener or a corner angle.

Stiffener Load Organization

Section 4 discussed design loads in general and Section 5 discussed loading combinations. This section deals with design loads as they apply specifically to stiffener elements. The two main categories of loading information are load types and loading direction. Loading direction controls whether the load puts the outstanding flange in compression or tension. Each stiffener on the duct must be checked for the effects of the various different load combinations as presented in Section 5. The interaction of different load types presents potential problems because of the different allowable stresses applicable to each loading combination and the amplification of the effects one particular load may have on another load. Therefore, the structural engineer may have to develop a systematic and methodical approach to the analysis and design of duct stiffeners. The different combinations of design conditions can be pictured as a matrix consisting of four dimensions as illustrated

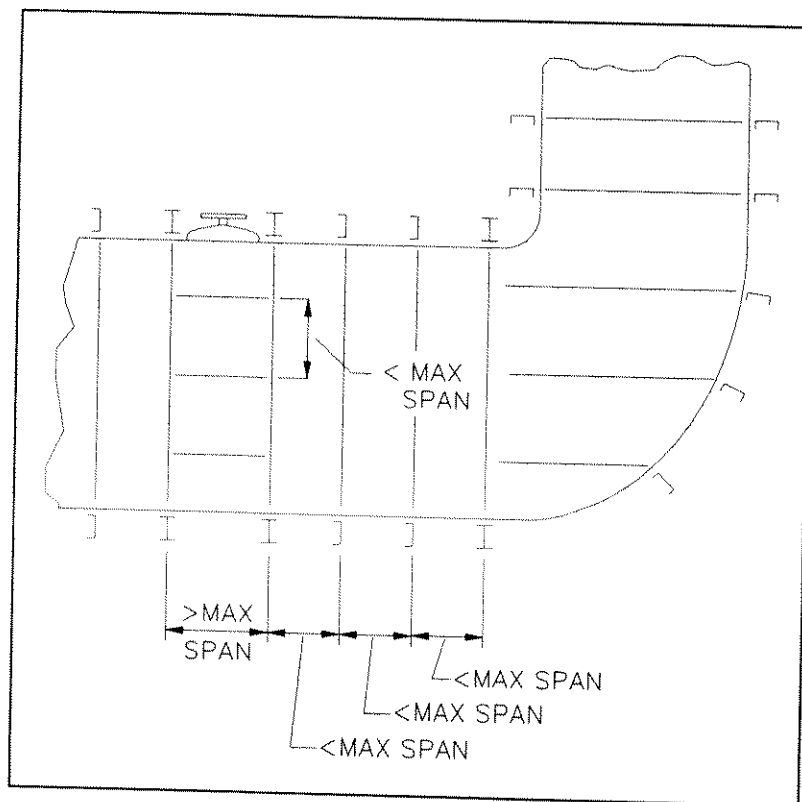


Figure 8.3
Example Stiffener Arrangement

in Figure 8.4. These conditions may be more complex if selected stiffeners are also used as vertical supports or are stayed by internal bracing. The organization of loads is essential for the analysis of stiffener elements because of the complexity of load types, loading combinations, loading direction, non-symmetric stiffener geometry and local buckling considerations.

Sizing Calculations

When choosing stiffener sizes, the structural engineer will usually choose as few different depths and sizes as possible. Common shapes should always be used. This approach is more economical from a material standpoint and when considering the installation of lagging and insulation. The structural engineer should predetermine a convenient set of structural steel sections that includes angles,

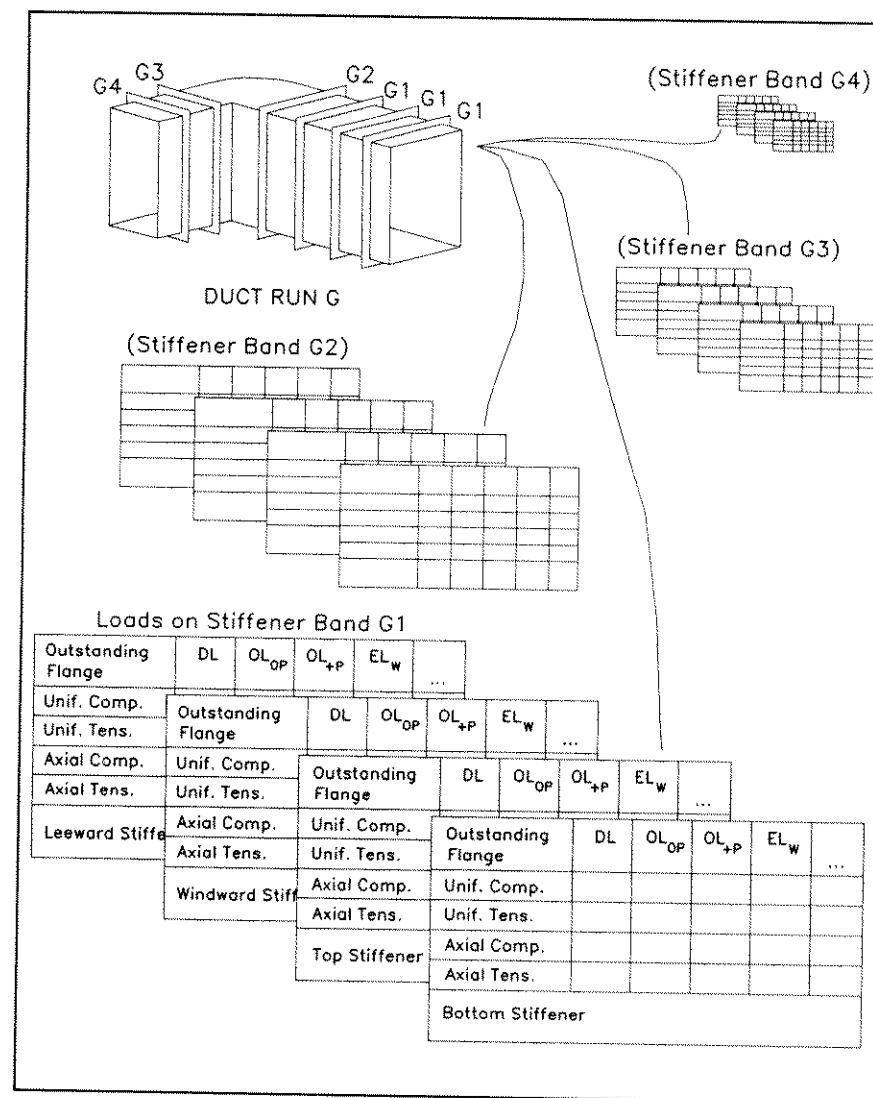


Figure 8.4
Typical Stiffener Loading Conditions

computer program should perform all of these tasks automatically if properly programmed and if the design data is properly loaded.

The design approach using stress ratios is based on superposition. A stress ratio calculated by dividing the actual stress by its allowable stress represents that fraction of the total strength capacity of the member at that particular location on the member. Of course, beam-column axial and bending stress interaction as presented in the AISC Specification, using the appropriate amplification factors, must be included. Section 5 presents the limits for allowable stresses for the various loading combinations which should be considered.

Member shear stresses need to be calculated if the stiffener elements carrying the shear load are thin and the load is relatively high. This usually is not the case. The shear stress may be compared directly with the appropriate allowable shear stress as a separate calculation.

As a final check, the design of some stiffeners may include a deflection calculation to verify that the stiffener cross-section meets any specified deflection criteria. Deflection checks are important for horizontal panel stiffeners where water ponding or high ash loads are possible. A deflection criteria may also be used to increase the stiffener's moment of inertia as a countermeasure against potentially excessive vibration.

Stiffener Sizing At Hopper Work Points

Figure 8.6 shows a condition where a lower side panel stiffener must also help form the lateral restraint for an ash hopper sloped wall. The forces from the hopper contents will accumulate and travel up the sloping plate. The vertical component of

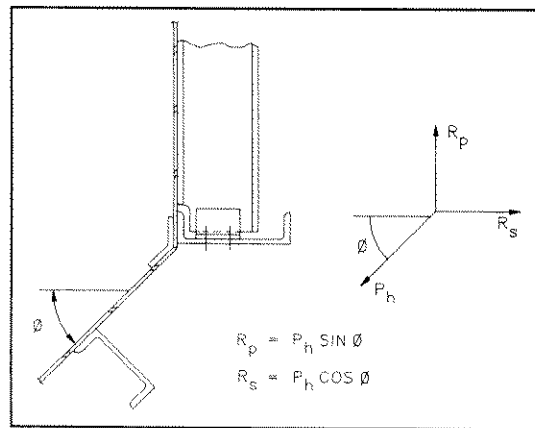


Figure 8.6
Duct to Hopper Interface

this force must get into the vertical duct side plate. The only way this can happen effectively is to provide a means for the force to turn the corner at the hopper workpoint. This is done by providing a horizontal stiffener and sometimes a reinforcing corner angle that will resist the horizontal component of the force in the sloped hopper wall. The remaining force is the vertical component which will be resisted by the side wall panel plate.

8.2.2 Stiffener End Connections

Most end connections for structural elements are welded and must be strong enough to transfer load into the adjacent wall or stiffener. Internal bracing and trusses utilize gusset plates to transfer their loads to certain stiffeners. Welding is traditionally used for making most ductwork element connections. Welding provides the erector with a certain amount of flexibility in assembly and erection, and usually allows smaller connections. Also, in high temperature application, welds behave better than bolts; bolts tend to loosen with continued exposure to high, fluctuating temperatures.

End connections may be designed as being either pinned or fixed. In the case of single span stiffeners, the most economical and proper design would be pinned connections due to their simplicity. This is true even though moment connections would allow the design of a lighter structural member. As in many cases, the structural engineer is usually better off to take a straightforward and predictable approach to the design process since the result is more reliable. Also, end connections designed as pinned connections will be smaller, less rigid and have less welding. Stiffer connections will tend to develop secondary stresses from strain controlled loadings.

Pinned Connections

Treating an end connection as though it has zero moment is a simplification of its real behavior. Some simple connections may have up to 20% fixity. However, permissible local yielding and deformation will still allow the stiffener to develop its full design capacity as a simply supported member.

There are many different ways of arranging pinned connections and Figure 8.7 shows some alternatives. In the design, the objective of a pinned connection is to provide an adequate path for the end reactions to be transferred into the adjacent stiffener or directly into the adjacent plate without developing appreciable end moments. Each element of the connection, including the welds, must be designed to transfer all loads without being overstressed.

Moment Connections

Moment connections are used to form a continuous frame structure around the duct so that moments can be transferred from one stiffener around the duct corner to another stiffener. These moments help to limit stiffener sizes by maintaining a negative moment balance at the end of each stiffener that helps counter some of the positive moment at the midspan of the stiffener. Moment connections are also used on stiffeners that serve double duty as duct supports. Sometimes, portal frames are used at duct support locations where sidesway must be resisted and where internal trusses are not desired. These duct portal frames transfer wind and other lateral loads to the duct support points. Moment frame configurations are highly indeterminate and the relative stiffnesses between the adjacent sides must be accurately accounted for in the analysis and design. The most efficient designs provide a comparable relative stiffness between adjacent members so that the weaker member does not distort or become overstressed.

Moment connections involve much more effort in their design and fabrication than pinned connections. The increased availability of computers and engineering software now makes the analysis and design of moment frames and moment connections much more practical. Calculating the design loads of a moment connection is really done when the stiffeners are sized. Since the duct stiffeners and their connections act together, the analysis of the system could be complex and the use of a computer program should be considered. An alternative would be to design moment connections that would develop the entire capacity of either of its two members. However, these connections may then be considerably over-designed and expensive. Figure 8.7 shows examples of two types of moment connections.

Moment connections are also labor intensive to fabricate and erect since they require the use of reinforcing plates and considerable welding. Reinforcing plates would be needed at locations where stiffening is required to develop the full strength capacity of the connection.

The structural engineer should be aware that even though end connections may be moment connections in the plane of the analysis, they may need to be considered as pinned connections in the out-of-plane direction.

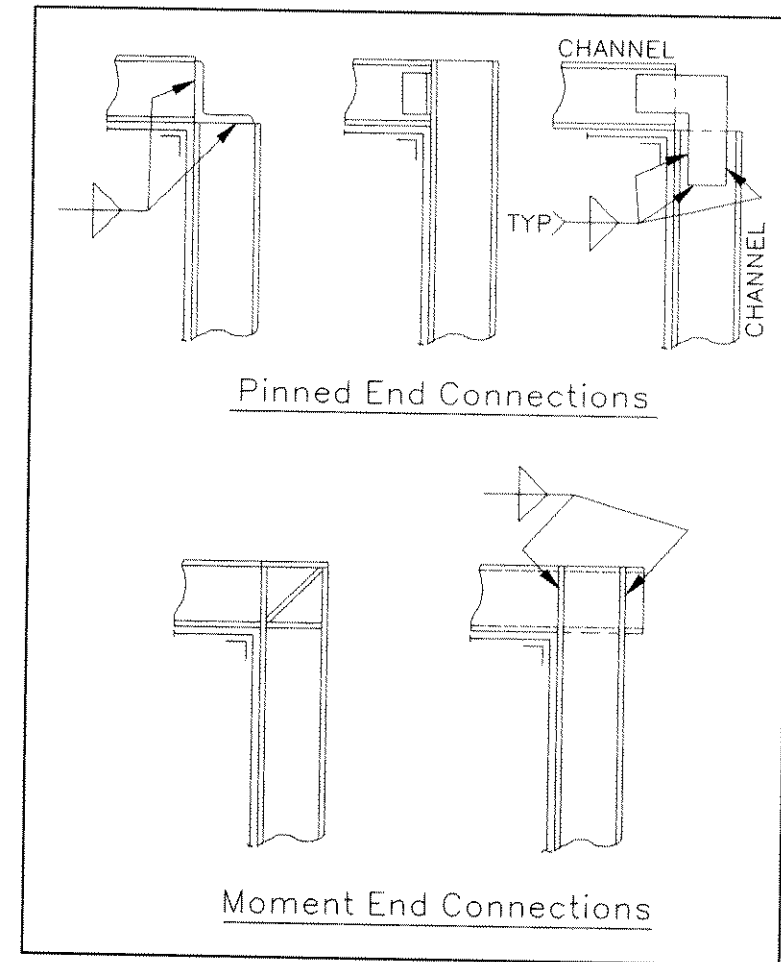


Figure 8.7
Examples of Stiffener Connections

8.3 INTERNAL TRUSSES AND STRUTS FOR RECTANGULAR DUCTS

Lateral loads on ducts need to be transferred to the structural support points; internal trusses may be the most direct way of achieving the proper load transfer. Ductwork internal trusses and struts are also used to provide intermediate supports for stiffener members. This technique allows the use of longer stiffeners with smaller cross-sections of less weight. The structural engineer must ensure that the connections of truss members

and intermediate struts are adequately attached directly to the ductwork external stiffeners, which usually serve as the truss chords, by penetrating the duct plate through a cut-out and welding directly to the stiffener. A detail of this concept is shown in Figure 8.8. Instances where internal trusses and struts might be used are discussed in Section 2.6.

A section of duct could have a very complex geometry because of limited available space or because it transitions into a major piece of equipment. This may occur when new equipment is designed to be installed among existing equipment. In these cases, internal trusses are helpful in transferring the loads around the corners and through the transitions.

The decision to use internal trusses or struts usually involves some trade-offs. The structural engineer faces increased costs for internal elements but reduced costs for the stiffeners. The structural engineer should recognize the functional impact of using internal bracing since the mechanical performance of the duct will be degraded due to higher pressure drop. Pressure drop calculations usually have some additional allowance for undefined internal obstructions, however, the structural engineer should notify the mechanical process engineer if internal bracing is required.

Single struts are often used as intermediate supports or span breakers for duct stiffeners. These struts are analyzed and designed to carry usually only the equal pressure reactions from both sides of the duct. With symmetrical stiffener framing, the pressure load cancels through the struts. Sometimes they are used to allow the stiffeners on both sides of a duct to share in the applied external load, such as wind. The use of span breaker struts can drastically reduce stiffener sizes.

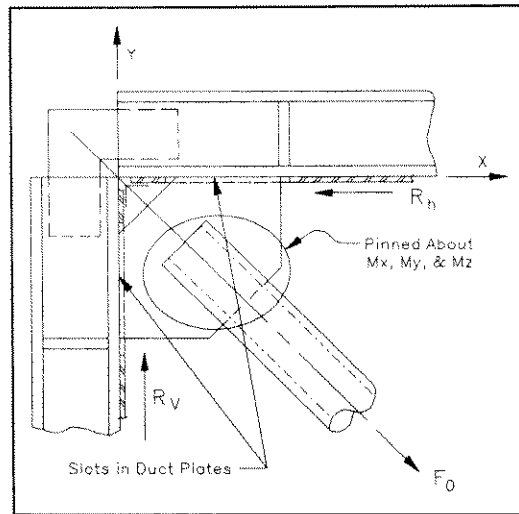


Figure 8.8
Typical Truss Connection

8.3.1 Analysis Methods

The structural analysis of a truss can be performed using classical manual calculation procedures if the truss is statically determinate. Trusses are typically analyzed assuming that all truss elements have pinned ends. This is typically the case when gusset plates are used in the connections as shown in Figure 8.8. Given these two assumptions, a basic static analysis can be performed to determine the axial forces in the truss members. The slightly larger member sizes resulting from this assumption are generally acceptable. When performing a manual analysis, free body diagrams are helpful as are shear and moment diagrams. From these diagrams, the points of maximum stress can easily be determined. If truss diagonals are connected in a manner that cannot be assumed by the structural engineer to be pinned, then the analysis must be performed with these members having full moment capacity ends. The moments from this analysis must then be considered in the design of these diagonals.

If the structural engineer decides that an indeterminate structural analysis is worthwhile because of member end conditions that cannot be assumed to be pinned, a computer analysis should be performed using a verified structural analysis program. In this analysis, the structural engineer must be sure to model the end connection condition that exist in the plane of the analysis, even though the connection may have a different condition in the out-of-plane direction. For most truss analysis applications, especially when there are many loading combinations to investigate, the most convenient and efficient tool is a verified structural analysis and design computer program.

8.3.2 Truss Element Design

Tension Elements

Stresses in pure tension elements may be compared to the allowable tension stress of the material at the design temperature. This is assuming the structure has been analyzed as though the member has pinned ends and it is loaded through its neutral axis. If the member has moment connections, and was analyzed as such, or is eccentrically loaded, then the worst combination of axial tension stress and bending tension stress needs to be considered as well as the worst case of bending compression stress minus axial tension stress.

Compression Elements

Stresses in compression elements must be compared to the allowable compression stress of the section at the design temperature. This is assuming the structure has been analyzed as though the member has pinned ends and it is loaded through its neutral axis. If the member has moment connections, and was analyzed as such, or is eccentrically loaded, then the worst combination of axial compression stress and bending compression stress needs to be considered. Compression elements can have very complex loads imposed on them. Both column buckling and local buckling need to be examined. As recommended in the AISC's *Specification for Structural Steel Buildings - Allowable Stress Design and Plastic Design (ASD)*, compression elements should be restricted to having a maximum L/r ratio of 200.

There may be circumstances, especially with thermal differential loadings, where $P-\Delta$ effects should be taken into consideration. The structural engineer should not confuse $P-\Delta$ effects with the beam-column interaction effect. In beam-columns, the lateral displacement is caused by a lateral load on the member. This lateral load causes the compression stresses to be magnified. With the $P-\Delta$ effect, the initial Δ may be caused by thermal effects, initial displacement or manufacturing tolerance. The axial compression load, P , will cause an induced moment equal to the product of P and Δ . The bending stress from this moment must be added to the other bending stresses. Sometimes this must be done manually because some computer programs will not account for this effect automatically.

Duct Stiffeners

The most complex loading condition for duct stiffener elements occurs when stiffeners are used as chords of trusses. Bending in the member is caused by moments from: pressure, ash, dead, live and wind loading. The moments will be different at the member midspans, at the connections, and at any intermediate supports. When designing truss chord members that also act as duct stiffeners, their bending stresses and axial stresses from the stiffener beam analysis must be properly combined with the axial stress and any moments calculated from the truss analysis. These members are best designed by superimposing the bending stress onto the axial stress from the truss analysis, investigating both the outstanding flange and the plate side. Figure 8.5 shows a way to perform this design efficiently. The difference between this case and regular duct stiffeners is that there is usually more than one critical section on each member due to the complex loading and the truss arrangement.

Vibration Considerations

There may be additional constraints placed on a truss element's stiffness because the element may be subjected to flow induced vibration. Flow induced vibration can be analyzed directly if the flow velocity, density and viscosity are known. The resulting vortex shedding frequency may be compared with the natural frequency of the member in a direction perpendicular to the flow. The natural frequency of the element should be less than or greater than the vortex shedding frequency by at least 20%.

The calculation of the natural frequency should be based on simply supported end conditions unless the evaluation of the connection details and the structural element arrangement can justify full or partial rotational end restraint. The material properties used to determine the natural frequency should be adjusted to reflect the duct operating temperatures. Stiffness evaluation methods based upon deflection limits or span ratios of plates and stiffeners may also be used. These methods rely on increasing the stiffness of a member to create a natural frequency above that of vortex shedding. The criteria for this method is usually developed from past experience and may be expensive and overly conservative.

The following is an accepted conservative guideline for assuring that a structural elements will not be in resonance with fan induced vibrations.

$$f_N < 0.8 f_F \quad \text{or} \quad f_N > 1.2 f_F$$

where,

$$\begin{aligned} f_N &= \text{natural frequency of the stiffener or plate} \\ f_F &= \text{operating frequency of the fan, or the frequency range of a variable speed fan} \end{aligned}$$

Flow velocities at internal structural elements should also be significantly higher or lower than the resonance flow velocity of the structural elements. Similarly, the following criteria could be used to assure that the structural element will not be in resonance with flow induced vibrations.

$$V_G < 0.8 V_R \quad \text{or} \quad V_G > 1.2 V_R$$

where,

$$\begin{aligned} V_G &= \text{flow velocity, ft/sec} \\ V_R &= \text{flow velocity at which resonance occurs, ft/sec} \end{aligned}$$

V_R may be calculated in different ways. One method, based on vibrations due to vortex shedding, is presented in *Shock & Vibration Handbook* by C. M. Harris and C. E. Crede.

$V_R = 0.38 D f_N$ for round shapes, where D is the diameter in inches.

$V_R = 0.76 T f_N$ for rectangular shapes or plate, where T is the thickness or frontal dimension in inches.

Sometimes, restricting an internal member's L/d ratio to a maximum value will provide a section that is stiff enough so that vibration will normally not be a concern. Typically, a maximum L/d value of between 20 and 30 can be used. This penalizes the economy of the member design, but sometimes potential problems can be alleviated by using this approach.

Temperature Differential Considerations

If significant temperature differentials are expected within the duct, this should be accounted for by a thermal loading condition in the analysis. These thermally induced stresses in truss elements should be added to the primary stresses from the other loading combinations as indicated in Section 5. The resulting stresses may be compared to a higher allowable stress as also presented in Section 5.

8.3.3 Truss Member End Connections

Most structural engineers treat truss elements as pinned members. However, even if fixity is assumed in the analysis and moments result, certain simplifying assumptions can be made to allow the connection to be designed properly.

The simplest diagonal connection uses a welded gusset plate for attachment of the member to the duct stiffeners. This is a low cost method of connecting truss elements together. Figure 8.8 shows the diagram of a corner gusset plate to illustrate a simplified design for a generalized loading. The welds connecting the truss diagonal to the gusset must be sized for the axial load, F_o . The welds for the gusset plate to the stiffeners should be sized for the horizontal, R_h , and vertical, R_v , components of F_o . The thickness of the gusset plate can be determined in the same way as the weld sizes. In order not to block too much of the flow, gusset plates should be designed with their dimensions minimized at the cost of additional thickness if

The structural engineer should always specify details that weld the gusset plate directly to the duct stiffeners. This is achieved by notching the duct plate around the gusset. This detail will provide a favorable load path directly from the diagonal into the stiffeners, which usually act as the truss chords.

An exact analysis of the actual connection would require a much more sophisticated approach since it is highly indeterminate. However, simplifying assumptions as described above are often made. These assumptions allow the structural engineer to treat the connection as being determinate. Given valid simplifying assumptions, an adequate end connection can be designed even if the actual load distributions were different than assumed. Local deformations in the gusset plate and welds allow the loads to redistribute more like the assumed loading pattern.

8.3.4 Vertical Duct Support Elements

The primary purpose of vertical duct support elements is to transfer vertical loads from the duct to the supporting structure. At the same time these supports may also be used to resist pressure and external horizontal loads. There are two types of vertical supports: hanger rods and bottom supports. The choice of one support method or the other resolves down to convenience and economics. If the steel superstructure extends to elevations above the duct then hanger rods would be a convenient method of support. However, with hangers, duct external tie elements or bumpers are required to carry the duct's lateral loads. If extra steel is needed to extend above the duct, or if the duct is within a few feet or meters of the foundation, then bottom supports may be more economical.

Hanger Rods

Hanger rods support a duct from a superstructure located above the duct. Connections to the superstructure may be made with commercially purchased clevises or with fabricated plates. Connections to the duct may be made with simple plates welded to the duct side plates or with wing plates that are welded to stiffeners and extend out away from the duct to avoid clearance problems. Figure 8.9 shows some examples of hanger rod arrangements.

Hanger rods may or may not be used in conjunction with spring hangers. Spring hangers may be one of two types: constant support or variable support. If spring hangers are used, they must be sized

duct behavior. When hangers are used to carry the vertical load of a duct section, external bumpers or lateral tie elements must be included to take the duct's lateral loads to the support structure.

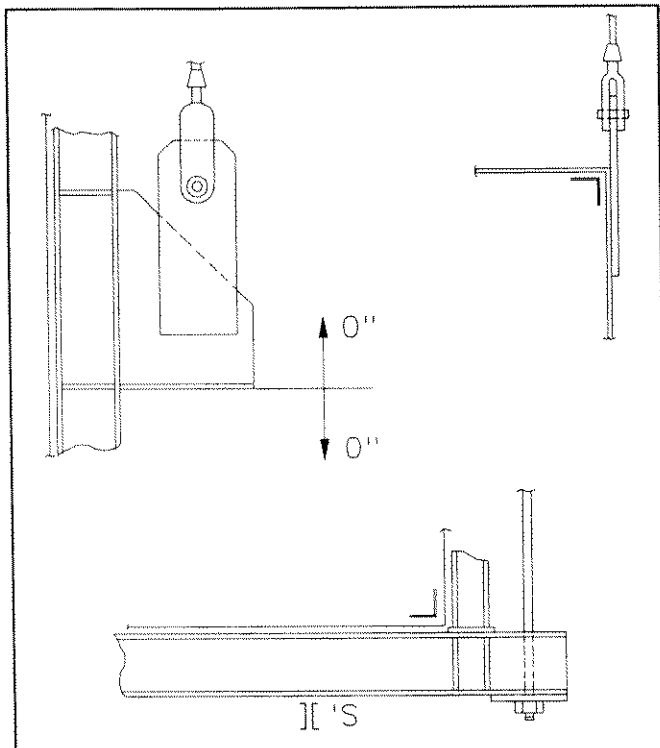


Figure 8.9

Typical Hanger Rod Support Arrangements

Bottom Supports

Bottom supported ducts use independent members or stiffener extensions to post down to the support structure. The posts should be designed for all vertical loads as well as the bending moments and shears from the lateral loads that go through the posts down to the support structure. Slide bearing plates are typically provided under the posts, except at the duct anchor point, to reduce the friction loads from thermal expansion of the duct. In addition to other lateral loads, such as wind, seismic and unbalanced pressure, coming from the duct, the posts should also be designed for the moments and shears from these friction forces. Figure 8.10 shows examples of bottom support arrangements.

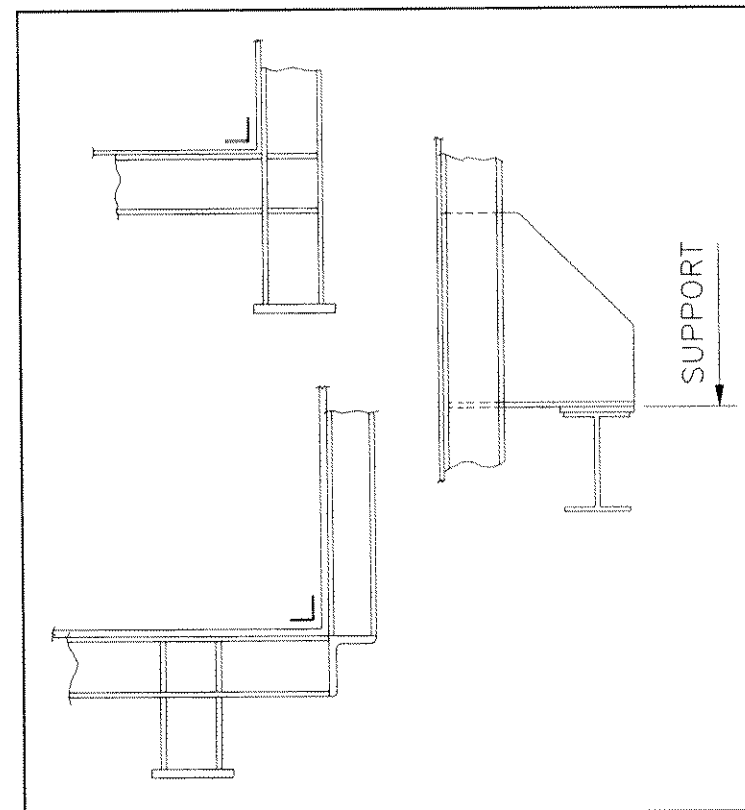


Figure 8.10

Typical Bottom Support Arrangements

8.4 CIRCULAR DUCTS

As discussed in detail in Section 2, circular ducts are often used in locations where there are straight duct runs with sufficient space and a conveniently located support structure. Circular ducts are designed with some of the same types of structural elements as rectangular ducts, however, there are differences which will be explained here.

8.4.1 Ring Stiffeners

Just as in the design of pressure vessels, stiffener rings for circular ducts are more efficient at retaining internal pressure force than straight stiffeners on rectangular ducts. In circular ducts, the

internal pressure is resisted by axial hoop stress in the shell. Additional economy is realized by the lack of end connection hardware, however, the cost of splicing the stiffener rings must also be considered.

Ring stiffeners also serve as the attachment for the duct supports. See Figures 8.12, 8.13 and 8.14 for examples of circular duct support schemes. The composite section of the stiffener ring must have the strength to resist both the forces due to internal pressure and the additional local forces and moments from the duct supports. These forces and moments can be determined using common circular ring formulas such as those presented in the book *Formulas For Stress and Strain*, by Roark and Young. The effects of internal pressure and support stresses can be combined by superposition. Figure 8.11 shows an example of the local moments and forces which are developed at a circular duct support point. These internal forces and moments are a function of the load to the supports, W , the radius of the ring, R , and the support geometry.

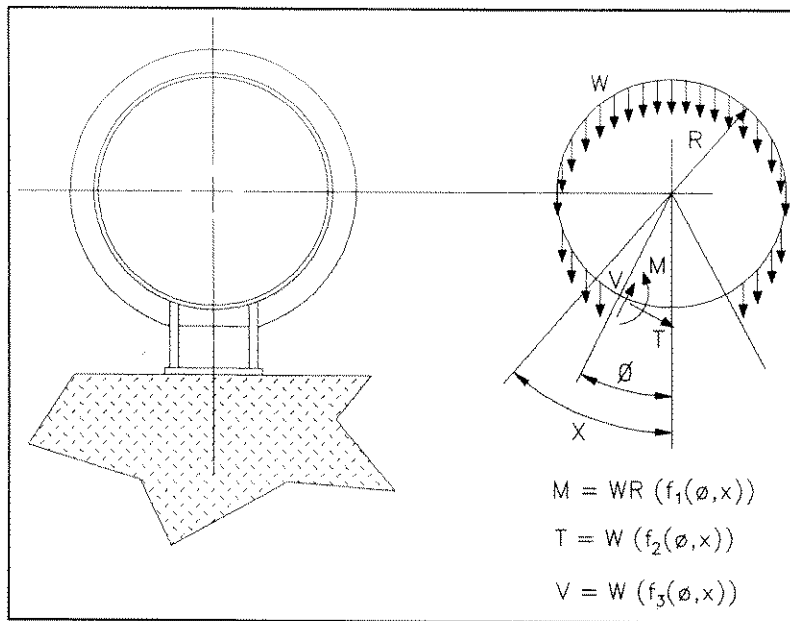


Figure 8.11
Local Stresses in Circular Rings

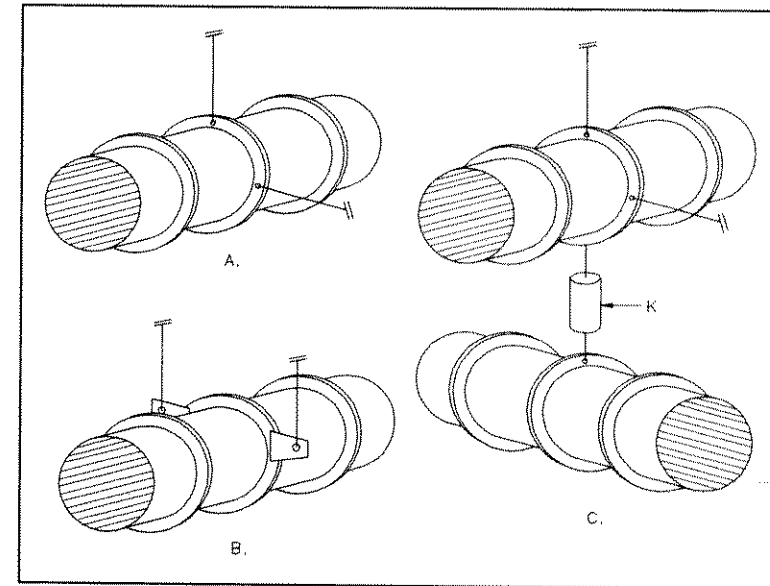
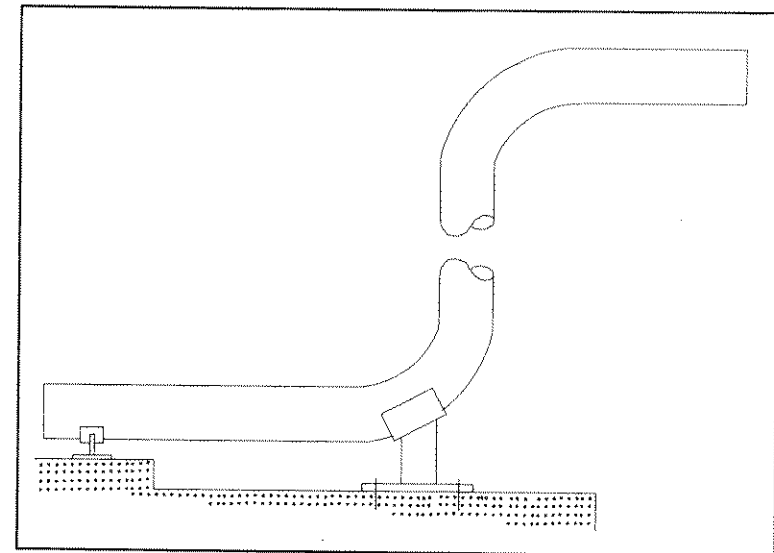


Figure 8.12
Typical Circular Duct Support Hanger Arrangement



Ring stiffeners must be welded to the duct plate so that the pressure loads can be transferred to the stiffener and so that there is an adequate horizontal shear transfer to form a composite section. As with rectangular ducts, axial stresses will be carried by this composite section through its centroidal axis.

8.4.2 Internal Struts

Internal struts in circular ducts are rare occurrences since the inherent strength of the cylindrical section usually is more than adequate to carry the loads. However, a circular duct with high external pressure may receive the most benefit from internal struts. The structural engineer should be aware that enough struts must be used to force buckling in the higher mode shapes that correspond to critical loads greater than the applied load times a rational factor of safety. Also, sometimes internal struts are used at the support locations to reduce the plate stresses.

The decision to use internal struts versus strengthening of the stiffener section depends on various factors including flow pressure drop requirements, clearance requirements, temperature differentials and flow induced vibration. The structural engineer should be able to recognize all the factors involved and coordinate efforts to arrive at a design acceptable from both a structural and functional aspect. In addition to functional design conditions, internal struts can be used as temporary bracing to control ovaling during shipping and manufacturing. Temporary bracing is discussed in further detail in Section 10.

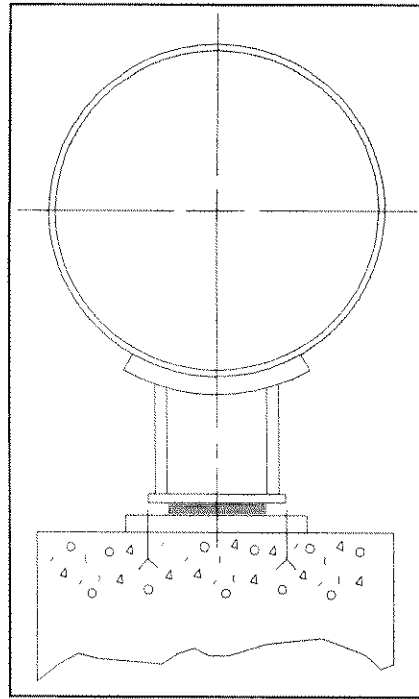


Figure 8.14
Typical Circular Duct
Saddle Support

8.5 LATERAL EXTERNAL TIE ELEMENTS

Lateral ties are used to restrain ducts in the horizontal direction against lateral loads and to guide thermal growth. Lateral ties are external to the duct and laterally attach the duct to the support structure. Ideally, lateral ties would be located to adequately restrain a duct without having to resort to overturn couples in the vertical supports. However, this approach is sometimes impractical and uneconomical and therefore often is not done.

Just as with other forces, lateral loads tend to take the stiffest load path to an external restraint. Simple statics proves that the closer a load is to a restraint, the greater portion of the load will go to that restraint. As with vertical loads, there are different methods used to distribute lateral loads to the restraint system in a rational manner. Loads that are applied overall to the duct may be spread evenly to the restraints via the duct plate and plate stiffeners. Loads that are concentrated in one area may be distributed to only the nearest restraints. Lateral ties are almost always pure tension or compression elements. They should be designed accordingly for all of the expected loads and loading combinations.

SECTION 9
Structural Design of Flow Distribution Devices

	<u>Page</u>
9.1 FUNCTION OF FLOW DISTRIBUTION DEVICES	201
9.2 FLOW LAYOUT AND STRUCTURAL CONSIDERATIONS ..	203
9.2.1 Flow Resistance	203
9.2.2 Local Design Requirements	203
9.2.3 Global Design Requirements	204
9.2.4 Physical Arrangement Considerations	204
9.3 SUPPORT CONSIDERATIONS	205
9.4 STRUCTURAL ANALYSIS	205
9.4.1 Stiffness Requirements	206
9.4.2 Dynamic Loads	208
9.4.3 Static Loads	209
9.4.4 Minimum Loads	210
9.5 STRUCTURAL DESIGN	210

SECTION 9

Structural Design of Flow Distribution Devices

9.1 FUNCTION OF FLOW DISTRIBUTION DEVICES

Turning vanes, splitter plates, baffles and perforated plates are types of flow distribution devices that are located within the duct's flow path. Their function is to control the flow of the air or flue-gas across the duct cross section. Typical flow distribution device configurations are presented in Figure 9.1.

Turning vanes and splitter plates have similar functions. Turning vanes are used to change the direction of the stream, reduce flow turbulence, develop uniform distribution of flow and minimize pressure drop. Splitter plates are linear elements used to divide and direct the stream to obtain uniform distribution of flow across the entire duct section, reduce turbulence and minimize pressure drop. Development of uniform flow distribution and reduction of flow turbulence will also minimize the accumulation of ash and sludge that settles out onto the ductwork floor. Trailing edge liquid collectors can be provided on turning vanes and splitter plates to collect and direct liquid runoff from condensed moisture in the flue-gas stream, if necessary.

Baffles and perforated plates are placed perpendicular to the flow. Their function is to develop resistance to the flow. A baffle is installed across part of the duct section to direct a concentrated flow stream across the entire section of the duct. A perforated plate is installed across the entire duct section to cause the air or flue-gas to flow across the duct's full cross section. Baffles and perforated plates also function to absorb the energy of fast moving streams and to dissipate large swirls and eddies within the flow stream, reducing the flow's turbulence. Perforated plates are most often used at abrupt changes in duct cross sectional area, such as in the inlet and outlet ductwork of precipitators and scrubbers. Perforated plates are not used extensively because of the large pressure losses associated with their use. Baffles are seldom used in ducts. An increase in pressure drop means that larger fans will be required in the system.

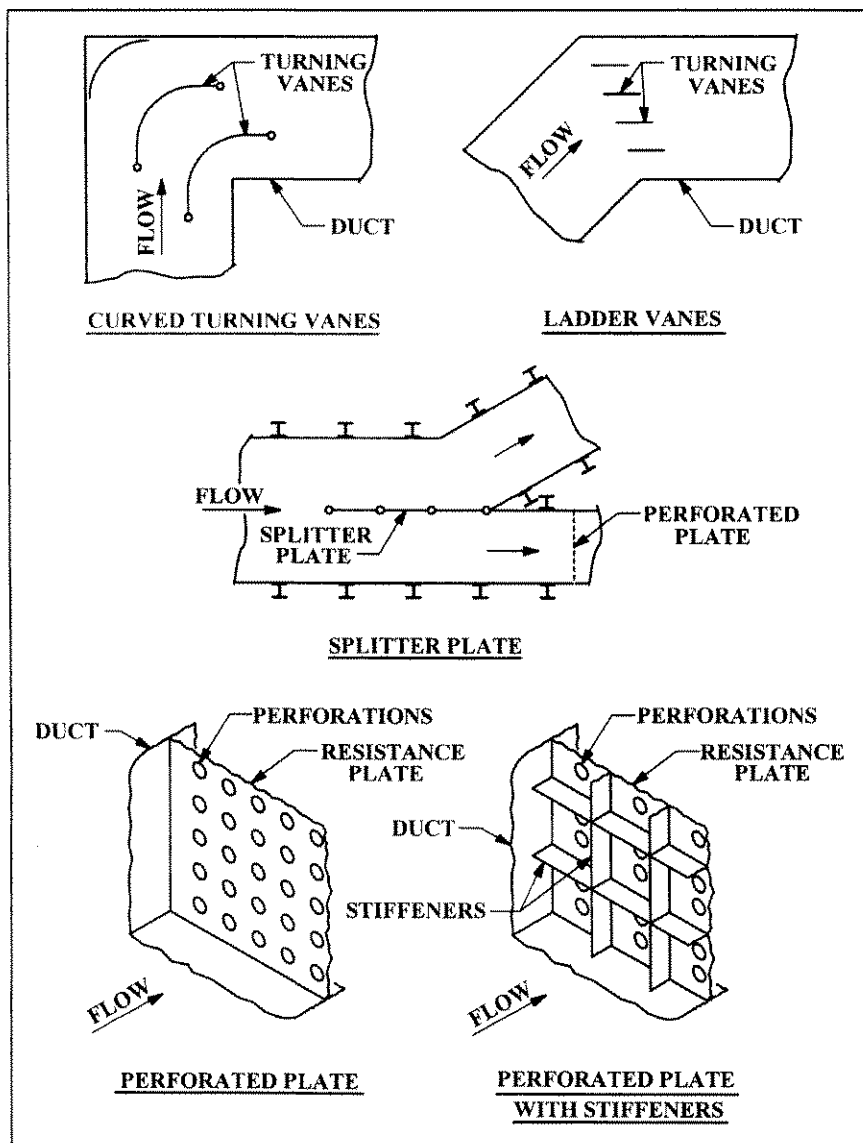


Figure 9.1
Typical Flow Distribution Device Configurations

Internal gutters, downspouts and other liquid flow collection devices are sometimes used in ducts where the flue-gas is below its acid dew point and excessive internal liquid condensation is expected. When this is the case, internal drains must be installed in the ducts that then carry the flow to a proper repository. Because of the corrosive nature of the liquid, these liquid flow collection devices and drains must be made from a corrosion resistant material.

9.2 FLOW LAYOUT AND STRUCTURAL CONSIDERATIONS

The general configuration, quantity and arrangement of splitter plates, turning vanes and perforated plates are determined in accordance with criteria established by the system's flow analysis. Development of the conceptual configuration and arrangement of flow distribution devices is often based upon flow model testing. The testing may be either by computer simulation or by actual reduced scale physical flow models. The structural configuration of each flow distribution device is governed by the optimum combination of the following parameters.

9.2.1 Flow Resistance

Flow resistance from splitter plates and turning vanes should be minimized. Their structural elements usually consist of plate sections stiffened with pipe sections, angles or plates. The total projected surface of the stiffened flow device perpendicular to the flow should not significantly reduce the cross section of the duct available for flow. Limiting the total projected surface of the stiffener system to less than 5% of the total flow path is considered to be a reasonable control on flow resistance.

Perforated plates normally have closely spaced openings providing a ratio of open area to total area of between 30% and 75%. The opening ratio is determined by a flow analysis which may or may not include a flow model test. Stiffeners for perforated plates are usually located on the downstream surface to minimize ash or sludge accumulation and to not disrupt the flow pattern, unless the flow analysis recommends an "egg crate" arrangement on the upstream side of the perforated plate. Baffles may be perforated, but are usually solid plate.

9.2.2 Local Design Requirements

The plate and stiffener system should be sized for the combination of ash or sludge accumulation, operating pressure and dynamic pressure forces, and stiffness requirements as defined in Section 9.4.

9.2.3 Global Design Requirements

The structural load carrying capability of splitter plates and turning vanes may reduce the span of the exterior duct walls. In new duct design, a reduction in the duct wall span due to the existence of a flow distribution device is usually not done. However, in some instances flow distribution devices are designed as primary structural elements that contribute to the overall duct strength. A design incorporating a flow distribution device as a wall plate support should be approved by the owner so that this will be considered in any future duct modifications. If rigidly attached to the duct walls, the structural components of the flow distribution device should always be sized for the reactions from the wall system whether the flow distribution devices are classified as primary structural elements or not, because in actuality they will see the loads. During modification or re-evaluation of duct systems, consideration of wall span reductions based upon the presence of flow distribution devices may be an effective alternative to duct stiffening. In all cases, the structural elements of flow distribution devices should be designed for any and all contributory forces resulting from the duct structural system.

If flow distribution devices are designed as an integral part of the ductwork structure, the customer or owner should be properly informed. At a minimum a note should be placed on the design drawings indicating this design consideration. This is done so that the owner or operator will know that if the flow distribution devices are damaged they must be replaced or else the ductwork structure will be in jeopardy. It will also inform the owner that the flow distribution devices cannot be removed without revising the ductwork structure.

9.2.4 Physical Arrangement Considerations

The physical arrangement of splitter plates and turning vanes is usually developed to prevent intersections or interferences with duct internal trusses or struts. The structural engineer must come to an agreement with the mechanical process engineer if one of these two must be relocated. If the flow distribution device must intersect a duct internal brace or truss, details should be provided to allow for the independent movement of the two different structural systems. The plate elements of splitter plates and turning vanes should not be connected to intersecting members of duct internal trusses or struts unless the trusses have been designed for the loads that will be transferred from the flow distribution devices.

Flow distribution devices subjected to corrosive or erosive flow conditions are usually provided with sacrificial shielding or corrosion-erosion thickness allowances for the structural material. Increased material thickness or supplemental members added as shielding should not be considered in the evaluation of the structural capacity of the flow distribution device. Historically, a corrosion allowance of 1/16 inch (1 to 2 mm) has often been provided in the design of flow distribution devices. Flow distribution devices within wet scrubber outlet ducts must be made from the same corrosion resistant material used to cover the inside of the duct.

9.3 SUPPORT CONSIDERATIONS

The supports for turning vanes, splitter plates, baffles and perforated plates must be capable of transmitting all applied forces into the duct main structural system.

Turning vanes, splitter plates and baffles are usually attached to the duct plate. Flow distribution devices that are not used as an integral part of the duct's global structural system need only be connected to the duct plate. The structural engineer should develop connection details that distribute their reactions to the duct plate so that stress concentrations at the attachment location are minimized. Turning vanes, splitter plates and baffles that are integral parts of the duct's structural system are usually attached directly to duct stiffeners, bypassing the duct plate. The structural engineer should develop details which transmit their reactions directly to the duct stiffener system, avoiding through-thickness loading of the duct plate.

Perforated plates are usually suspended within the duct cross section to preclude interaction of global duct forces with the diaphragm formed by the perforated plate. Isolation of the perforated plate element from the duct structure is also necessary for the efficient operation of rapper elements that are used to prevent particulate build-up. Connection details must be able to transmit the static and dynamic reactions of the perforated plate to the duct structure without inducing significant restraint to the duct structure and without loading the perforated plate structure. Baffles are also sometimes installed in this manner.

9.4 STRUCTURAL ANALYSIS

The structural analysis and design of turning vanes, splitter plates, baffles and perforated plates needs to address stiffness requirements, dynamic forces, static loads and localized loads or effects. Each of these requirements is discussed in the following sections.

9.4.1 Stiffness Requirements

Rolled structural shapes, pipe sections and plates are the structural elements of flow distribution devices. Flow distribution structural elements within the flow stream are subjected to two possible sources of vibration excitation: flow induced vibrations and fan induced vibrations.

Fan induced vibrations are a concern immediately upstream and downstream of the ID, FD and PA fans or other large fans as discussed below. The pressure downstream of the fan is postulated to contain a harmonic component which would be a multiple of the fan's operating speed. Flow induced vibration is caused by the generation and collapse of eddy currents formed by the flow around and over the internal structural elements. The structural engineer may decide to consider flow induced vibrations based on the service history of similar installations and anticipated flow conditions within the duct. When variable speed fans are used, a range of operating speeds needs to be considered to establish a range of frequencies that need to be checked for resonance with the fan induced vibrations. Fan induced vibrations should be addressed at the first flow distribution devices upstream and downstream of all large fans. The structural engineer may decide that other devices may also need to be addressed.

To reduce the potential for vibrations, the use of flow distribution devices should be avoided immediately upstream or downstream of large fans. The exact requirements should be requested from the fan manufacturer. In the absence of specific criteria from the fan manufacturer, the design team should consider providing a constant duct section at the fan outlet with no flow distribution devices for a length equal to the "100% effective duct length" as defined in Section 8 of the Air Movement and Control Association, Inc. document 201-90, *Fans and Systems*. This publication sets the 100% effective duct length equal to $2\frac{1}{2}$ duct equivalent diameters for a flow of 2,500 cfm (70 cubic meters per minute) or less and adds 1 duct equivalent diameter for each additional 1,000 cfm (30 cmm) of flow. The equivalent diameter may be taken as 1.13 times the square root of a rectangular duct's area. Flow distribution devices should be avoided within this section of duct. Failure to meet these or similar requirements could be detrimental to the performance of the fan or could be cause for voiding of the fan warranty. Structural damage to the fan, the flow distribution devices or the duct from flow related vibrations may also result.

The natural frequency of unstiffened sections of plate elements or the leading edge stiffener of stiffened sections can be determined and evaluated against critical operating ranges for the two possible sources of vibration. Thin elements susceptible to corrosion or erosion should be evaluated using full and partial thickness properties. The calculation of the natural frequencies is usually based on simply supported end conditions unless the evaluation of the connection details and the structural element arrangement can justify full or partial rotational restraint. As with all duct design procedures, the material properties used to determine the natural frequencies should be adjusted to reflect the duct's operating temperatures. Stiffness evaluation methods based upon deflection limits or span ratios of plates and stiffeners may also be used.

The natural frequencies of all structural elements, including flow distribution devices, should be sufficiently lower or higher than the operating frequency of the fan in the duct system. The following is an accepted conservative guideline for assuring that the structural elements will not be in resonance with fan induced vibrations.

$$f_N < 0.8 f_F \quad \text{or} \quad f_N > 1.2 f_F$$

where, f_N = natural frequency of the stiffener or plate
 f_F = operating frequency of the fan, or the frequency range of a variable speed fan

Flow velocities at flow distribution devices should also be significantly higher or lower than the resonance flow velocity of the structural component of the flow distribution device. Similarly, the following criteria can be used to assure that the structural element will not be in resonance with flow induced vibrations.

$$V_G < 0.8 V_R \quad \text{or} \quad V_G > 1.2 V_R$$

where, V_G = flow velocity, ft/sec
 V_R = flow velocity at which resonance occurs, ft/sec

V_R may be calculated in different ways. One method, based on vibrations due to vortex shedding, is presented in *Shock & Vibration Handbook* by Harris & Crede.

$$V_R = 0.38 D f_N \quad \text{for round shapes - } D \text{ is the diameter in inches.}$$

$$V_R = 0.76 T f_N \quad \text{for rectangular shapes or plate - } T \text{ is the thickness or frontal dimension in inches.}$$

9.4.2 Dynamic Loads

The dynamic pressure, or velocity pressure, should be considered in the design of turning vanes, splitter plates, baffles and perforated plates. The following equations to determine the dynamic pressure are based upon classical compressible flow theory.

Turning Vanes

The dynamic thrust on a turning vane or a solid baffle is:

$$F_{OD} = (2\rho Q^2/A) \sin(\alpha/2)$$

The corresponding dynamic pressure is:

$$SL_{DP} = F_{OD}/A_P$$

The parameters in these equations are defined in Figure 9.2 where,

F_{OD} = dynamic thrust on the duct wall or turning vane, pounds

SL_{DP} = dynamic pressure on the duct or turning vane, lbs/ft²

ρ = mass density of the flow, usually taken as 0.002 lbs-sec²/ft⁴ (0.1 kg-sec²/m⁴)

Q = flow rate between the turning vanes or duct plates, ft³/sec

A = cross-sectional area of the duct at the bend or the area between turning vanes, ft²

A_P = area of the projected duct plate or vane surface in the direction of flow, ft²

α = change in direction of the duct or vane, degrees

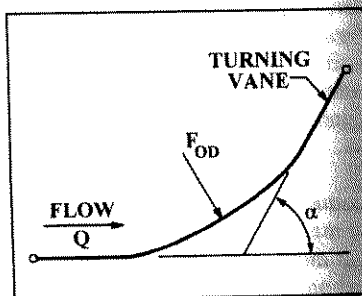


Figure 9.2
Dynamic Thrust on
Turning Vanes

Perforated Plates

One method which may be used to determine the pressure acting on a perforated plate is as follows. This equation is derived from fluid mechanics principles which is presented in Hunter Rouse's textbook, *Elementary Mechanics of Fluids*.

$$SL_{DP} = \frac{1}{2}\rho V^2/(kR)^2$$

where,

SL_{DP} = differential pressure on the perforated plate, lbs/ft²

ρ = mass density of the flow, usually taken as 0.002 lbs-sec²/ft⁴ (0.1 kg-sec²/m⁴)

V = velocity of the flow, ft/sec

R = ratio of the open area of the perforated plate to the cross sectional area of duct

k = a coefficient of discharge, which varies logarithmically from 0.6 at $R = 0$ to 0.75 at $R = 1$

The differential pressure always acts on the upstream face of the perforated plate and in the direction of the flow.

9.4.3 Static Loads

Splitter plates, baffles, turning vanes and perforated plates should be designed for all of the applicable loads used to design the main duct section. Dependent upon the flow velocity, ash and sludge may accumulate on flow distribution devices. Where applicable, ash or sludge loads should be applied to horizontal surfaces of splitter plates and turning vanes as discussed in Section 4. The clear distance between turning vanes or splitter plates shall be used to establish the ash or sludge loading where the load is assumed to be a function of the duct height.

Where splitter plates, baffles or turning vanes are used as an integral member of the duct structure to resist or transmit dead, live, operational, system related and environmental loads, the corresponding global static loads, obtained from the wall analysis as discussed in Section 7, are additive to the static loads due to ash or sludge accumulation and the dynamic pressure forces.

Structural elements of all flow distribution devices should always be checked for the potential compressive forces which may be induced at connections to the main duct structure when the duct is subjected to negative pressures.

9.4.4 Minimum Loads

After the selection of the initial sizes based upon stiffness criteria and dynamic loads, the structural elements of flow distribution devices are frequently checked for a minimum load case. The structural elements include all plate sections and stiffeners. The minimum load is independent of the loads obtained from the dynamic pressure evaluation and the static loads. Typically used minimum values are a uniform pressure load equivalent to 25% of the duct operating pressure or 6 inches (150 mm) of water pressure, whichever is greater. The minimum uniform pressure load is applied normal to the plane of the structural element. Reactions from this minimum load on the structural elements of the flow distribution device do not need to be considered in the design and evaluation of the overall duct structure.

9.5 STRUCTURAL DESIGN

The design of splitter plates, baffles, turning vanes and perforated plates must consider the combination of the individual static and dynamic loads as defined above. If a group of vanes are structurally connected, they should be treated as one structural element. As with all ductwork structural elements, the allowable stresses must be adjusted to reflect the operating and transient temperatures of the duct.

Plate sections are to be sized on the basis of forces and moments obtained from the analysis of the flow distribution device's structural systems. Plate span lengths are usually taken as the clear distance between stiffeners for flat plates or the chord distance for curved plates. The device's stiffeners should be sized to support all contributory loads on the basis of forces and moments obtained from the analysis of simply supported structural elements, unless fixity can be justified by frame analysis.

After initial sizing of plate and stiffener sections, the dynamic response of the system to flow and fan induced vibrations is usually evaluated. Structural element size should be increased if necessary to obtain a system of sufficient stiffness to assure resonance will not occur. When the size of leading edge stiffeners significantly reduce the cross section available for gas flow, intermediate support plates or struts should be considered to reduce the span of the structural elements. Limiting the total projected

surface of the leading edge stiffener to less than 5% of the total flow path is considered to be a reasonable control on flow restriction.

Where the splitter plate, baffle or turning vanes are part of the global structural system, stiffeners on the turning vanes or splitter plates should be connected directly to stiffeners on the main duct structure so as to properly transfer the forces. Independent splitter plate or turning vane assemblies may be attached to the duct plate if their connections do not induce stress concentration in the plate.

SECTION 10
Drawing, Fabrication and Construction
Techniques and Considerations

	<u>Page</u>
10.1 GENERAL CONSIDERATIONS	215
10.1.1 Shipping Modes and Dimension Considerations	215
10.1.2 Construction Economy	217
10.1.3 Field Splices	221
10.2 DRAWINGS AND SPECIFICATIONS	223
10.2.1 Drawing Preparation	223
10.2.2 Fabrication Specification	226
10.3.2 Erection Specification	227
10.3 FABRICATION	228
10.3.1 Plate Fit-Up	228
10.3.2 Fit-Up of Stiffeners, Flanges and Attachments	229
10.3.3 Assembly of Duct Sections	229
10.4 WELDING	230
10.4.1 Welding Codes and Standards	231
10.4.2 Types of Welding Processes	232
10.4.3 Welding Electrodes	232
10.5 SHOP INSPECTION	233
10.6 SURFACE PREPARATION	234
10.7 HANDLING AND SHIPPING	235
10.7.1 Piece Marking	235
10.7.2 Lifting Lugs	235
10.7.3 Temporary Bracing	236
10.7.4 Loading, Receiving and Unloading	238
10.8 ERECTION	238
10.8.1 Erection Sequencing	238
10.8.2 Special Erection Considerations	239

SECTION 10

Drawing, Fabrication and Construction Techniques and Considerations

10.1 GENERAL CONSIDERATIONS

Before starting the structural analysis and design of a ductwork system, consideration should be given to fabrication, shipping and construction. Too often the structural engineer fails to give sufficient consideration to these vital operations. No ductwork design can be considered optimized unless these operations are given due consideration in the design process.

10.1.1 Shipping Modes and Dimension Considerations

Since the early 1970's, freight costs in the United States have risen faster than most sectors of the economy. Currently, shipping costs are typically at least ten percent of the fabricated ductwork material total cost. These costs may be much greater depending on the project location and the shipping distance. Thus, shipping costs are an important financial consideration in any ductwork project.

The ductwork structural engineer should be cognizant of the shipping method to be used on the project. Because of the significance of freight cost and the importance of including this cost in the project estimate, the shipping method is often pre-determined prior to the engineer's involvement in the project. The structural engineer must then execute a design that can be erected consistent with the pre-determined shipping method.

There are three basic modes of shipping ductwork components: rail, truck and barge. By far, the most commonly used method is via truck. Barge and rail shipments are uncommon but sometimes practical. Depending on the project site location, one of these methods may even be necessary. The requirements of barge and rail shipping are highly specialized and should be investigated

thoroughly on a project unique basis. Discussions in this section are primarily centered on truck shipping with some information presented on rail shipping. Shipment by truck is currently the most common method. For truck shipping, duct component piece width is the critical consideration. The shipping width may be the major factor in determining the shipping cost. Sometimes, height and length are also significant factors. Weight, while important, is not usually a controlling factor in shipping ductwork. The following provides some specific information relating to cost and width for shipping via truck.

Truck Shipment

Shipping via truck is regulated at the state level by the individual state's governing entity in conformance with federal guidelines. A condensed document entitled *Permit Manual*, published and updated quarterly by the Specialized Carriers and Rigging Association, Fairfax, Virginia, provides invaluable information relating to truck shipping. This manual provides the user with legal load limits and special permit requirements for oversize and overweight loads for each state. The manual provides information such as: contact, legal limits, special permit limits, general restrictions, types of permits available, fees, escort needs, fines and restricted travel areas.

As stated previously, shipping costs are a significant portion of the overall ductwork cost and the width is usually the critical factor in the shipping cost. In general, components up to 8 feet (2.5 meters) wide require no special shipping considerations, permits are required for widths from 8 feet to 12 feet (2.5 to 3.6 meters), and widths greater than 12 feet (3.6 meters) require both permits and escorts. Height and length may on occasion govern the necessity for permits and/or escorts. The maximum shipping height is generally limited to 14 to 15 feet (4.2 to 5.3 meters) above the road surface. The maximum shipping length, including the truck tractor and load, is generally 75 feet (23 meters), however lengths up to 150 feet (45 meters) are possible with permits and special shipping equipment. For comparison purposes, Table 10.1 provides

Shipping Width	Cost Factor
8 feet or less (2.5 meters)	1.0
8 to 12 feet (2.5 to 3.6 meters)	1.2
12 to 14 feet (3.6 to 4.2 meters)	2.5

Table 10.1
Shipping Cost Factors

cost information relative to truck shipping width and assumes no over-length or over-height conditions. This comparison, provided by Structural Steel Services Trucking in Meridian, Mississippi, is based on a 40,000 pound (180 kN) load of ductwork panels shipped from Meridian to an unspecified destination 1,000 miles (1,600 km) away. The figures in this table may not apply to all locations, because shipping costs vary due to the requirements of individual states. Figure 10.1 provides critical dimensions for some commonly used shipping trailers. This data may assist the ductwork design team in determining field erection section sizes based on permissible truck shipping lengths and heights.

Rail Shipment

Figure 10.2 shows an example of clearance requirements specified by one rail carrier. For exact limitations on width, length and height, the rail carrier contracted to ship the material should be contacted.

Barge Shipment

Barge shipment allows for shipping very large ductwork sections. However, large sections may require special lifting and handling equipment at the project site. Site laydown area must be adequate for such large pieces.

Having established the shipping method and therefore knowing the field erection dimension constraints, the structural engineer or fabricator can proceed with field splice location and stiffener placement. These field splices should be properly located and denoted on the design or fabrication drawings. See Section 10.1.3 for a discussion on field splices.

10.1.2 Construction Economy

In addition to the shipping considerations discussed in Sections 10.1.1 and 10.7.4, there are several additional factors that are important in arriving at an economical duct design. They are: stiffener shape selection, field construction costs, shop pre-assembly and the project site conditions.

Stiffener Shape Selection

Commonly used stiffener shape profiles are WT-shapes, channels, angles and wide-flange or W-shapes. WTs are derived by splitting a W-shape. This splitting operation will add cost to the fabrication, but maybe not to the overall cost because of material savings. Also, warpage may result when splitting W-shapes to obtain WTs.

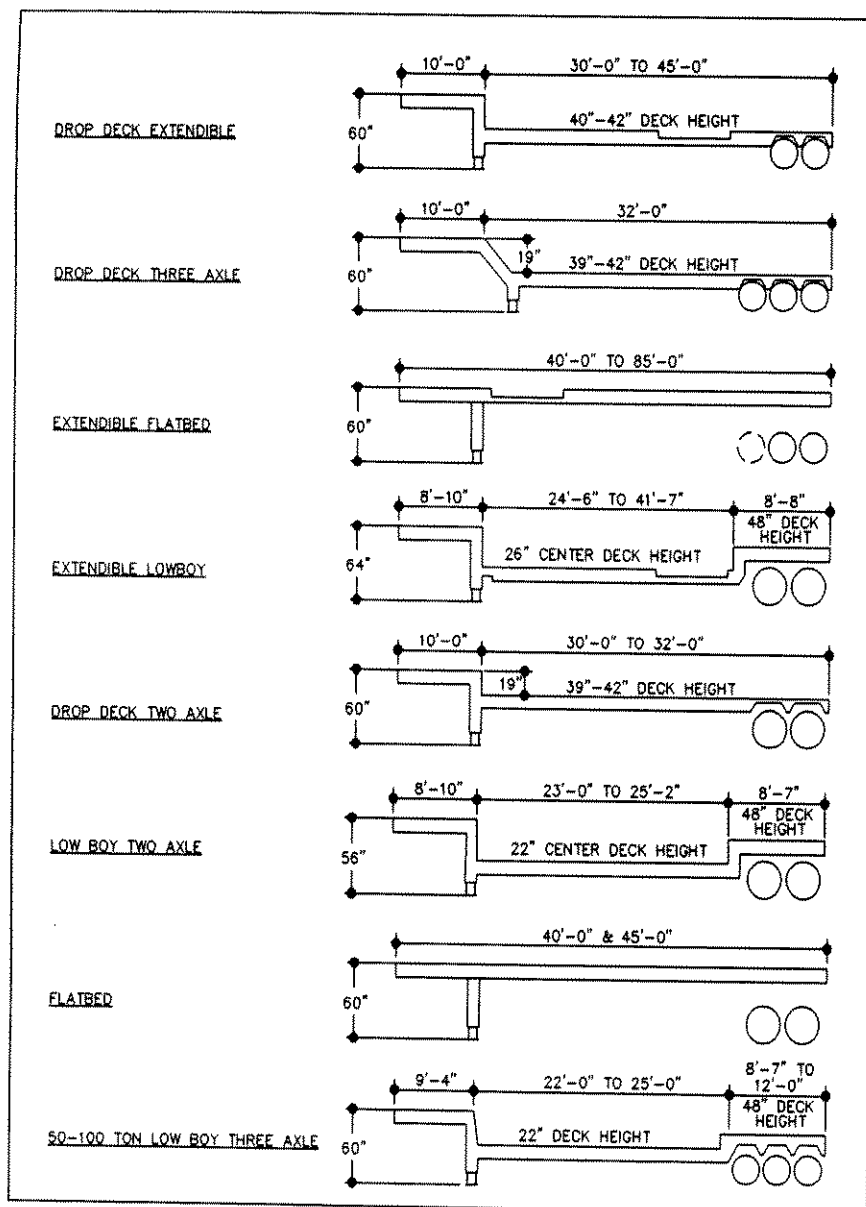


Figure 10.1
Common Shipping Trailer Dimensions

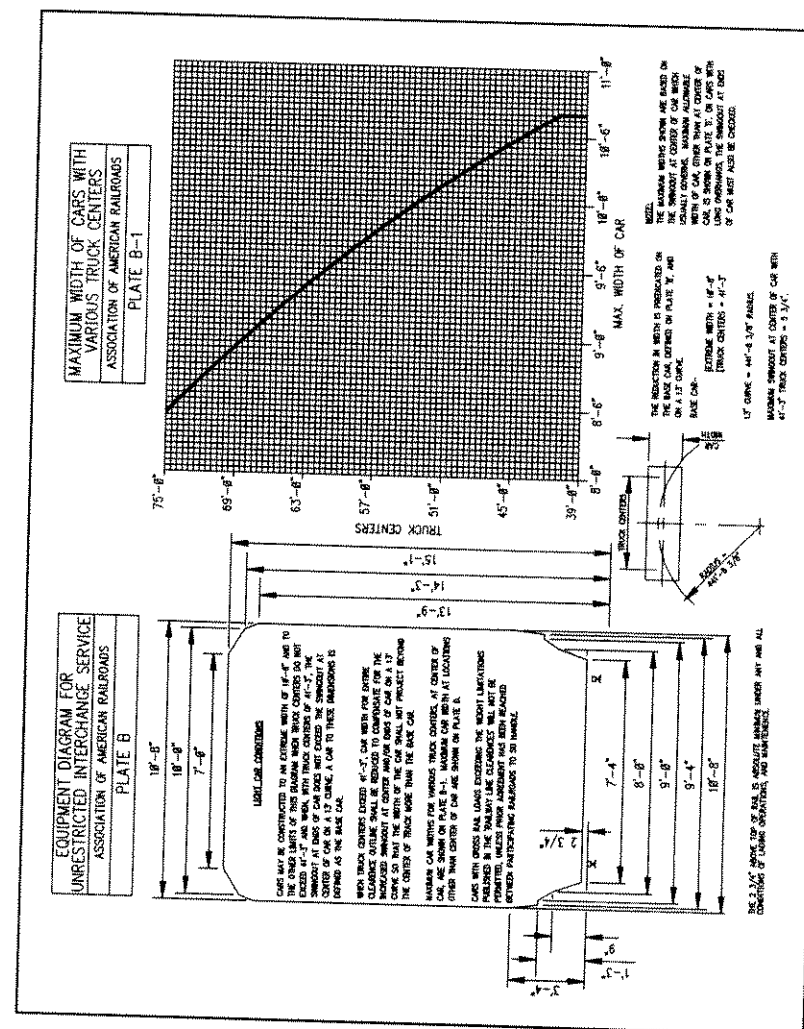


Figure 10.2
Typical Rail Shipping Widths

Circular ductwork is most commonly stiffened by rolled angles or bars. Most fabrication shops are equipped to roll angle shapes, but may have difficulty rolling other heavier shapes. Rolling shapes to small diameters may warp or crack the member or may set up undesirable stresses.

The cost of rolled steel shapes varies. Today, some new steel mills equipped with state-of-the-art equipment can roll selected shapes at prices well below the average market price for rolled shapes. Prices are, of course, subject to change and should be periodically investigated by the structural engineer. The structural engineer should be keenly aware that the profiles selected can and do influence the erected cost of the ductwork being designed. Stress and deflection considerations alone are not the sole criteria for ensuring that the most economical stiffener is selected.

Field Construction Costs

Field construction costs are an important consideration. Unfortunately, it is sometimes difficult during the design stage to obtain comprehensive data relating to site specific field construction costs and, particularly, crane capacity. For many projects, the erection contractor may not be selected at the time the design is started. Thus, data needed to make the proper determination between shop and field fabrication operations unfortunately may not be available. When available, this data should be considered during the design process.

However, historically it has been understood by structural engineers that shop fabrication is less expensive than field construction. In addition to lower costs, operations such as welding, cutting, fitting and handling are inherently of a higher quality when performed in a fabrication shop as opposed to at the project site. Therefore, it is best to specify as much shop work as possible.

Shop Pre-Assembly

Sometimes the physical dimensions of a duct cross-section permit the duct to be partially pre-assembled into box sections in the fabrication shop. Conventionally constructed stiffened panels can be pre-assembled in the fabrication shop to form ductwork sections in various lengths. Shop pre-assembly of ductwork obviously requires more shop labor. Shipping costs are also increased with these larger pieces. However, field labor, which is usually more expensive and of lesser quality, is reduced. Critical construction time can possibly be reduced using extensive shop pre-assembly of ductwork.

When the duct size permits one-piece shop construction of rectangular and circular ducts, the ductwork structural engineer, working with the project leaders, can determine whether box construction or panel construction is best. Considerations include: shop labor cost versus field labor cost, shipping costs for panel construction versus box construction, and potential reduction in the project schedule.

Project Site Conditions

Project site conditions are also an important consideration. Any possible lay-down space constraints should be investigated. Lay-down area and site pre-assembly area can be scarce and should be a factor to be considered in the design. Site equipment capacity and availability are also an important consideration when determining duct component shipping sizes and weight to be delivered and erected at the job site.

10.1.3 Field Splices

Section 10.1.1 discussed the importance of freight cost and the structural design engineer's role in defining ductwork component pieces, particularly the width and height, consistent with the shipping mode chosen for the project. Field splices, also referred to as field joints, commonly occur at ductwork corners and at panel-to-panel joints on rectangular ducts. For circular ducts, field splices occur where duct lengths are joined. Several configurations and arrangements of field splices are used. Not all configurations will be covered here. Commonly, configurations of field joints are dictated by the fabrication and construction techniques to be used on the project. Of course, design stress requirements must also be satisfied.

The structural engineer, working with the fabricator and erector, should agree on the field splice configuration best suited for the project. A common method is for the structural engineer to locate and denote the field splices on the design drawings, thus defining the sizes of the pieces to be shipped. Often the designation "F.J.", for field joint, or "F.S.", for field splice, is used on the drawings to denote the ductwork field splice locations.

Figure 10.3 shows some commonly used field splice configurations for rectangular and circular ducts. The use of a wide-flange profile at the splice, as shown in Figure 10.3A, provides good continuity in the duct plate and facilitates the panel-to-panel fit-up.

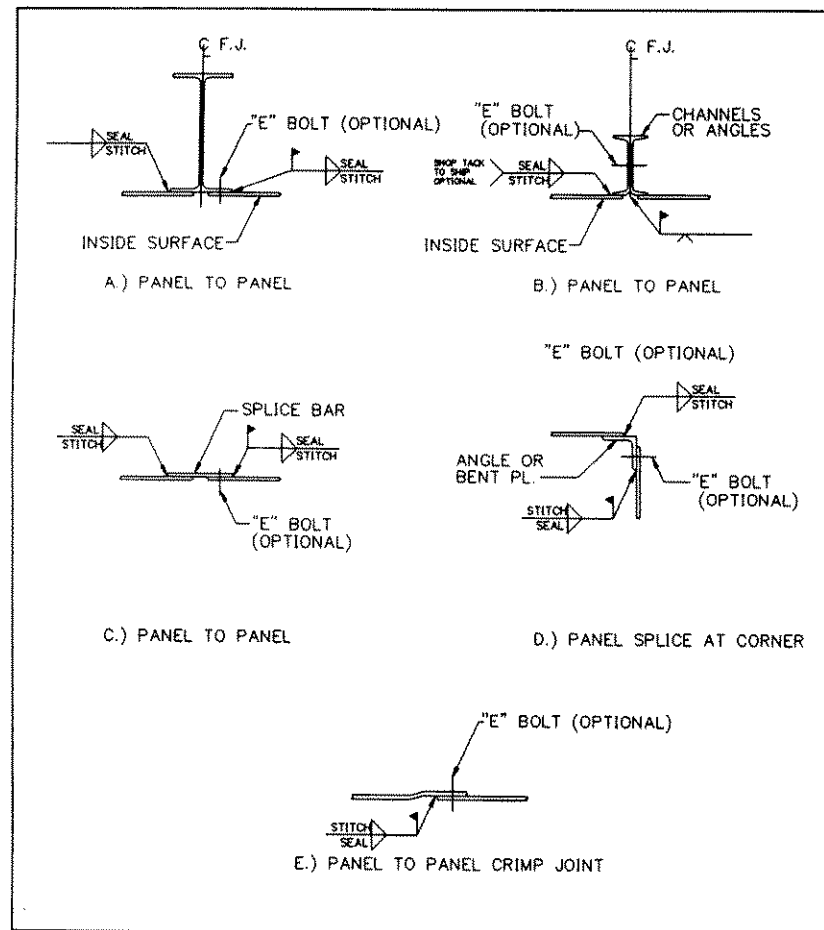


Figure 10.3
Typical Field Splices for Ducts

An "E" bolt - erection bolt - is shown in each detail in Figure 10.3. These bolts allow the erector to pull, fit and hold adjacent panels together without requiring temporary welds and with adding minimal temporary attachments. The bolts can be spaced as required and the structural engineer needs only to designate the bolt material, size and maximum spacing on the design drawings. The fabricator or detailer will locate and dimension on the shop drawings the erection bolt holes required in the panels. Erection bolts are typically 5/8 inch (16 mm) diameter ASTM A307 with a

13/16 inch (20 mm) diameter oversize hole to permit minor adjustment and alignment of the panels. If erection bolts are used, the design drawings should contain a note to the erector clearly stating that the erection bolt is to facilitate fit-up only and is not to be used to set the critical dimensions of the ductwork. Also, the structural engineering should indicate on the design drawings that after installation the erection bolts must be seal welded on the inside of the duct to prevent leakage around the bolt. An alternative is to have the bolts removed and the holes covered or plug welded.

A typical field splice at duct corners is shown in Figure 10.3D. As with all splices, the structural engineer should give consideration to the fabrication and erection operations when selecting the corner splice configuration. Corner splices also can and do play an important role in the transfer of forces in the stiffened panels, as discussed in Section 8.

When joining box sections and circular sections in the field, lap type joint configurations should be avoided. Lap type joint configurations require a duct section to be inserted into the adjacent section in a telescopic fashion. This is a difficult and time consuming operation for the erector. Box sections should be joined using a butt type or flange type field splice like those shown in Figures 10.3. Stiffeners that are shipped loose or only tack welded for shipment may allow for field adjustments during erection.

10.2 DRAWINGS AND SPECIFICATIONS

The ductwork structural design engineer must understand that when preparing ductwork drawings, nothing should be left to the imagination of the fabrication shop personnel. The design drawings, shop drawings and fabrication specifications must convey all necessary information to the fabrication shop. Erection drawings and erection specifications must convey all necessary information to the field personnel.

10.2.1 Drawing Preparation

There are three different ductwork drawing creation processes used to convey this information. The process used is a function of the contract responsibility terms and the preference of the firm responsible for the design.

In the first process, the structural engineer prepares general arrangement type drawings from which the fabricator prepares the

ductwork design drawings and the shop fabrication drawings. In this case, the fabricator assumes more design responsibility. In the second process, the structural engineer prepares engineering design drawings that show all supports, stiffener sizes and framing, and truss framing and member sizes with accurate details and welding symbols. The fabricator may choose to prepare shop fabrication drawings or he may use the engineer's drawings for fabrication by modifying them as necessary. In the third process, the structural engineer prepares detail type drawings. In this case, all of the necessary information for fabrication and erection is conveyed on one set of drawings precluding the need for shop fabrication drawings.

The preparation of ductwork erection drawings is also recommended. These are usually prepared by the same organization that prepares the shop fabrication drawings. Besides piece marks, these drawings can show erection sequence, field fabrication details, lifting restraints, and weights. This information is sometimes shown on drawings as in the third type process described above. If erection drawings are not prepared, critical erection information and restrictions must be placed on the design drawings in a conspicuous manner.

Ductwork Design Drawings

The purpose of ductwork design type drawings, along with the structural engineer's fabrication specification, is to convey all structural design information to the fabricator. These drawings are created from the plant arrangement drawings and are based on structural engineering calculations performed by the responsible structural design engineer.

In the preparation of ductwork engineering design drawings, the following may be considered:

- Usually at least two views of each duct run are provided. A third view sometimes may be necessary to show a complicated duct section.
- The design drawings should be clear as to whether the dimensions are to the exterior or interior of the plate or shapes.
- The work point of all structural members, especially truss diagonals, should be clearly presented.

- All support details should be clearly shown. This includes slide plates, guide bars and anchor points. Special care should be taken to clearly show their proper orientation so that thermal growth problems will not occur.
- Construction materials, type, size and thickness are best shown on each duct section on all drawings.
- All member connection detailing and design information should be clearly indicated. This should include all structural elements and flow distribution devices.
- Required specific welding requirements should be clearly indicated on the design drawings using the welding symbols and procedures specified in *AWS D1.1 - Structural Welding Code, Steel*.
- The structural engineer should consider designing loose expansion joint flanges, cut-to-field-fit sections and other means to allow easier field fit-up of duct sections.

Ductwork Shop Fabrication Drawings

The purpose of ductwork shop fabrication drawings is to convey all structural design information to the fabrication shop. These drawings are created either directly from the owner's specification and plant arrangement drawings based on structural engineering calculations performed by the fabricator's structural engineer or are created from information presented on the responsible structural engineer's design drawings and specification.

In the preparation of ductwork shop fabrication drawings, the following may be considered:

- Usually, all views of each duct run are provided. They are usually true to scale views.
- The drawings should be clear as to whether the dimensions are to the exterior or interior of the plate or shapes.
- Details are best placed on the drawings where they are referenced, as opposed to another drawing.
- Surface preparation and coatings requirements should be clearly marked for the interior and the exterior of each duct section and are best shown on each drawing.

- Construction materials, type, size and thickness are best shown on each duct section on all drawings.
- Required specific welding requirements should be clearly indicated on the drawings using the welding symbols and procedures specified in *AWS D1.1 - Structural Welding Code, Steel*.
- Non-destructive examination (NDE) requirements should be shown on each drawing.
- In general, ductwork fabrication drawings should not only follow industry accepted standards, but also the engineer's and the customer's standards.

Ductwork Erection Drawing

The purpose of ductwork erection drawings is to convey all pertinent erection details to the erector. These drawings are created from the ductwork design drawings and the shop fabrication drawings.

In the preparation of erection drawings, the following information may be shown.

- The proposed erection sequence of all duct sections.
- Lifting points and lifting cautions.
- The location of field splice and the field splice details, including all field welding or bolting requirements.
- Piece marks and markings, usually on at least two places per piece.
- Any special field erection tolerances.
- Duct section or piece weights.

10.2.2 Fabrication Specification

Concise fabrication requirements are necessary to ensure the quality fabrication of ductwork components. It is not always practical to include all such requirements on the design drawings. Therefore, a document commonly referred to as a fabrication specification should supplement the design drawings. The design drawings

should always reference the fabrication specification. They both must be included in the fabrication bid documents and in the erection and construction contracts.

The fabrication specification should include all the fabrication, material and shipping requirements. Additionally, the fabrication specification should reference all of the codes and standards applicable to the fabrication. Special non-destructive testing and examination (NDE) requirements should also be included in this specification.

The following is a list of typical information and requirements that should be included in a ductwork fabrication specification.

- Definitions and Abbreviations
- Scope of Work by the Vendor/Fabricator
- Required Documentation Supplied by the Fabricator
- Work by the Purchaser
- Documentation Supplied by the Purchaser
- Specific Customer/Owner Requirements
- Applicable Codes and Standards
- Materials Specifications
- Fabrication Requirements
- Permissible Shop and Erection Tolerances and Shop Errors
- Shop Connection Requirements
- Field Connection Requirements
- Welding Requirements
- Non-destructive Testing and Examination Requirements
- Cleaning and Painting
- Quality Assurance and Inspection
- Weight Measurement Procedure
- Piece Marking and Identification
- Shipping and Handling Requirements
- Shipping Information

10.2.3 Erection Specification

Concise field fabrication and erection requirements are necessary to ensure the quality field assembly and erection of ductwork components. As with fabrication requirements, it is not always practical to include all such requirements on the design drawings. Therefore, an erection specification may supplement the fabrication specification and the design drawings. The design drawings should reference the erection specification.

The erection specification should include all of the field fabrication, erection, unloading and laydown requirements. The erection specification should also summarize all the codes and standards applicable to the field fabrication and the erection. Special field non-destructive testing and examination requirements should also be included in the erection specification.

10.3 FABRICATION

In a large part, the structural engineer is responsible for the erected product. Specifying fabrication requirements and acceptable fabricated and erected tolerances are ways to help assure a quality ductwork installation. Presented here are ways that the structural engineer can help accomplish this task.

10.3.1 Plate Fit-Up

The structural engineer can aid in assuring the squareness of all duct plate by considering plate fit-up when working on the duct arrangement. This activity is the first step in the assurance that the duct fabrication will conform to the required tolerances.

Plate fit-up should recognize final overall dimensions required, gap spacing for welding required, and acceptable tolerances. Sufficient temporary internal and external braces should be used by the engineer, the fabricator or the erector to insure fabrication and erection to the dimensions indicated on the design drawings, within the acceptable tolerances. Shop and field plate splicing may be performed by many methods as discussed in Section 10.1.3. Care must be taken in the fabrication process to insure proper splice preparation for welding and bolting. This includes edge beveling, back-up bar attachment and match drilling of elements.

Tolerances

- Misalignment between plates at any butt joint should not exceed 33% of the thickness of the thinner plate. When clad plate is used, the maximum misalignment cannot exceed 1/32 inch (1 mm).
- Out-of-square of the rectangular duct cross section should not exceed 1% of the diagonal measurement or 1/2 inch (13 mm), whichever is less.
- Out-of-round of the circular duct cross section should not exceed 1% of duct internal diameter. However, plate

mismatch of adjoining pieces should not exceed 33% of the thickness of the thinner plate.

- Peaking, the deviation from a true circle at the seams, of circular duct seams shall not exceed 1/4 inch (6 mm) as measured by an 18 inch (0.5 meter) long template centered at the weld seam and cut to the prescribed radius.

10.3.2 Fit-Up of Stiffeners, Flanges and Attachments

Close adherence to design drawing requirements for the attachment of stiffeners, equipment flange connections and supports is mandatory since the structural engineer has taken into special account many considerations when locating and designing the stiffeners and the duct supports.

Tolerances

- Stiffeners should be located within 1/4 inch (6 mm) of the location indicated on the design drawing.
- Equipment connection flanges should be perpendicular to the duct plate within 1/2 degree.
- Support brackets, other ductwork attachments and openings should be located within 1/4 inch (6 mm) of the location indicated on the design drawing.

10.3.3 Assembly of Duct Sections

Shop fit-up of adjacent sections must be carefully monitored. Erection using clear fit-up marks is preferred when possible. When this is not done, an extra total dimension check of all dimensions considering tolerances should be performed. The structural engineer should consider designing and showing on the drawings loose expansion joint flanges, cut-to-field-fit sections, and other means to allow easier field fit-up of duct sections.

Tolerances

- For a finished duct section between expansion joints, the total length, width or height dimensions should not deviate by more than 1/4 inch (6 mm) from the dimensions indicated on the design drawings.
- Bowing of completed box duct sections should be limited to 1/2 inch (13 mm) as shown in Figure 10.4.

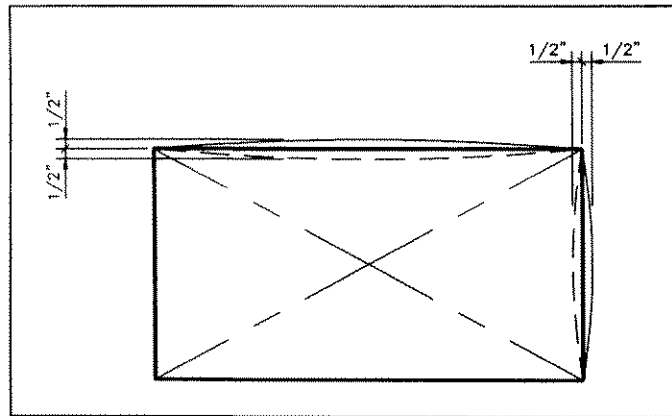


Figure 10.4
Duct Cross Section Bowing Tolerance

10.4 WELDING

Considering all of the operations involved in ductwork construction, perhaps the most critical is the welding. The quality of a completed piece of ductwork can often be judged by the quality of the welding used in constructing the duct section.

Welding processes and methods have improved drastically since the early 1970's. Automated processes are now widely used in fabrication. They provide outstanding quality as well as enhancing productivity. As a rule, ductwork problems associated with welding are rare thanks to today's advanced welding procedures. However, welding problems still occasionally occur in ductwork construction. Unfortunately, the problems are often not detected in a timely fashion and usually show up after the unit goes operational. This can cause unit operation problems. If ductwork welding problems occur, they are usually widespread and very costly to correct.

Welding is a science, a highly specialized science. Today's welding processes and procedures can be complex. A ductwork structural engineer should not assume the role of welding engineer. When dealing with unusual materials, extreme service temperatures, and other unusual design parameters which affect welding, experts should be consulted. Some firms have welding or metallurgy experts on staff available to assist the duct design engineer in the design process. If welding consultants are available and utilized, they can preclude expensive welding repairs and the delivering of sub-standard ductwork to the customer.

However, the ductwork structural design engineer needs to have a general knowledge about welding. Some familiarity with welding processes and electrode materials is essential. The structural engineer must also have a sound understanding of AWS welding symbols. One of the foremost challenges for the structural engineer is to design accessible welded joints which are structurally adequate and economical to construct. Without knowledge of the welding process, the structural engineer may locate weld joints and configure them in such a way that allows limited access. The resulting welds are usually of poor quality and inefficient.

10.4.1 Welding Codes and Standards

Two organizations provide welding requirements which cover welding of most ductwork. They are the American Welding Society (AWS) and the American Society of Mechanical Engineers (ASME). Individual company welding standards are sometimes used to supplement the requirements set forth by AWS and ASME.

AWS - American Welding Society

The American Welding Society provides the necessary welding requirements for most ductwork applications. Specifically, *AWS D1.1 - Structural Welding Code, Steel* is available as a comprehensive guideline for achieving quality welding. Ductwork intended to be welded by the requirements of AWS should specifically reference AWS D1.1 in the ductwork drawing package.

ASME - American Society of Mechanical Engineers

The American Society of Mechanical Engineers provides the *ASME Boiler and Pressure Vessel Code, Section IX - Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators*, which covers welding of metal products such as ductwork. Welding requirements of ASME Section IX are considered to be generally more stringent than those of AWS. Many fabrication shops are not certified to do ASME welding and would thus not be qualified to fabricate ductwork requiring ASME Section IX welding. The same is true for many erectors. Thus, the structural engineer choosing ASME Section IX welding should be cognizant of the potential of restricting the choice of fabricators and erectors for the project. Requiring ASME Section IX welding can potentially impact the project cost.

Manufacturer or User Company Welding Standards

Often, specific welding requirements are delineated in the owner's or the ductwork structural design engineer's welding standard. Many companies that work extensively in the ductwork field have

such standards. These standards supplement the primary welding document which may be the AWS or ASME code as mentioned above. Where company standards are used, they must be included as a part of the project contract documents issued to the fabricator and erector. A company's welding standard may stipulate any special documentation requirements on a project. For example, welder qualification, weld procedure qualification, and additional weld inspection and testing may be required of the fabricator and erector by the owner. Special weld non-destructive examination (NDE) requirements not usually specified may also be in the company's standards. The use of these standards can potentially impact the project cost and schedule, so they should only be used when required and with the permission of the owner.

10.4.2 Types of Welding Processes

By far, the most commonly used method of welding carbon steel ductwork is the manual shielded metal-arc welding (SMAW) process. This process is commonly known as stick-rod welding. Field welding is performed primarily with the SMAW process. To enhance productivity and weld quality, fabrication shops commonly use automated processes such as submerged arc welding (SAW), flux cored arc welding (FCAW), and gas metal arc welding (GMAW). These welding processes have specific applications too numerous to mention here. The AWS provides an introduction to and detailed explanation of these various welding processes in its publication, *AWS Welding Handbook - Vol. 2, Welding Processes*.

Most of the common welded joints applicable to carbon steel ductwork design are prequalified. By definition, they are exempt from testing and qualification. AWS prequalifies weld joints based upon experience that sound weld metal with appropriate mechanical properties can be deposited. Prequalified welded joints should always be used, except in very unusual circumstances where unique conditions prevail. In general, all fillet welds are deemed prequalified provided they conform to the AWS D1.1. Prequalified joints are limited to those made by the manual shielded metal arc, submerged arc, gas metal arc and flux cored arc welding processes. AWS D1.1 should be referenced for specific welded joint and weld process information.

10.4.3 Welding Electrodes

For the various welding processes available, many electrode types and sizes can be used for welding ductwork. Chapter 2 of the

American Institute of Steel Construction's *Manual of Steel Construction, Volume II - Connections* provides illustrations of the classification system for electrodes used in the various welding processes.

The structural engineer need not specify the electrode type to be used for most welding of mild carbon steel. The fabricator and the field erector will select the electrode suitable for the welding application to be used. The structural engineer should specify the electrode to be used when welding ductwork joints made from materials other than mild carbon steel or when strength is an issue. Quite often the structural engineer will base the design on a 70 ksi electrode. If this is the case, a 70 ksi electrode must be specified so that a 60 ksi electrode is not used in the construction.

In addition to selecting the correct electrode for a particular application, electrode storage and handling are critical to weld joint quality. The electrode material must remain dry and clean prior to its use. Fabricators and erectors should have a welding consumable procedure included as a part of their quality program. This procedure should include descriptions for shipping containers, receiving inspection, storage of electrodes and storage containers, baking and redrying, and the disposal of contaminated electrodes.

10.5 SHOP INSPECTION

Periodic shop inspections by the customer and the structural engineer should be performed during the fabrication process. The inspection schedule should be agreed to at the beginning of the work and it should be maintained. The fabricator's own shop inspection should be an ongoing effort on a daily basis. Some fabricators have implemented Total Quality Management processes as a method of enhancing the quality process. ISO 9000 quality certification is also fast becoming a method of ensuring quality in manufacturing processes in the United States. The owner may sometimes require the fabricator to be ISO 9000 certified.

At a minimum, the following items should be included in the inspection.

- **Weld Quality**

The specified welding requirements (AWS, ASME or other) must be followed. Industry accepted standard weld quality inspection procedures for the specified welding methods and procedures should be used. The fabrication specification or ductwork drawings should state weld inspection criteria required above the minimum criteria given in the applicable welding specification.

- **Dimensions**

Dimensions should be verified. Specified tolerances as shown on the design drawings, in the fabrication contract, and as indicated in this design manual should be used.

- **Material**

Material purchase orders and mill material test reports should be reviewed for compliance with the project specifications.

- **Fabricator's Records**

The fabricator's inspection records should be available for review.

10.6 SURFACE PREPARATION

Since most ducts are fabricated from some grade of carbon steel, a surface protection following fabrication is sometimes recommended regardless of the final specified surface treatment. The surface protection can vary depending on the surface to be protected and the field applied final coating. This is discussed further in Section 3.7.2.

- **External Surfaces**

Degreasing, weld splatter removal and the general removal of fabrication debris is recommended as the minimum surface preparation. A subsequent coat of primer paint can be applied to deter surface corrosion during shipping and storage. Sometimes it is desirable to shop apply a coating in accordance with a the Steel Structures Painting Council (SSPC) surface preparation procedure SP 6, *Commercial Blast Cleaning*. Special duct attachments such as instrument port flanges should be greased, coated, covered or otherwise protected before the duct section leaves the fabricator's shop.

- **Internal Surfaces**

In addition to the treatment discussed above for external surfaces, special treatment for internal duct surfaces is often specified for heat or corrosion protection. Supports for linings are often shop applied. Before the duct leaves the shop, the fabricator must take care to protect the internal surfaces and surface shop preparation against possible damage or contamination in transit.

- **Stainless Steel**

External and internal surfaces of stainless steel and high nickel alloy ducts should be passivated (acid wash followed by neutralizing) in the shop prior to shipment to clean the surfaces of iron contamination.

10.7 HANDLING AND SHIPPING

The proper handling and shipping of ductwork is the responsibility of either the fabricator or the erector, depending on the project specific agreed upon scope of services. However, the ductwork structural design engineer should be aware of proper handling and shipping methods and requirements and traditionally successful methods and procedures.

10.7.1 Piece Marking

The fabricator must clearly mark each piece, assembly, and sub-assembly with an erection and shipping mark number. The same mark numbers should be clearly shown on the erection drawings. Only those pieces that are shipped independent of other pieces should receive an erection and shipping mark number.

Each fabricator should have a written procedure for marking. This procedure may be requested from the fabricator and reviewed by the customer and the structural engineer. The procedure for marking should stipulate that the mark number be tied to the detail drawing number on which the piece is detailed and the section of ductwork that the piece will become a part of. This enables field personnel to quickly tie the piece to its detail drawing and to its duct section for storage and erection sequencing.

Mark numbers should be applied to the components with high-visibility durable paint in the most conspicuous location. The size of mark should be such that it can be read easily. Preferably, each individual piece should have at least two identical marks on opposite surfaces.

10.7.2 Lifting Lugs

Lifting and handling of large ductwork components or completed assemblies usually requires lifting devices. When ductwork is shipped preassembled in relatively large sections, handling can be difficult and the inclusion of lifting lugs on the duct sections is a necessity.

The ductwork structural design engineer should always work with the fabricator and erector to determine the requirements for lifting lugs. The type of equipment used in handling the large duct pieces and the lifting procedures are important variables in determining the need for lifting lugs and in sizing the lugs. Without input from the parties doing the actual lifting of the pieces, the structural

engineer risks placing the lugs in the wrong location. However, the design drawings can indicate suggested locations for field applied lifting lugs or points of lift. Precautions concerning specific inappropriate handling should be clearly noted on the design drawings and in the fabrication specification. A construction impact factor of 1.5 is considered appropriate for design.

Sizing of lifting lugs is a fairly simple procedure. Chapter D3 of the *AISC Specification for Structural Steel Buildings - Allowable Stress Design and Plastic Design (ASD)* addresses the design of pin connections. It provides a conservative method of determining the size of lugs. The most important steps in the process are to determine the lug material and the design load for the lug. To account for lifting impact effects, the design load should be increased by a factor of 50%. An article in the *AISC Engineering Journal*, Second Quarter of 1974, entitled *Experimental Investigation of Lug Stresses and Failures*, by R. N. Tolbert and R. M. Hackett, provides a good explanation of lug behavior and the various stresses associated with lugs.

10.7.3 Temporary Bracing

The fabricator who ships the ductwork components is also responsible for any temporary bracing required for shipping. Components must be adequately braced during shipment such that they arrive at the project site undamaged and still within tolerance. In addition to shipping temporary bracing, site handling often requires temporary bracing to stabilize the duct section and preserve its shape during erection. The obligation of the fabricator to provide this bracing should be clearly stated in the contract documents in the form of a drawing note or in the fabrication specification. The structural engineer may be called upon to assist the erector in determining the bracing needs.

Circular ducts have a special sensitivity to transportation and handling because of the large potential for plate buckling. When shipped in one piece as a cylinder, provisions for analyzing and designing circular ducts for impact due to shipping and handling should be considered. These provisions would apply to the duct supports, bracing, elements and the plate.

Temporary bracing required for shipping should be marked by the fabricator in such a way that the receiving party will clearly know that the bracing is not permanent and is to be removed after erection is completed. One way to accomplish this is by coding

temporary pieces with a special color paint marking. Occasionally, temporary bracing requirements may be shown by the structural engineer on the design drawing for very large pieces or pieces with critical dimensional tolerances. Figure 10.5 shows suggested temporary bracing schemes.

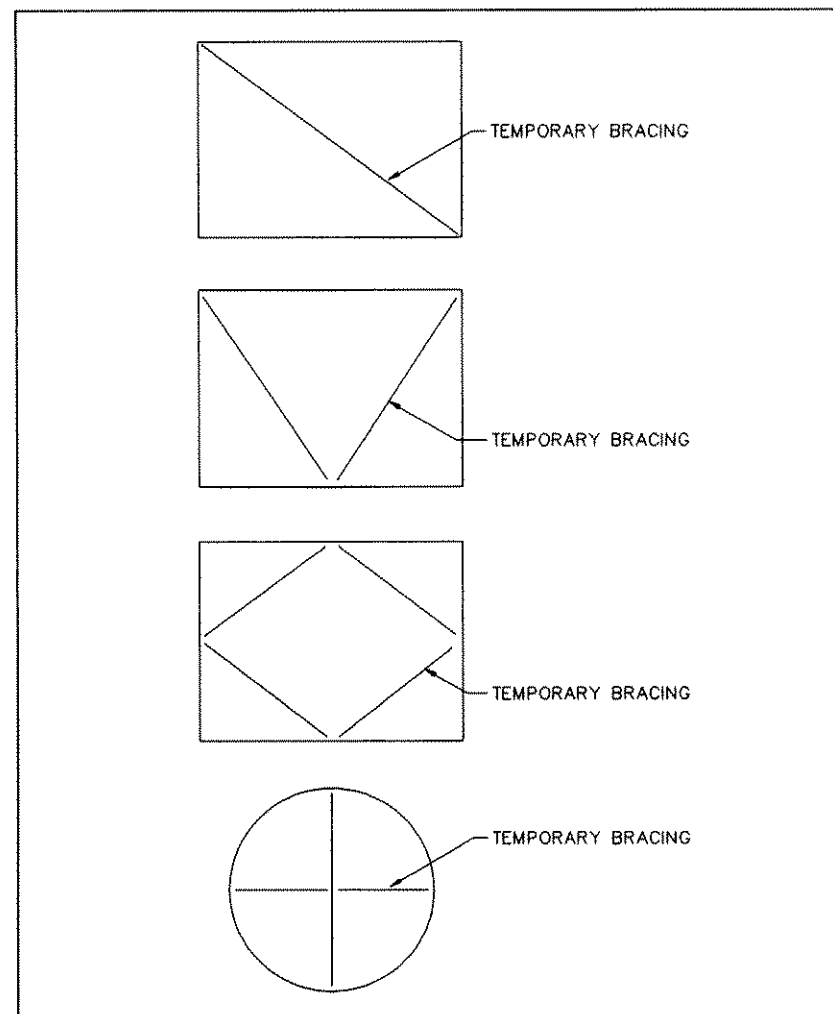


Figure 10.5
Typical Temporary Bracing Schemes

10.7.4 Loading, Receiving and Unloading

The shipping party, usually the fabricator, is responsible for loading the ductwork components onto the carrier's transport media. He must supply all cribbing and dunnage necessary to position the items securely on the media. Tie-downs, turn buckles, and come-alongs are usually supplied by the carrier. If the load is specified to be covered, the carrier must supply the covering.

The carrier's representative, usually the truck driver for truck shipment, must inspect the loaded vehicle and must be satisfied that the load is properly secured. A shipping bill should be prepared by the shipper listing all of the loaded components. This shipping bill should always accompany the shipment. When satisfied with the load, the carrier's representative signs the shipping document and the carrier then assumes responsibility for the load until its arrival at the project site.

Receiving and unloading is the responsibility of the owner, erector, or other authority assigned by the owner to receive the material. Upon receipt, the receiver should carefully inspect the material. The inspection should include a check to ensure all quantities of material are correct as shown on the shipping bill. Accordingly, if any shortage is identified, the receiver should immediately notify the carrier and the fabricator so that the claim may be investigated.

If materials arrive at the destination in a damaged condition, it is the responsibility of the receiving party to notify the customer, fabricator and carrier prior to unloading the material.

10.8. ERECTION

As with fabrication, handling and shipping requirements, the ductwork structural engineer should be aware of proper erection methods and requirements and traditionally successful methods and procedures. Specifying erection requirements and acceptable erected tolerances are ways to help assure a quality ductwork design. Here are some erection consideration for the structural engineer.

10.8.1 Erection Sequencing

Since ducts are designed as structural members spanning support points, proper sequencing for safety should be followed. The structural engineer should note any special erection sequencing requirements and any necessary precautions on the design drawings.

10.8.2 Special Erection Considerations

Temporary Bracing and Supports

The erector should design and furnish any temporary braces or supports required for the erection. This position is taken from Chapter M4 of the *Specification for Structural Steel Buildings - Allowable Stress Design and Plastic Design (ASD)* and the *AISC Code of Standard Practice*. The obligation of the erector to provide this bracing should be clearly stated in the contract documents in the form of a drawing note or in the erection specification. Any erection temporary braces or supports should be removed as soon as practical, and definitely before the duct is insulated and the system goes into service.

The structural engineer may be called upon to assist the erector in determining the bracing needs. Occasionally, temporary erection bracing requirements may be shown by the structural engineer on the design drawing for very large pieces or pieces with critical dimensional tolerances. Figure 10.5 shows some suggested temporary bracing schemes.

Field Welding

The specified field weld designation, procedures and welding material should be followed explicitly by prequalified welders provided by the erector.

Field Modifications

During erection of duct systems, some field modifications sometimes must be made to shop fabricated components or assemblies because of errors in fabrication or actual field dimensions that differ from the design information. Any field modifications should be approved by the structural engineer responsible for the duct design or the engineer's field representative prior to making the modification. The structural engineer may have a good reason to choose an alternate modification in lieu of the choice selected by the erector. Any field modifications performed should be properly documented by the erector in the final job records and ultimately clearly indicated on the engineer's design drawings.

Coating and Lining Repairs

Shop applied coating and lining should be repaired at field joints and areas of erection damage. These affected areas should be restored by the erector to the originally specified quality.

Inspection

Erected duct systems should be inspected for compliance with the design and fabrication drawings. Verification should include: location, dimensions, support clearances, proper bolting and welding, proper attachment of accessories, proper setting of slide bearing plates and guides, and cold position expansion joint setting. Pressurized duct systems should be inspected for gas tightness by some method such as sonic testing or vacuum box pressure testing using soap or smoke. These testing requirements should be in the erection specification.

Erection Tolerances

The tolerances presented in Section 10.2 should also apply to erection. In addition, the length dimension of an erected duct section should not deviate more than 1/2 inch (13 mm) from the dimensions shown on the design drawings. At expansion joints and dampers, all duct locations and dimensions should not deviate more than 1/2 inch (13 mm) from the design.

SECTION 11

Insulation and Lagging

	<u>Page</u>
11.1 INTRODUCTION	243
11.2 PURPOSE OF INSULATION AND LAGGING	243
11.2.1 Thermal Efficiency	243
11.2.2 Corrosion Prevention	244
11.2.3 Personnel Protection	244
11.2.4 Protection Against Water	244
11.2.5 Reduction of Steel Temperature in Very Hot Ducts	244
11.2.6 Sound Attenuation	245
11.3 TYPES OF INSULATION AND LAGGING	245
11.3.1 Insulation	245
11.3.2 Lagging	247
11.4 AFFECTS OF INSULATION AND LAGGING ON THE STRUCTURAL DESIGN OF DUCTS	247
11.4.1 Layout Considerations	247
11.4.2 Duct Design Considerations	248
11.4.3 Dead Load Determination	248
11.4.4 Wind Load Determination	248
11.5 METHODS OF INSTALLATION AND QUALITY OF THE WORK	249
11.5.1 Construction Details	249
11.5.2 Installation Methods	249
11.6 CONSTRUCTION DETAILS	253
11.6.1 Insulation Across Expansion Joints	253
11.6.2 Insulation Around Hoppers	255
11.6.3 Insulation Around Duct Appurtenances	256
11.6.4 Attachment of Lagging	256
11.6.5 Subgirts	256

SECTION 11

Insulation and Lagging

11.1 INTRODUCTION

The design and specification of insulation and lagging is usually the responsibility of the project mechanical engineer. However, there are several aspects of insulation and lagging which have a bearing on the ductwork structural design. Also, it is beneficial for the structural engineer to be familiar with the materials and methods of installation for insulation and lagging.

11.2 PURPOSE OF INSULATION AND LAGGING

Ducts in power plants and similar installations can carry very hot air and flue-gas. Gas temperatures can range up to 1,100°F (600°C). The main purposes of insulation and lagging are for thermal efficiency, corrosion prevention, sound attenuation at fan outlets, personnel protection, and keeping water off of the hot duct steel. Additionally, in high temperature gas turbine exhaust ducts, internal insulation is used to protect the steel from the metallurgical effects caused by exposure to the very high temperature gas.

Sometimes air ducts are not insulated and lagged. Insulation is often not required for ambient air ducts because the system temperature is not a problem for the duct, the flow or personnel. Also, quite often scrubber outlet ducts are not insulated and lagged. In either case, the engineer should consider protecting the duct steel against the environment with some sort of coating. This is discussed in more detail in Section 3.7 and Section 10.6.

11.2.1 Thermal Efficiency

Duct insulation helps maintain the hot temperature of air and flue-gas and, thus, the overall thermal efficiency of the unit. The efficiency of boilers, and thus the unit, is dependent in part on the

temperature of the air and flue-gas in the ductwork system. Therefore, the ductwork must be very well insulated so that the minimum amount of heat is lost through the duct system.

11.2.2 Corrosion Prevention

Another purpose for duct insulation is to prevent corrosion of the duct steel. Depending on the dew point of the flue-gas, corrosion can occur at relatively low temperatures in flue-gas ducts. This dew point temperature can be as low as 200°F (90°C). Corrosion is caused when water vapor in the flue-gas combines with sulfur from the coal or oil ash and forms sulfuric acid. Over time, this acid will corrode the duct casing. Generally, unless the steel duct plate is properly protected or fabricated from a corrosion resistant material, the duct steel plate temperature should be kept above the dew point of the flue-gas. This is an important function of the insulation.

11.2.3 Personnel Protection

A third reason to provide ductwork insulation and lagging is as a barrier for personnel protection. Although the above two factors generally control, the exposed exterior of ducts must be kept at a low enough temperature so that it is safe for plant workers to touch. This temperature is specified as 140°F (60°C) in ASTM C-1055, *Standard Guide for Heating System Surface Conditions That Produce Contact Burn Injuries*.

11.2.4 Protection Against Water

The greatest external cause of damage to duct steel is prolonged exposure to water. Very hot duct plate can buckle and crack from thermal shock if exposed to cool water on one side and hot flue-gas on the other side. Standing water on the top of a duct can also cause accelerated corrosion. If the insulation gets wet, it can act like a sponge and retain water for a long time. This only further accelerates the corrosion process. Keeping water away from the duct steel and the insulation is the most important function of the lagging.

11.2.5 Reduction of Steel Temperature in Very Hot Ducts

Carbon steels undergo metallurgical changes when exposed to temperatures in excess of 750°F (400°C). Most of these effects can be considered in the design and/or by the choice of steel to be

used. Once the temperature gets above 1,000°F (540°C), the penalties associated with the high temperature raises the cost of the duct considerably. Either high priced alloy steel or carbon steel with low allowable stresses must be used. Because of the low allowable stress, the use of carbon steel would cause the ducts to be very heavy and thus expensive.

To make carbon steel an economic option, high temperature gas turbine exhaust ducts typically have internal insulation to protect the duct steel from the metallurgical effects caused by exposure to the very high temperature gas. This insulation method lowers the duct steel design temperature to a reasonable level so that the steel's performance will not be adversely affected.

11.2.6 Sound Attenuation

The large fans associated with power stations and industrial boilers can be very noisy. Because of this, silencers are often located on the inlet side of some fans. Less frequently, mufflers are sometimes installed within fan outlet ductwork. However, the pressure losses associated with mufflers usually make their use unacceptable. Insulation and lagging will also reduce the sound coming from fans through the ductwork.

11.3 TYPES OF INSULATION AND LAGGING

Insulation may be applied to the inside or outside of ductwork and must be asbestos free. Today, externally applied insulation covered with lagging is most commonly used.

11.3.1 Insulation

There are a multitude of materials which are used as external duct insulation. The most commonly used insulation materials are as follows.

Inorganic Glass Fiber

Inorganic glass fiber is an external insulation that is normally used for temperatures up to 850°F (450°C). Its temperature range is dependent on its resinous binders. The material is supplied in various sizes in semi-rigid boards or blankets from 1 to 4 inches (25 to 100 mm) thick.

Non-Combustion Wool

Non-combustion wool insulation is produced from mineral fibers. It is an external insulation that can be used for temperatures up to

1,000°F (540°C). It is supplied in various size batts from 1 to 4 inches (25 to 100 mm) thick.

Insulating Mortar

Ductwork installations of 25 or more years old were commonly insulated internally. This process involves applying a mortar or sand aggregate concrete insulation by a method commonly known as "shotcrete" or "gunite" to the internal duct plate. The standard practice is to apply a 2 to 6 inches (50 to 150 mm) thick layer of mortar over wire mesh. This reinforced mortar is anchored to the duct by studs welded to the plate. This insulation method would normally only be used today at the client's request, to match an existing condition or to protect the duct steel plate against harsh flue-gas. There are several reasons why this method is no longer commonly used. It is much heavier than fiberglass or mineral wool and is more expensive to install. This adds to the cost of the duct and its support structure. Mortar insulation also can contribute to corrosion by trapping moisture and acid between the mortar and the duct plate when cracking of the mortar occurs. History has shown that internal mortar has a tendency to crack and will not always adequately protect the duct plate after a few years of service. However, manufacturers have recently developed protective membranes which are spray applied to the duct plate and then top coated with mortar by shotcreting or guniting. This method provides steel corrosion protection plus insulating value and it protects the protective membrane from abrasion.

Ceramic Fiber

Ceramic fiber insulation is often applied internally, typically in very high temperature gas turbine exhaust ducts. It is supplied in various thicknesses up to 6 inches (150 mm). Ceramic fiber is usually covered by thin gauge stainless steel internal lagging to protect it from the flue-gas. The stainless steel lagging is attached in such a manner so that it can expand with increasing temperature. A rigidizer coating is available to resist erosion of the ceramic fiber.

Refractory Lining

Refractory lining is a high temperature internal lining which is available for use in ducts with operating temperatures above 1,000°F (540°C). It may also be used where a gas or oil fired burner is installed inside of a duct or in circulating fluidized-bed gas ducts. Refractory lining is not commonly used in lower temperature ductwork.

Borosilicate Block

Borosilicate block internal insulation is another relatively new product. It provides an acid resistant surface and also provides insulating value. It is installed similar to a brick or refractory lining. When using this material for acid protection, the proper acid resistant adhesive must also be used.

11.3.2 Lagging

Lagging is the covering used to protect insulation. External lagging protects the insulation from weather, especially wind and rain. Therefore, external lagging must be constructed from a material that is resistant to weather. Internal lagging must protect the insulation from the abrasive effect of the high velocity flue-gas. Light weight material is usually used for lagging to reduce the overall duct weight, reduce the cost of the lagging, and for ease of construction. The most common materials used for lagging are aluminum, fiberglass reinforced plastic (FRP) and galvanized, coated or stainless steel. Lagging is commonly supplied in corrugated sheets to provide some rigidity in handling and so it can more efficiently carry externally applied loads such as laydown loads, wind and foot traffic. For ease of construction, flat sheets of lagging are sometimes used for circular or irregular shaped ducts and in areas of tight clearance.

11.4 AFFECTS OF INSULATION AND LAGGING ON THE STRUCTURAL DESIGN OF DUCTS

The type and thickness of insulation and lagging should be determined early in the ductwork design process. The insulation should be chosen by the mechanical process engineer. Both the mechanical process engineer and the structural engineer should have input to the design of the lagging. Information regarding the insulation affects certain aspects of the structural design of the ductwork.

11.4.1 Layout Considerations

The sizing, layout and routing of a duct system must take into consideration the projected thickness of the insulation and lagging all around the duct in order to allow for proper installation of the insulation and lagging without any interference from adjoining equipment or structural steel. The top of horizontal duct lagging surfaces should be pitched to divert rain water. Gutters and downspouts attached to the duct lagging are also sometimes used to channel water away to proper areas.

11.4.2 Duct Design Considerations

In the early stages of the duct layout and structural design, the structural engineer must obtain from the mechanical engineer the type and thickness of insulation and lagging being specified for the ductwork. If the ducts have external stiffeners, the structural engineer should size the stiffeners on each duct panel to be of a uniform depth provided an economical duct design can be achieved. This will make it much easier and less costly to install a uniform thickness of insulation and lagging over the stiffeners. This approach is shown in Figure 11.2.

The project team may request that the structural engineer specify the thickness and profile of the lagging. The structural engineer would then design the lagging for the appropriate spans, the expected live load, and the proper snow and wind loads. More typically, the loading requirements are included in the lagging procurement specification and the thickness, profile and support requirements would be determined by the insulation contractor.

11.4.3 Dead Load Determination

The structural engineer must include in the dead load calculations the weight of insulation, lagging, and their attaching systems, if any. This attaching system is usually referred to as subgirt framing or stand-offs. The average density by volume of fiberglass insulation varies from 3 to 6 pcf (48 to 96 kg/m³), while mineral wool may go up to 12 pcf (190 kg/m³). Lagging weights vary from 0.5 psf to 1.0 psf (24 to 48 kg/m²) for aluminum, 0.5 to 0.75 psf (24 to 36 kg/m²) for fiberglass, and 1.5 to 3 psf (72 to 144 kg/m²) for steel. These ranges are dependent on the thickness of the lagging material. The weight of the attaching system is included in these figures. Should mortar or sand aggregate concrete be utilized as internal insulation, the approximate weight is 12.5 psf per inch (235 kg/m² per cm) of thickness. Borosilicate block weighs 1.5 psf per inch (30 kg/m² per cm) of thickness.

11.4.4 Wind Load Determination

The wind load on the ductwork sections must be calculated based on the overall outside dimensions of the duct plus external stiffeners plus the insulation and lagging. This additional area of insulation and lagging outside of the stiffeners can vary from 2 inches (50 mm) to as much as 9 inches (230 mm). When installing these cantilevered sections of insulation and lagging, the contractor

must make sure that the wind conditions are considered.

When designing the lagging and its attachments for wind load, local parts and portions wind effects as specified in the publication ASCE 7-93, *Minimum Design Loads for Buildings and Other Structures*, must be considered. If the lagging is designed by the supplier, the structural engineer should insist in the procurement specification that this reference be followed.

11.5 METHODS OF INSTALLATION AND QUALITY OF THE WORK

Insulation and lagging construction and installation methods and details are, in general, determined by the insulation and lagging supplier or contractor. Because the insulation and lagging is so important in protecting the duct steel, the structural engineer should review the contractor's installation methods and details. Any failure of the insulation and lagging to protect the duct could affect the performance of the duct steel and the structural integrity of the ductwork.

11.5.1 Construction Details

When the installation details are prepared by the contractor, there are three important installation requirements that the structural engineer should specify.

- A continuous and a uniform thickness of insulation should blanket the entire duct exterior in accordance with the specification and proper installation practice.
- The insulation should cover the entire exterior faces of all steel stiffeners so that minimum thermal gradients will be created.
- The insulation around expansion joints and their frames should be installed in accordance with the expansion joint manufacturer's recommendations or requirements.

11.5.2 Installation Methods

There are many methods for installation of insulation and lagging. Some typical methods are discussed here. Some of these methods may be used for either shop or field installation. These are only illustrative in nature since many contractors may have developed their own acceptable methods.

External Insulation Applied Directly to the Duct Plate

The installation of external insulation applied directly to the duct plate is shown in Figure 11.1. For this method, installation is usually performed in the following manner.

- Metal pins are welded directly to the duct plate.
- The insulation boards are impaled over the metal pins and are held in place with metal clips, sometimes called speed clips, which fasten onto the pins. If blanket-type insulation is used, it is usually held in place over the pins with a layer of wire mesh.
- The lagging is applied over the insulation and is fastened to the clips.

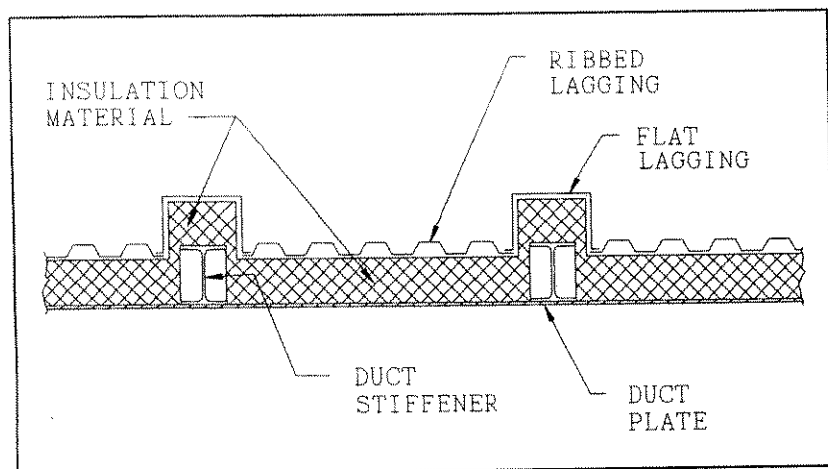


Figure 11.1

Typical External Insulation Attached to the Duct Plate

External Insulation Applied to a Subgirt System

This installation method is shown in Figure 11.2. When the insulation and lagging is installed onto a subgirt system over the external stiffeners, installation is usually performed in the following manner.

- Light gauge metal subgirts are attached to the external stiffeners, usually by welding. The subgirt size and spacing

is dependent on the structural properties of the subgirts and the lagging in resisting wind, snow and live loads.

- The insulation batts are placed between and are supported by the subgirts. The insulation sometimes is held in place over the subgirts by a layer of wire mesh.
- The lagging is installed over the insulation and subgirts and is fastened to the subgirts, usually by screws.

When this installation method is used for hot ducts, the space between the duct side wall and the insulation allows a "chimney effect" up the sides of the duct which may drive the temperature of the lagging at the top of the duct beyond the specification requirements. This effect could also cause hot air to escape from the lagging at the top edges of the duct, which could cause personnel safety problems.

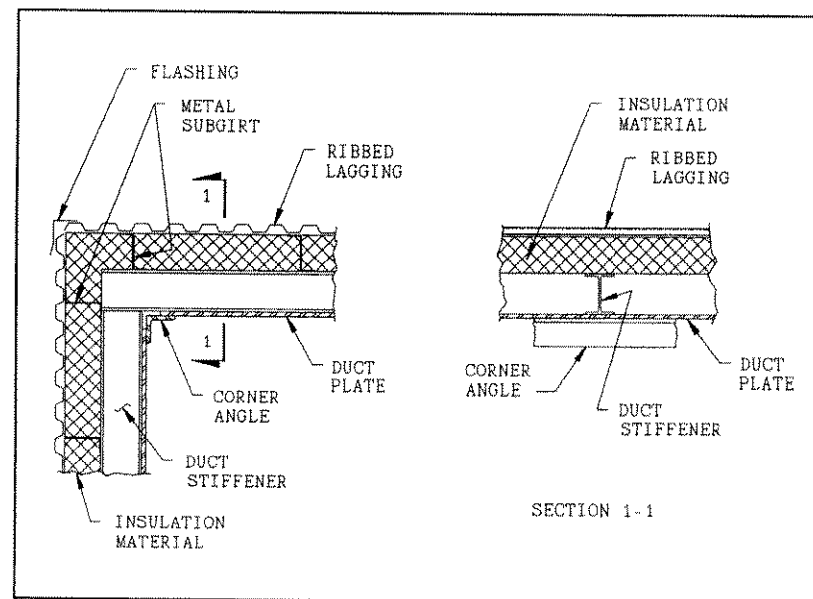


Figure 11.2

Typical External Insulation Attached to Duct Stiffeners

Internal Mortar or Refractory Insulation

This method is shown in Figure 11.3. When the mortar insulation is installed internally, it is usually installed to the duct plate in the following manner.

- Studs or anchors are welded to the interior duct plate.
- The inside surface of the duct plate is sandblasted.
- A protective membrane is applied.
- Refractory or sand aggregate mortar is applied to the surface to a depth of 2 to 6 inches (50 to 150 mm).

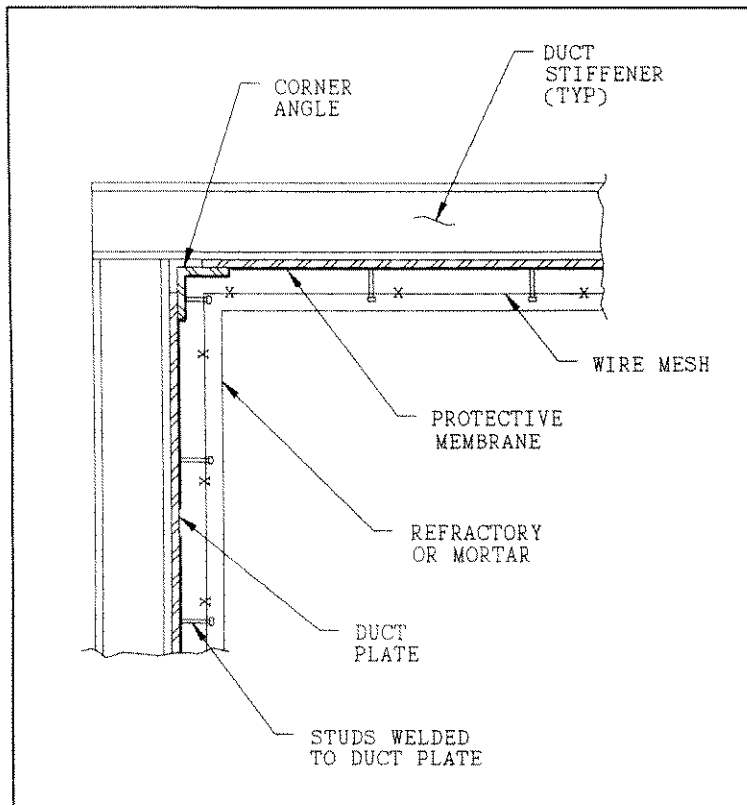


Figure 11.3
Typical Internal Insulation Details

Internal Insulation Applied Directly to the Duct Plate

This installation method is similar to that shown in Figure 11.1 except that the insulation is applied to the inside of the duct and the lagging is usually flat and thicker stronger than external lagging. When internal insulation and lagging is attached directly to the duct plate, installation is usually performed in the following manner.

- Metal pins or studs are welded directly to the duct plate.
- The insulation is impaled over the pins and are held in place with metal clips which fasten onto the pins. The insulation is sometimes held in place over the pins with a layer of wire mesh.
- The lagging is applied over the insulation and is fastened to the clips. This must be done in a manner so that the lagging can expand as the gas temperature rises. The lagging must also be installed so that the seams are lapped in the direction of the gas flow so that it is not lifted up by the velocity of the gas flow.

11.6 CONSTRUCTION DETAILS

There are several aspects of the installation of insulation and lagging which should be of interest to the structural engineer.

11.6.1 Insulation Across Expansion Joints

Insulation and lagging at and around expansion joints poses a unique problem. The insulation should be continued as close to the expansion joint flanges as possible without interfering with the expansion joint removal. However, the outside flanges of the expansion joint channel frames are usually uninsulated to allow for removal of the joint while the portion of the channel closest to the duct plate is insulated. With hot ducts, this sets up an undesirable thermal gradient in the frame channels since one flange is exposed to the hot flue-gas temperature while the exterior flange is exposed to ambient air. This temperature differential can cause distortion and cracking in the expansion joint frame channels, especially near their connections. This problem predominantly occurs when the flue-gas temperature is higher than 300°F (150°C). One way of alleviating this problem is to modify the expansion joint and insulation detail as shown in Figure 11.4.

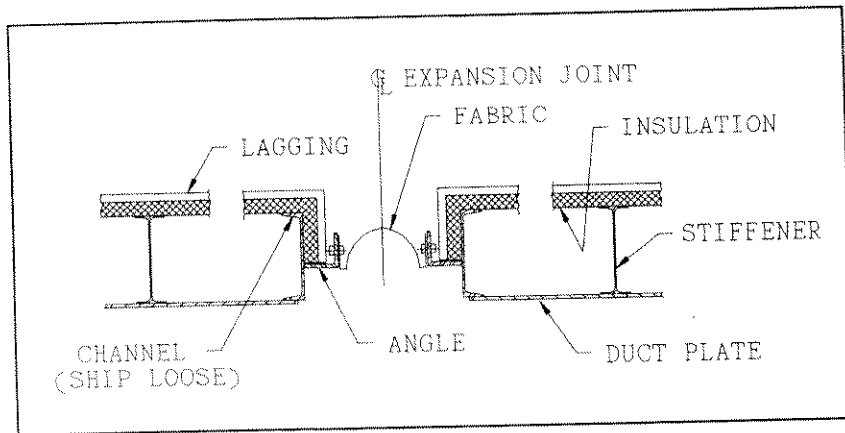


Figure 11.4
Typical Insulation Detail at Expansion Joints

For air ducts a detail similar to Figure 11.5 may be used. This detail can also be used for cold-side flue-gas ducts if the duct and the expansion joint frame are sufficiently flexible to accommodate the rotations due to the thermal gradients which are set up in the expansion joint frame.

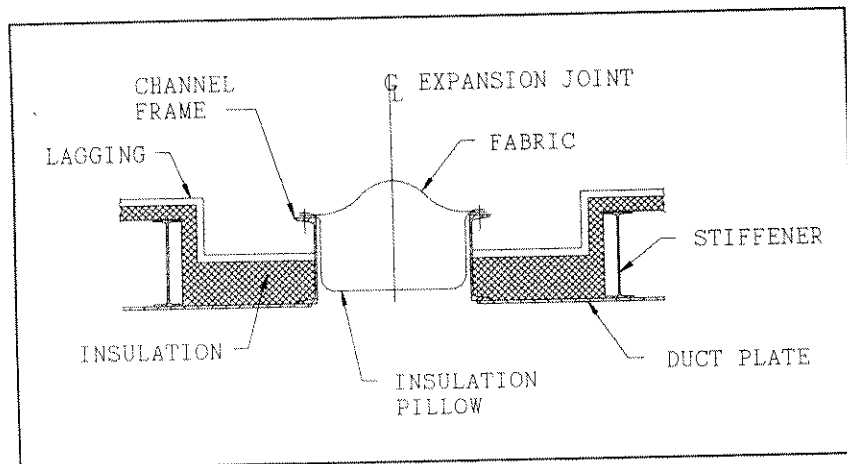


Figure 11.5
Alternate Insulation Detail at Expansion Joints

11.6.2 Insulation Around Hoppers

Another potentially serious problem can occur in hopper crotches adjacent to exterior support steel. If the insulation and lagging is not properly installed in these areas, structural problems could occur. The easiest method from a construction standpoint would be to install the insulation and lagging below the support steel between adjacent hoppers. However, this encases the structural support steel inside the insulation envelope and increases the temperature of this structural steel. Insulating in this manner will set up large thermal stresses in the exterior support steel structure. This potentially serious effect should always be avoided. One way to avoid this problem is to use a detail similar to Figure 11.6.

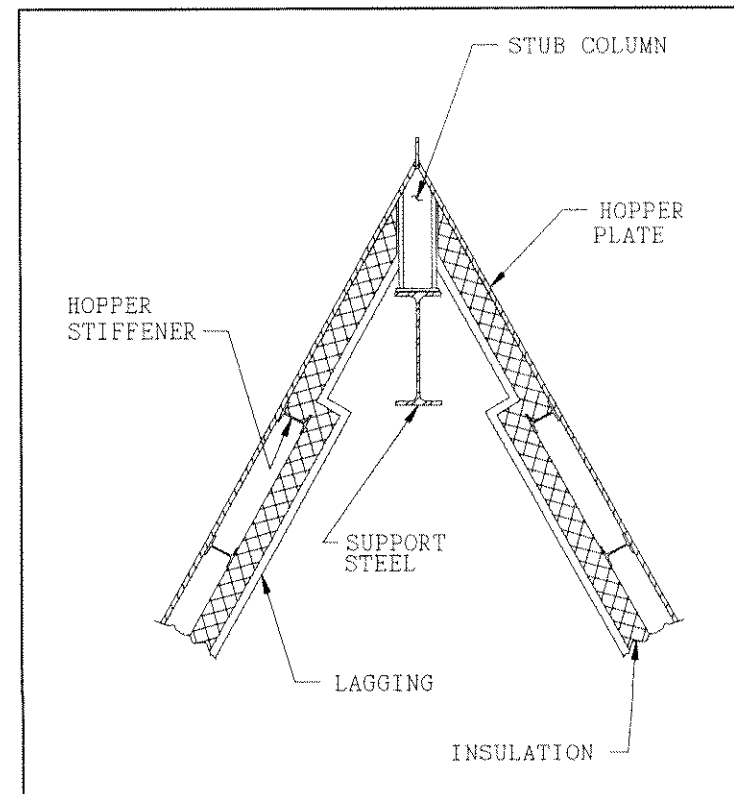


Figure 11.6
Typical Hopper Crotch Insulation Detail

11.6.3 Insulation Around Duct Appurtenances

Duct appurtenances, such as access doors, flow monitoring ports, dampers and expansion joints provide an opportunity for heat loss and the accompanying metal corrosion. Access doors may be pre-insulated by the manufacturer before shipping. However, if field fabricated or flush mounted doors are being used, a removable piece of insulation and lagging should always completely cover the door. This removable piece should always be securely attached with bolts.

11.6.4 Attachment of Lagging

Lagging should always be firmly attached to its supports. It should be laid out with sufficient overlap to prevent intrusion of water. This will also prevent wind from getting under the sheets and lifting them off. Also, all edges and corners should be covered with flashing for the same reasons. Lagging on the top surfaces of ducts should always be sloped so that rain water will drain away. When this is done, the seams must be lapped so that the water will flow over the seam, not under the seam and onto the insulation and duct plate. At the edge of the duct at the bottom of the slope, there must not be any flashing dams that will stop the water from flowing over the edge of the duct. All of these drainage details are very important because the top duct plate and external stiffeners should never be exposed to standing water.

In areas of tight clearance, the insulation and lagging system may have to be locally modified. Flat sheets of lagging may be used in these areas instead of ribbed material. Also, if the specified method is external insulation attached to subgirts, in areas of tight clearance the engineer may elect to locally place the insulation directly against the duct plate, as shown in Figure 11.1, to save space or to make the installation easier.

11.6.5 Subgirts

When attaching the subgirts, an allowance must be made for the thermal growth of the duct in relationship to the much cooler lagging. This is particularly true when the lagging spans across expansion joints. In this case the lagging must be design and constructed to accommodate all of the expansion joint's design movements.

Also, on tall vertical duct surfaces, such as precipitator inlets, a horizontal barrier should be installed between the duct plate and the insulation to prevent a chimney effect draft from occurring. This chimney effect could cause cold air to be sucked into the dead space between the duct plate and the insulation, which could cause a cold spot on the duct plate which would subsequently corrode.

SECTION 12**Maintenance Examination of Existing Duct Systems**

	<u>Page</u>
12.1 FACTORS THAT INFLUENCE THE NEED FOR STRUCTURAL EXAMINATIONS	261
12.1.1 Original Design Basis Versus Operating Basis	261
12.1.2 Exposure to Weather, Chemical and Thermal Conditions ..	262
12.1.3 Operations Records	263
12.1.4 Cumulative Effect of Exposure and Operating Condition ..	264
12.1.5 Ensuring Structural Adequacy	265
12.2 FIELD EXAMINATION TECHNIQUES	265
12.2.1 Preparation and Planning	265
12.2.2 Safety Considerations	266
12.2.3 Equipment	266
12.2.4 Identification of Critical Duct Sections	268
12.2.5 Exterior Walkdowns	269
12.2.6 Interior Walkdowns	270
12.2.7 Thickness Measurements	270
12.2.8 Temperature Monitoring	270
12.2.9 Displacement Measuring	271
12.2.10 Infra-Red Survey	271
12.2.11 Laboratory Test Samples	272
12.2.12 Documentation	272
12.3 POTENTIAL DAMAGE AREAS	273
12.3.1 Indicators	273
12.3.2 Structural Elements	276
12.4 EXAMINATION DATA, EVALUATION AND DISPOSITION	278
12.4.1 Examination Data Assimilation	278
12.4.2 Repairs	279
12.4.3 Evaluation and Disposition Considerations	279
12.4.4 Final Report	280

SECTION 12

Maintenance Examination of Existing Duct Systems

12.1 FACTORS THAT INFLUENCE THE NEED FOR STRUCTURAL EXAMINATIONS

Ductwork systems are often exposed to adverse chemical conditions and high temperatures. Additionally, many ducts are also subject to the varying environmental conditions associated with local weather and atmospheric pollution. The purpose of a preventive maintenance examination of existing duct systems is to ascertain the structural adequacy of the ducts to function safely and efficiently as originally designed after repeated exposure to these adverse conditions.

Owners and plant operators usually consider ducts to have virtually unlimited strength and durability. However, experience has shown this belief to generally be untrue. Regular ductwork structural examinations should be part of a planned preventive maintenance program that would preclude structural deterioration and costly repair or replacement of the ducts. Therefore, such structural examinations are just as important for ducts as normal scheduled examinations and maintenance are for other plant equipment.

Selection of and consistent use of common terminology at the start of a structural maintenance examination is beneficial for all involved. An understanding of the duct system definitions will contribute to successful communication of examination tasks, procedures, data and reports.

12.1.1 Original Design Basis Versus Operating Basis

Both the original design and the historic operating basis for the duct system should be reviewed prior to performing any comprehensive examination. The objective of the review is to fully understand the service conditions assumed by the original design engineer, as well as the conditions under which the duct system has been operating. A comparison of the two basis can be

very informative and can assist in identifying potential problems or explaining observed problems.

Items to be reviewed may include the design input or criteria, design calculations, and design drawings for the original system design. Further attention should be given to available shop fabrication details and erection drawings, previous inspection reports, ongoing maintenance reports and operating data. Operating data could include normal occurrences such as operating temperatures and pressures as well as unusual events that have occurred during operation.

The structural engineer should become aware of any modifications to the ductwork system, support structures or the mode of operation made during the system's operating history. Equipment additions or changes may cause the redistribution of loads to a structure originally intended to solely support only the duct. Upgrades or changes to internal flow distribution devices such as splitter plates and turning vanes may increase the dead loads or alter the duct system's vibrational characteristics. Revised plant or boiler operating conditions may result in the ducts being exposed to elevated pressures, increased temperatures and thermal gradients. Also, changing to a different fuel source may produce increased loads, due to the accumulation of ash or sludge, or accelerate the rates of erosion or corrosion. Finally, updates to local building codes or industry design specifications may alter the design wind or seismic loads acting on the duct structural system.

While most duct system designs incorporate a certain degree of conservatism, the accumulated effect of these modifications could present a safety concern. Areas that exhibit differences between the original design basis and the current operating basis warrant a more detailed structural examination.

12.1.2 Exposure to Weather, Chemical and Thermal Conditions

Outdoor ducts may incur damage due to the accumulation of snow and ice or the variable loads associated with gusting wind and driving rain. Snow drifts may melt and subsequently refreeze, expand within the insulation and result in damage to the insulation and lagging. Subsequent damage could produce paths for further water intrusion. Water from frequent dampness, rain or melting snow also may find a path through seams in the lagging to the underlying insulation, duct plate, stiffeners and expansion joints. For ducts located indoors, plant washdowns can transport plant by-

products and serve as a source of water. Once beneath the duct lagging and within the undrained areas between stiffeners or at expansion joints, the process of deterioration will progress. Additionally, the chemistry of the accumulated water may be altered by plant by-products, creating acidic conditions which may accelerate the damage to the steel duct.

Insulated ducts may experience thermal variations commonly known as "cold spots" at areas of damaged insulation, areas of external water or air contact, expansion joints, test ports, supports and platform penetrations. This condition results in a cooler duct surface which causes subsequent internal condensation and eventual deterioration.

The impact of flue-gas desulfurization (FGD) processes on the integrity of a duct system is of particular importance because of the highly corrosive nature of the by-products created and collected by the process. The FGD processes use a variety of additives to condition the flue-gas and to enhance the removal of pollution particles. These additives may also be contributors to the internal degradation of the duct. Consequently, progressive interior deterioration can result in holes in the duct plate which will cause inleakage, expose plant personnel to potential hazards, and threaten the external structural elements and the overall structural integrity of the duct.

Thermal growth presents numerous opportunities for the development of structural damage. Such growth, whether uniform or distorted, produces friction forces within bottom supported ducts which must be resisted by the supporting structure. Original designs typically anchor a duct at one location and guide the system's thermal growth at other locations where slide bearing plates are usually provided. Progressive deterioration or misalignment can increase these friction forces. Consequently, any examination should include an assessment of the capability of the duct support legs, the support steel, and the slide plates to transmit thermally-induced friction forces and resist associated thermal deformations.

12.1.3 Operations Records

Many plants maintain extensive records of ductwork structural problems, behavior problems, damage and associated structural repairs. Repairs of duct accessories, such as expansion joints, dampers and control linkages, may be indicative of a problem

within the ductwork structure or with its arrangement. Also, inefficiency of the fans may be attributed to extensive duct air leakage caused by plate deterioration. When historical records indicate that frequent outages of significant duration have been necessary for the repair of ductwork, a comprehensive maintenance examination should be scheduled.

Plant records may also identify unusual events of major or minor significance to the structural engineer. From a structural standpoint, information pertaining to the magnitude, duration and frequency of transient pressure and excursion temperatures may provide a basis for review or resolution of ductwork structural concerns. Any information regarding past fires in the ducts may also be significant. Knowledge of chronic large ash or sludge deposits in sections of the ductwork is also helpful when planning the examination and when reviewing and evaluating the collected examination data.

The lead examining structural engineer should also interview the plant staff, preferably before starting the examination. Historical concerns or ongoing chronic problems are most often clearly presented by plant operators, site-based results engineers and long term maintenance staff.

12.1.4 Cumulative Effect of Exposure and Operating Conditions

As mentioned in Section 12.1.3, rain, snow, ice, washdown water and plant by-products can provide the catalyst for accelerated duct deterioration. Frequent exposure to water may deposit acidic concentrations which can accelerate the corrosion of the duct plate and external stiffeners. For hot ducts, cold spots may induce thermal shock, metallurgical changes within the steel (quenching), corrosion, cracking and subsequent deterioration. Such cumulative effects often develop within ductwork systems which are externally lagged and insulated. However, these concerns can go unnoticed, since leakage at lagging seams may not be obvious from outside the duct.

The cumulative effects of plant operations also may influence ongoing structural deterioration. Repetitive exposures to such unusual conditions as transient pressures and excursion temperatures may induce mechanical damage or accelerate material deterioration. The occurrence of unexpected thermal gradients can also cause damage. These conditions, when combined with cyclic plant operations, can result in the binding of

sliding surfaces and damage to the critical interfaces with the support structure. Consequently, forces and events not necessarily considered in the original design may induce buckling and tearing of the duct plates and structural elements of the ducts.

12.1.5 Ensuring Structural Adequacy

A structural preventive maintenance examination should assess the cumulative effect of plant operations upon the structural adequacy of a duct. Plant downtime and unit outages for structural repairs are obviously not desirable. Simply stated, the function of ducts is the movement of air and flue-gas. Many potential problems that can jeopardize this function, as well as the safety of plant personnel and the duct's structural integrity, can be identified and corrected with scheduled, preplanned preventive maintenance examinations. The scheduling of preventive maintenance examinations may be heavily influenced by the plant operating cycle, thus plant outages may not coincide with desired monitoring frequencies. However, structural preventive maintenance examinations for ductwork should always be part of regular plant maintenance.

These routine condition assessments should also be considered to be an integral part of all safety related and plant life extension programs.

12.2 FIELD EXAMINATION TECHNIQUES

To facilitate both exterior and interior ductwork examinations, sufficient time must be invested in adequate preparation and pre-outage planning. Based on the importance of the factors presented in Section 12.1, the following types and methods of preventive maintenance structural examination should be evaluated and appropriately selected.

12.2.1 Preparation and Planning

A basic understanding of the duct structural system design and intended behavior can be beneficial when coupled with a pre-examination site visit. Every detail of an examination should be fully developed well in advance so that valuable plant outage time is not sacrificed due to lack of access, equipment and support personnel. An allowance for cool-down of the ductwork and owner checkout must be factored into the schedule. Field preparation activities, such as the installation of temporary lighting, ladders and scaffolding and the cleaning of interior

surfaces by vacuuming, waterwashing or grinding, should be planned ahead of time to reduce the critical outage time committed to these tasks. Also, if the examination is planned well before the outage, the amount of ash or sludge accumulation can be documented. The availability of laborers to assist with the examination efforts should also be established with the plant personnel prior to the examination.

Preparations should always address personnel safety. Planning for the considerations as described in Section 12.2.2 is essential and must be coordinated with the owner.

Daily or frequent meetings between the plant personnel and the lead structural examining engineer are essential to enable clear communications throughout the examination. Final planning should also include the preparation of contingency plans in the event that the scope of an examination must be changed during the effort.

12.2.2 Safety Considerations

The procedures for duct examinations should address the owner's responsibility and safety requirements plus current United States government Occupational Safety and Health Administration (OSHA) requirements. Two particular OSHA regulations pertain to duct examinations. OSHA Standard 29CFR, 1910.146, *Permit Required Confined Spaces*, addresses working within a confined space and 29CFR, 1926.59, *Hazard Communication*, addresses exposure to hazardous materials. Tests to check for existence and levels of hazardous materials should be performed with, or preferable by, the owner. If this information is unknown and is not to be determined, the worst conditions should be assumed.

Project related duct examination procedures should also identify other precautions, including working in areas of: hot ash; soft deep ash; items weakened by corrosion or erosion such as handholds, ladders, handrails and duct floor plate; slippery surfaces; and abrupt changes in duct direction. Also important is understanding the need to wear paper face masks or respirators.

12.2.3 Equipment

The selection of equipment for a preventive maintenance examination is subject to the project scope and available resources. The items listed in Table 12.1 may be appropriate for

an effective and efficient preventive maintenance examination of ductwork.

Items to facilitate access, such as ladders, Bosun's chairs, scaffolding, safety belts and harnesses, and climbing cages, should be available as appropriate. These items are normally provided by the plant. Planning ahead of time to arrange for the use of these access items is just as important as providing the items on the suggested equipment list presented in Figure 12.1. The use of plant labor to assist with the examination effort is also very important and must be well coordinated with the plant personnel.

Quite often, the installation of thermal displacement measuring devices at strategic locations on the ducts is helpful. These devices are commonly called trams. Obtaining cold and hot duct location measurements from a fixed reference point will indicate the amount and direction of thermal expansion.

Flashlights	___	Ultrasonic Thickness Detector	___
Flashlight Holsters	___	Liquid Dye Penetrant Test Kits	___
Camera and Flash	___	Infra-red Imaging Equipment	___
Camera Film	___	Inclinometers	___
Video Camera	___	Thermocouples	___
Video Camera Tapes	___	Accelerometers	___
Binoculars	___	Spark Testers	___
Tape Measurers	___	Ph Meter	___
Calipers	___	Weld Profile Gage	___
Thickness Gages	___	Ladders	___
Chipping Hammers	___	Bosun's Chair	___
Picks and Shovels	___	Scaffolding	___
Wire Brushes	___	Safety Belts	___
Stationary Mirrors	___	Harnesses	___
Telescopic Mirrors	___	Climbing Cages	___
Plumb Bobs	___	Eye Protection	___
Clip Boards	___	Dust Masks	___
Pens (many)	___	Gloves	___
Ruled Paper	___	Coveralls	___
Cloth Rags	___	Key Chains	___
Crayons, Chalk	___	Work Shoes	___
Markers	___	Two-way Radios	___

Table 12.1
Structural Maintenance Examination - Equipment Checklist

The use of more specialized equipment may be warranted for more comprehensive or unusual examinations. Such items could include an ultrasonic thickness detector, infra-red imaging equipment and thermocouples. Temperature indicating crayons may also be of value. For the examination of duct linings, spark testers, PH meters and thickness gages for thin material measurement may be appropriate.

12.2.4 Identification of Critical Duct Sections

Ducts vary in size and shape for a variety of reasons. Transition sections, elbow sections that abruptly change directions and manifolds are examples of duct sections that may require regular preventive maintenance examinations. Depending on the duct system's design and configuration, certain sections may experience higher than expected loadings, higher than expected temperatures, subsequently elevated stresses, and perhaps extensive thermal movements. With continued operations, these sections may not perform as the structural design engineer intended and they may undergo significant wear, deformation and deterioration.

The type and arrangement of supports are important considerations in a determination of the scope of a duct maintenance examination. Duct systems may be hung by variable or constant support hangers or they may be bottom supported. The bottom supports may be at an anchor or a guide. Sometimes ducts are supported by a combination of the aforementioned means. The degree of structural determinacy is often related to the potential for structural distress. Ducts with minimal supports (4 to 6) are more likely to behave in a manner consistent with the structural analysis. The behavior of indeterminate ducts with many supports tends to be quite different than that predicted by classical structural analysis. Such differences are the result of thermal growth or restraint, secondary stresses, and the stress induced by the construction sequence. The arrangement of the structural supports, the means by which the system loads are distributed to the supporting structure, and the degree of redundancy all contribute to a duct section's structural behavior and the likelihood of structural deterioration.

Other critical duct sections include areas with internal flow distribution devices. Concentrated erosion may occur at these sites which reduces the thickness of structural components and threatens their structural integrity. In some cases, the flow distribution devices also serve as internal struts for structural load

transfer or wall panel support. The location of these devices within the duct system and the amount of particulate within the flow are factors to consider when prioritizing maintenance examination tasks.

Any preventive maintenance examination should include the points of entry into the ductwork, including access doors, grab bars, handrails and platforms. The examination should also include all ductwork probe penetrations. Since the condition of hatches and access doors is critical to both personnel safety and the system's gas tight integrity, the examination should include all seals. Ductwork probe penetrations, for such items as thermocouples and gas test sample ports, offer possible areas for accelerated deterioration from air or water intrusion or cracking from high stresses or vibrations.

12.2.5 Exterior Walkdowns

Observation of the external features of a duct system can provide valuable information related to the duct's behavior and condition. This type of examination may be performed in advance of a plant outage and the subsequent detailed external and internal examination. In many cases, indicators of potential damage can be noted during exterior walkdowns, as discussed in Section 12.3.1, which may identify problems or locations that should be emphasized during a more comprehensive or detailed exterior and interior examination. Removal of selected insulation and lagging may be necessary to perform an initial walkdown. This is usually only done after the unit comes out of service.

Exterior walkdowns should also include a cursory examination of duct system elements which are remote or inaccessible from grade or viewing platforms. Binoculars or a video camera may provide adequate viewing for these areas. A cursory examination may substantiate the need for a comprehensive examination, necessitating the erection of scaffolding, climbing cages or ladders. Also, if the structural engineer performing the examination believes that a comprehensive examination of certain remote areas is required, the required access should be provided.

When possible, both a "hot" on-line and a "cold" off-line exterior walkdown should be considered to observe and record the movement and thermal growth during load and temperature variations. Baseline measurements while the plant is off-line, referenced to permanent stationary structures, may provide

valuable insight with regard to thermal growth and support alignment. Displacement measuring trams are normally used to collect these readings.

12.2.6 Interior Walkdowns

Assuming adequate access, internal ductwork structural elements can and should be examined in a detailed manner. To perform a comprehensive examination, careful planning should be done. Subsequently, the condition of critical structural elements, as described in Section 12.3.2, can be determined. The condition of these internal structural elements should be thoroughly and accurately recorded. Since internal examinations may be limited in time and schedule, the examination team should work as efficiently and fast as possible. A detailed condition assessment of certain duct internal structural elements can subsequently be performed on the basis of documented observations. Other than the obvious condition of structural elements, observations worthy of documentation include the distribution and depth of ash accumulations, surface discolorations, and the general alignment of parallel members and walls.

12.2.7 Thickness Measurements

Both internal and external duct elements may experience corrosion and erosion. The field measurement of the material thickness is not always practical; however, thickness measurements are essential for determining an element's current structural properties in order to evaluate its load carrying capability. Local loss of thickness in steel shapes and plate can result in weak elements and offers sites for future failures. All paint, corrosive matter, ash or sludge, and general debris should be carefully removed without damaging the element to obtain accurate thickness readings. If extensive cleaning and preparation will be required, detailed planning should be performed to select, gain access to, and prepare these areas for measurement. Some areas may require the drilling of holes to allow thickness measurements to be taken with calipers if an ultrasonic thickness detector is not available or practical to use. Plans should include capping or plugging these test holes after completion of measurements.

12.2.8 Temperature Monitoring

The temperature of flue-gas or air within ducts can vary considerably from the established design basis. In some instances,

the expected temperatures and the actual on-line temperatures may vary enough to warrant field measurement. Also, unanticipated thermal stratification and temperature differentials may occur within the ducts. Specific localized temperatures of elements within the duct can be obtained and recorded instantaneously over a period of time through the installation of thermocouples. Thermal records developed during plant start-up and shutdown, as well as those associated with steady-state operations, often identify thermal gradients. During start-up and shutdown, structural elements may experience a time related temperature lag when compared to adjacent elements within the system. This can also be identified if the data is collected properly. When strategically placed and properly installed, thermocouples can provide the additional information necessary to explain the structural behavior of the duct.

During external on-line examinations of operating ducts, temperature indicating crayons or digital thermometers can provide accurate measurements of hot and cold spots on the lagging and duct plate.

12.2.9 Displacement Measuring

To collect information pertaining to the actual thermal growth and expansion of the ducts, thermal displacement measuring devices, or trams, should be installed at strategic locations on the ducts. The best locations are usually at the corners or ends of each duct section. The trams must be installed such that they are referenced to permanent stationary structures. They should be installed as far from each other as practical in order to measure significant movements. Readings should be obtained when the ducts are at their operating temperature and when the plant is off-line. Comparing the cold and hot duct location measurements will indicate the amount and direction of thermal expansion.

12.2.10 Infra-Red Survey

Infra-red surveying of the exterior of the ducts can be performed during an exterior walkdown while the plant is in operation. This temperature survey can provide information related to air or gas leakage and poorly installed or deteriorated insulation and lagging. Qualified operators of this equipment can detect local hot spots which can generally be correlated with a structural concern or developing structural problems.

12.2.11 Laboratory Test Samples

In some instances, samples of duct steel should be obtained for chemical and physical laboratory analyses. A means to obtain, identify and transport the samples should be a part of the comprehensive duct examination plan. Specification of the desired laboratory tests should be determined well in advance of the examination. These tests include those associated with material verification or classification, strength, the determination of creep, impact properties and contamination identification.

The results of the material testing program should be used as part of any subsequent assessment of the duct system's structural adequacy. Comparison of the results to the established design basis, industry standards, and available historical or academic data may offer insight pertaining to the material strength, serviceability and rate of deterioration.

12.2.12 Documentation

The investment in the performance of preventive maintenance ductwork system examinations can be enhanced by the complete and accurate recording of the collected information. First, a procedure should be created to properly record the examination field notes. This procedure should address basic considerations such as the uniform use of pens, paper, markers, and the type, format, and desired detail of notes and abbreviations. Specific instructions should include the exact type of information to be recorded, such as references, orientation, sizes, type of damage and visual observations.

The presentation of information on previously developed data sheets will facilitate collection, compilation and evaluation of the examination field notes. Where practical, markers or paint may be used directly within the duct system and support structure to highlight critical findings or merely indicate that a portion of the examination is complete.

Photographs and video recording of damage and any unusual observations is highly recommended. Good and safe lighting must be provided in order to obtain quality photographs.

All information collected during a duct field structural examination, including photographs, should be included in the final report. See Section 12.4.4 for more recommendation

regarding the examination final report. This report should serve as an important reference document for the continued future evaluation of the ductwork system.

12.3 POTENTIAL DAMAGE AREAS

The structural condition assessment of ductwork should include an investigation of any indicators of potential damage areas as listed in Section 12.3.1. The presence of some of these indicators or problems with others, as the case may be, may warrant a detailed, rather than a cursory, examination of the key structural elements in the area of the indicators. See Section 12.3.2 for discussion on examination details of these key structural elements.

12.3.1 Indicators

The following items should be examined during a structural maintenance examination as they might be indicators of adjacent structural damage.

Lagging:

Visual observation of the lagging can provide information pertaining to the condition of a duct structural system. Several indicators of potential structural problems include localized stains, general deterioration, buckling, separation of seams, binding at supports or slide plates, and the ponding of water. The topographic condition of lagging surfaces can be an indicator of the configuration or settlement of the duct surface beneath the lagging.

Insulation:

Some duct systems have only insulation and no lagging. Again, a preventive maintenance examination should identify areas with missing, damaged or non-uniform insulation. Hot spots that cause stress variations in these duct sections and cold spots that accelerate corrosive deterioration may then be avoided or eliminated by repairing the insulation.

Expansion Joints:

Cracked or torn expansion joints may be an indicator of erosion, ash packed and hardened in the joints, and unusual duct movements. A more careful examination of the duct supports adjacent to damaged joints may be warranted to determine the extent of any duct damage and the amount of duct support thermal movements. The material and configuration of any

damaged expansion joints should be investigated to assess its compatibility with the operating environment. Ash or sludge buildup in expansion joints is a frequent cause of damage. Once the joints get packed with ash or sludge, the duct sections may be unable to freely expand, which could result in damage to the duct sections. Erosion shields or covers for thin metal joints and liners or baffles for non-metallic joints should be examined for deterioration and ash buildup.

Expansion joint frames should also be examined for damage. Damage to these rigid frames is usually caused by improper insulation details, improper joint seals or a packed joint. See Section 11 for a discussion of proper insulation around expansion joints.

Condition of Coatings and Linings:

Small cracks in surface treatments can be an indication of the direction of stresses within a element. A detailed examination report should include an accurate depiction of such patterns. Peeled paint on adjacent support steel could indicate that the steel has been subjected to very high temperatures, while the spalling of paint may indicate the buckling of underlying plate. If the support steel is painted in the vicinity of sliding supports, worn paint surfaces can accurately indicate the amount of thermal growth.

Excessive Deflections:

Duct structural internal members may exhibit vertical or horizontal buckling, deflection or rotation. Also, external stiffeners may become buckled, warped or severely bowed. Member web crippling and excessive connection deformation may also be observed. In all of these cases, the condition of the member and its associated end connections should be recorded. All sags and bows in the duct plate or stiffeners should be accurately measured during the examination. Accurate measurements of deformations and rotations may facilitate the assessment of the potential causes.

The buckling or out-of-plane distortion of duct plates often indicates that the external stiffeners have separated from the plate. If not, they are usually quite damaged. Distorted roof plates could indicate a loss of lagging integrity. This damaged plate is usually caused by ponding of external water or thermal gradients associated with poorly distributed flows.

Fly Ash and Scrubber Sludge Accumulation:

Particular attention should be given to areas where high volumes of flyash and scrubber sludge accumulate. These areas should be examined before and after removal of the accumulations. Since flyash and scrubber sludge acts as an insulator, duct floors may be cooler than the wall and roof sections. Temperature differentials and corrosion of the duct plate can occur in these locations. Duct corners should be closely examined for the presence of cracks in the duct plate, welds, stiffeners and corner angles, since large thermal stresses buildup and produce the greatest damage in areas which lack flexibility.

The amount and locations of significant deposits should be recorded during the examination. Samples may be collected if density tests are needed to accurately determine the weight of the accumulation.

Discoloration:

Interior duct surfaces frequently exhibit a reddish brown or gray color. Examiner should note blackened areas that may indicate the prior existence of an overheated condition such as a fire. White or very light colored areas indicate severe inleakage of water. Subsequently, in both of these areas the material properties and the strength of adjacent elements may have been effected. Structural damage might also be present in these areas.

Corrosion:

Internal duct elements may be subjected to extreme corrosion. Corrosion may be attributed to operating temperatures or local plate temperatures which are below the dew point of the flue-gas. Since corrosion will reduce the strength of the plate and elements, attention to the safety of examiners should be considered throughout an examination, especially within FGD system ducts.

External duct members may be subjected to corrosion from external water sources.

Erosion:

Internal duct members are subject to abrasion from particulate matter carried by the flow. The conservative design of these members, as well as the attachment of sacrificial shielding members, can provide additional protection and prolong service life. However, almost all internal surfaces are subject to some degree of erosion. Noticeably worn or polished areas typically develop at flow distribution devices, in corners, and in areas where

the duct configuration changes. Areas of high local velocity and high particulate content should be examined to ascertain the extent of any erosion.

Spalled or Honeycombed Mortar or Refractory:

There are different concerns for ducts with internal mortar or refractory insulation. Mechanical attachments are used to anchor the insulation to the steel plate. Damage to the duct plate usually starts at the location of the attachments. Worn areas, sags and areas believed to have separated from the duct plate should be documented. These areas can be identified by rapping the interior surface with a hammer. Flue-gas leakage to the protected duct plate frequently occurs at areas where cracks and spalling occur. These are sites for condensation and inevitable corrosion, which can be correlated with exterior duct plate deterioration. Spalling or the presence of honeycombed mortar also indicates that the refractory may be locally unstable. Unusual deterioration may warrant taking refractory core samples for strength testing and petrographic analysis.

12.3.2 Structural Elements

The following structural elements should be examined during a structural maintenance examination.

Supports, Slide Bearing Plates and Guides:

All components of the duct's support system should be carefully examined. The condition of the various types of bottom supports may reflect different types of operational concerns and a history of events. For example, slide bearing plates with scorch marks and peeling surfaces would indicate that very high temperatures have existed at this location during operation. Guide bars at sliding supports should be examined for cracks in welds or plates, permanent deformation and wear marks. Where visible, low friction surfaces should also be examined for large scratches or gouges, delaminations, acid holes and bulges at the center of the plates. When examining off-line duct systems, thermal movements can be determined by measuring the clean areas of slide plates that develop as the ducts cool and contract from the operating position. Comparison of these measurements with those theoretically predicted is an essential method of assessing the duct's structural behavior.

At bolted connections, each bolt should be checked for shear or tension failure or any observed deformation, engagement,

looseness and deterioration. The amount of bearing or contact area should also be examined. Within sliding connections, bolts should be plumb, but loose enough to enable the design movement to occur.

Hangers:

Both variable and constant load type hangers are used to support ducts. Loads other than expected, excessive load changes or excessive vertical movement may occur in hangers that could result in damage to either the hanger, the hanger support steel or the duct at or adjacent to the hanger attachment.

The condition of the hanger connections to the duct and to the support steel should be examined. In addition, the hanger manufacturer, model number and spring constant should be recorded. For each hanger, the vertical movement and the position of the indicator pin should be recorded for both cold and hot conditions.

Stiffeners:

When accessible, duct stiffeners should be visually examined for continuity, deformations and corrosion. Sighting along the length of members will identify any bows. Close examination is required to find any cracks. For critical members, the extent of the bow can be determined by tensioning a string along the member's length and measuring the offsets. The end connections should also be examined for cracks, tears and deformation.

Internal Bracing:

Bracing members may be comprised of double angles, wide flange members, structural pipes or structural tubes. An examination should identify and measure the extent of bows as well as any deviations from the design drawings. Each member's connection plates should be examined for cracking, buckling, stability and sound attachment. Welded connections are typically used for these members and all welds should be carefully examined for the presence of cracks.

Structural bracing members should also be examined to determine if there are any thin sections caused by erosion. In some instances, sacrificial wear plates or angles may have become significantly deteriorated, jeopardizing the parent member's structural integrity. Examiners should be conscious of how a member's orientation and its associated connections contributes in restricting the flow.

Plates and Welds:

All accessible areas should be examined for cracks and general deterioration. Plate cracks generally occur adjacent to welds within the heat-affected zone (HAZ), at corners, and near the duct supports. These are areas where the structural system has greater rigidity and residual stresses may be present. The extent and orientation of surface cracks may be determined by the use of liquid dye penetrant or magnetic particle methods. As presented in Section 12.3.1, the condition of painted surfaces may also be an indication of underlying plate cracking.

Bolts:

Bolted connections should be checked for looseness, distress or failure. Missing or deformed bolts may be indicative of support overloads or irregular holes. To determine if bolts are loose, each assembly can be twisted or rapped with a hammer. The observation of bolt classification markings may be useful where different strength bolts may have been used.

12.4 EXAMINATION DATA, EVALUATION AND DISPOSITION

Field data collected from the examination should be neat, complete, accurate, carefully compiled, carefully evaluated, properly dispositioned, and organized into a final report for presentation to the owner. The field notes should also include maps of the noted damage so that it can be easily located later by the evaluation engineer, the owner's representatives and the repair contractor.

12.4.1 Examination Data Assimilation

Field data should be completely and accurately recorded. Photographs or video tapes should be taken of defective, damaged or problem areas. Field notes should indicate the associated location and date of each photograph. Pertinent data, such as a means of picture identification, orientation, reference directions, sizes, lengths and measurement scales, may be marked on or near the item being photographed prior to photographing.

Accurate sketches, showing dimensions and orientations, should be compiled for all areas examined. Maps of all examined areas will enable the correlation of field data to specific areas of the ducts. Maps showing the locations of thickness measurements are also required. Examination forms should be prepared ahead of time to reduce the amount of time recording field notes and sketches.

12.4.2 Repairs

Where damage is found, structural repairs are usually required. These repairs may be designed for a short-term or long-term life, depending on the circumstances. These repairs are necessary to render the duct safe for continued plant operation. Engineering sketches, in lieu of detailed design drawings, are often used to specify repairs quickly and efficiently in the field.

Prior to an examination, generic or standard repairs for anticipated damage should be prepared. Such an approach will minimize valuable examination and outage time dedicated to the development of repairs. Standard details will also promote uniformity and an orderly and cost-effective construction process.

In addition, certain repairs can be implemented while the plant is operating. Such options include the replacement of deteriorated lagging and insulation and modification of lagging. This is assuming access and surface temperatures can be handled properly. Depending upon the extent and magnitude of the damage and deterioration, outage based repairs may be prioritized on the basis of criticality over several future outages. The lead times for replacement parts, such as expansion joints or certain structural members, could impact the scheduling of repairs. Any significantly damaged structural members should be addressed by immediate reinforcement or complete replacement.

Recognizing the need to assure the stability of the duct system and the safety of plant personnel, many of the repairs or modifications may need to be coupled with the design and installation of temporary support structures. In the case of refractory lined ducts, selective repair or removal may be the most effective approach when coupled with the resealing of areas where flue-gas leakage could occur. After repairing corroded areas or areas with deteriorated coatings, cleaning and recoating may be an appropriate measure to arrest future deterioration.

12.4.3 Evaluation and Disposition Considerations

Many factors must be considered regarding the disposition of structural examination findings. Potential issues for resolution include: the severity of damage or deterioration, future monitoring plans, the commitment of non-outage versus outage repair efforts, time constraints, capital expenses, and alternatives to plant operation philosophies. The purpose of a thorough

condition assessment goes beyond providing an immediate repair or estimating the frequency of future repairs. A full assessment should address the causes of damage, identify any concerns, attribute documented damage with one-time occurrences or ongoing mechanisms, and make recommendations for long-term corrective action.

Severe or unexpected damage will most likely require further evaluation. In some cases, a structural analysis of the duct system that incorporates those components with severe corrosion, buckles, cracks or excessive deflections might be necessary. Calculations and pertinent industry and academic data may be applied to predict the rate of deterioration. Subsequently, the remaining useful service life of duct structural components may be estimated.

A comprehensive evaluation should also differentiate between localized and potentially progressive failures. The evaluation should include a comparison of actual service conditions and loads as observed during the examination and those assumed in the original design. Stress intensities must be an integral part of the evaluation process for deteriorated members. Their remaining factors of safety, if any, must be determined. Finally, if the documented damage is deemed catastrophic, a detailed assessment should consider alternate modes of unit operation as a means of providing a resolution to the potential dangers.

Alternative resolutions to repairs, whether minor or major, often may have to be coupled with a change of operating conditions. This option is quite drastic and therefore, is rarely considered to be viable. However, should such extreme conditions warrant this type of evaluation, additional multi-discipline input should be sought, with special attention given to the experience of plant operators. Similarly, certain problems may be of a chronic, recurring nature and may never be resolved without a complete redesign of the duct system. However, experience has proven that most damage and deterioration can be alleviated through the development of a systematic, routine and comprehensive preventive maintenance structural examination.

12.4.4 Final Report

The final examination report will serve as an important future reference and should be comprehensive. All aspects of the preventive maintenance examination effort should be included within the final report. All field data, repair sketches and analysis

work, if any, should be summarized and presented in a very detailed fashion. All photographs and video tape should be included as an attachment. All information should be concise, clearly presented and carefully arranged. The report should include all conclusions and recommendations for future courses of action. Below is a suggested format for the final report. Due to the effort and the length of time that may be required to prepare this important document, exit interviews with plant personnel are frequently conducted as a preview to the final report.

Suggested Final Report Table of Contents:

1. Purpose
2. History
3. Summary
4. Scope and Methods of Examination
5. Details of Examination
6. Conclusions and Recommended Future Course

Attachments:

- A. Access Sketches
- B. Damage Report
- C. Inspection Photographs
- D. Repair Sketches

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INDEX

- Access doors 30, 44
- Access platforms 31
- Air cannons 76
- Air ducts 104; conventional boiler systems 12-13, 14; dead legs 43; fluidized bed boiler system 11-12; insulation 254
- Air pollution control device (APCD) 28
- Air preheater 12-13, 15, 26
- AISC-ASD specification 6-7
- Allowable creep stresses 89, 90
- Anchor bolts 164
- Anchor point 19
- Anchors 47-51, 59
- APCD *see* Air pollution control device
- Ash *see* Flyash
- Ash load 111-114, 154, 167
- ASTM A7 steel 89
- ASTM A36 steel 83, 85, 88-90, 92-94, 99
- ASTM A53 steel 90
- ASTM A182 steel 99
- ASTM A242 steel 83, 85, 88, 90, 92-94, 96
- ASTM A335 steel 85, 88, 90, 93, 96
- ASTM A387 steel 85, 88, 90, 93, 96
- ASTM A570 steel 92
- ASTM A572 steel 92
- ASTM A588 steel 85, 88, 90, 92-94, 96
- ASTM A606 steel 92
- ASTM A618 steel 90
- ASTM B564 alloy 95
- ASTM B575 alloy 95
- Austenitic stainless steel 85, 93, 94
- Baffles 201, 203, 205, 209
- Baghouse 13, 15, 28
- Balanced draft industrial boilers 107
- Balanced draft power plants 8, 10, 106
- Banded stiffeners 133
- Boiler plants, ductwork system 8-16
- Boilers 27, 107, 138
- Bolts 50; anchor bolts 164; damage 276-277, 278; erection bolts 222-223; material selection 95
- Borosilicate block, insulation 247
- Bottom supports 47, 48, 53, 62-63, 192, 193
- Bowing 274
- Bracing 236-237, 239, 277
- Buckling 142, 145, 162
- Building codes 6
- Butterfly dampers 40, 41
- Bypass ducts 8, 42
- Carbon migration 91
- CEMS *see* Continuous emission monitoring system
- Ceramic fiber insulation 246
- Chimneys 6, 29-30
- Circular ducts 68-69, 118, 131; load path 143, 144, 155; plate design 142-145; shipping and handling 236; stiffeners 68, 220; stiffness 162; structural element design 193-196
- Circular rings 194
- CL *see* Construction loads
- Clearances 52, 62
- Coal-fired boiler 13-15
- Coal-fired power plant 8, 15, 16, 105, 106
- Coatings 97, 239-240, 274
- Coefficient of friction 117
- Coefficient of thermal expansion 85
- Cold spots 263
- Cold-side ducts 17
- Combined cycle power plants 11
- Combustion air heater 27
- Combustion turbine power plants 11
- Composite action 176-178
- Compression elements, truss design 188
- Computer modeling 157-158, 166, 170
- Connections 159, 163, 183-185
- Constant support spring hangers 20, 165
- Construction; erection 238-240; fabrication 228-230; field construction costs 220; field splices 221-223; insulation and lagging 249-257; project site conditions 221; shop inspection 233-234; shop pre-assembly 220-221; welding 230-233
- Construction loads 118
- Continuous emission monitoring system (CEMS) 27
- Conventional boiler systems 12-13, 14
- Conventional power plants 8-10
- Corner angle 22, 160-161
- Corner configurations 141
- Corrosion 46, 94, 95, 244, 275

Crack control 147
 Creep, 88-91 122, 123
 Creep stress, 122-123; allowable creep stress 89, 90
 Creep-rupture failure 88-89, 121-122
 Crossover ducts, dead legs 42

 D/t *see* Diameter to thickness ring flexibility ratios
 Dampers 21; butterfly dampers 40, 41; guillotine dampers 21, 40, 41; interface with ductwork 39-43; isolation dampers 21; louver dampers 40-42; Poppet dampers 41; shut-off dampers 41-42
 Dead legs 42-43, 77, 78
 Dead loads 109-110; insulation and lagging 248; structural models 167; uplift 170
 Deflections 274
 Design 35-37, 152; circular ducts 193-196; clearances 52, 62; computer models 157-158, 166, 170; determinate or indeterminate support systems 56-59; duct panels 131; duct supports 152, 156; global approach 152-158; lateral ties 197; plate design 130-148, 174; rectangular ducts 173-194; service conditions 103-109; shipping 215-216; stresses 137-140, 145, 146; structural element design 173-197, 201-211, 247-249; structural models 161-162; support eccentricities 52-53; supporting structures 156; trusses 187-190; *see also* Plate design
 Design codes 6, 146
 Design drawings 223-225
 Design loads 109; construction loads 118; dead loads 109-110; environmental loads 110; live loads 110; moment connection 184, 185; platform loads 110; seismic loads 110, 168; snow loads 69, 110, 111; stiffener element 177-180; system loads 114-117, 154; thermal gradient loads 117-118; wind loads 110, 111, 154, 155, 163, 248-249; *see also* Loads
 Design stress 121, 131; creep stress 89, 90, 122-123; fatigue stress 123-124; fracture 123-124; normal allowable

Determinate structures 56, 58-59, 157, 164
 Diameter to thickness ring flexibility ratios (D/t) 142
 Discoloration 275
 Displacement 271
 DL *see* Dead loads
 Doors *see* Access doors
 Drawings 223-225
 Duct appurtenances 21-23, 256
 Duct conveyances 25-26
 Duct geometry 66-69; ash deposition 76-77, 113; complexity 186; dynamic pressure 75; metal expansion joints 77; transition duct sections 69; vibrations 75-80
 Duct plate design *see* Plate design
 Duct plates; composite action 176-178; insulation 250, 253
 Duct supports 19-21, 47-51, 54-65, 133; anchor point 19; ash deposition 76-77; bottom supports 47, 48, 53, 62-63, 192, 193; circular rings 194; constant support spring hangers 20; damage 276-277; design 152, 156; dynamic pressure 75; eccentricities 52-53; fit-up 229; guides 19-20, 47-51, 59, 276-277; hangers 20-21, 59-62, 99, 165, 277; interface with foundation 164, 165; net uplift 170; rectangular ducts 185-193; rigid hangers 21, 63; roller duct supports 52, 117; slide bearing plate assembly 20; sliding supports 20; static pressure 23, 74-75; structural examination 268; structural models 159; structure stiffness 62, 63-64; thermal expansion 52-53; thermal gradients 77-79; variable support hangers 21, 277; vertical elements 191-193; *see also* Stiffeners, Supports
 Ducts 7, 17-19; breeching ducts 7, 19; circular ducts 68-69, 118, 131, 142-145, 155, 162, 193-196, 220, 236; cold-side ducts 17; corrosion 96; critical duct sections 268-269; determinate structures 56, 58-59, 157, 164; field splices 221-223; high temperature ducts 92-94, 96; hot-side ducts 17, 19, 253; indeterminate

medium temperature ducts 92; materials 83-95; rectangular ducts 67-68, 131-141, 153, 160-162, 174-193; square ducts 66; structural element design 173-197; toggle duct section 17-19; wet ducts 94-95
 Ductwork 7, 17-19, 26-30, 35-36; bracing 236-237, 249, 277; clearances 52, 62; configurations 66-67, 74-79; corner configurations 141; critical duct sections 268-269; design drawings 223-225; design loads 109-118; equipment removal 39; flow considerations 35-36; global structural analysis 151-170; handling 142, 235-238; indoor vs. outdoor service 103; load paths 143, 144, 152-156, 166-168; materials 83-95; potential damage areas 273-278; retrofitting 65; shipping 215-216, 35-238; specifications 226-228; stiffness 65, 162; structural determinacy 56-59, 157, 164; surface protection 96-99, 234; thermal expansion 45-54, 61, 62; unloading 238; *see also* Construction, Design, Structural element design
 Ductwork accessories 30-32; insulation 31; interface with ductwork 37-44; isolation 38
 Ductwork equipment; air pollution control device 28; air preheater 12-13, 15, 26; ash removal equipment 27; baghouse 13, 15, 28; boiler 27, 107, 138; chimney 6, 29-30; continuous emission monitoring system 27; economizer 27; electrostatic precipitator 13, 28; fabric filter 13, 15, 28; fans 29, 38-39, 76, 148, 245; flue gas 26-28, 44, 94; interface with ductwork 37-44; isolation 38; scrubbers 13, 15, 28, 84, 94, 97, 98, 263; supporting ducts from 65
 Ductwork materials *see* Structural materials
 Dynamic loads, flow distribution device design 208-209
 Dynamic thrust, turning vanes 208
 Dynamic unbalanced pressure 24, 115

 E bolt 222

Effective width 175
 EL *see* Environmental loads
 Electrostatic precipitator 13, 15, 28
 End connections; damage 277; stiffeners 183-185; trusses 190-191
 Endurance limit 146
 Environmental loading combinations 126
 Environmental loads 110
 Equipment isolation 38
 Equipment removal 39
 Erection, ductwork 238-240
 Erection bolts 222-223
 Erection specifications 227-228
 Erection tolerances 240
 Erosion 46, 94-95, 275-276
 Erosion allowances 109, 205
 Excursion temperature 25, 105-108; distribution 138; loading combination 127
 Expansion joints 21, 31, 45-46; actuation forces 115; ash accumulations 77; damage 273-274; damper location relative to 41; equipment isolation 38; insulation across 253-254; metal 45, 77, 115, 165; non-metal 38, 45, 115, 165; static pressure 75
 Exterior walkdowns 269
 External insulation 250-252

 Fabric filter 13, 15, 28
 Fabrication 228-230
 Fabrication specifications 226-227
 Failure 60, 88, 123
 Fans 148; gas recirculation fans 15, 29; interface with equipment 38-39; sound attenuation 245; vibration 76
 Fatigue 123-124, 146-147
 FCAW *see* Flux cored arc welding
 FD fans *see* Forced draft fans
 FGD system *see* Scrubber
 Fictitious element approach 163, 167
 Field construction costs 220
 Field examination *see* Structural examination
 Field splices 221-223
 Field welding 239
 Fixed point 19
 Flanges; fit-up 229; mating flange 37
 Flat slide bearing plates 51
 Flow distribution devices 31, 76, 167; baffles 201, 202, 205, 206

- 203, 205, 209; splitter plates 23, 201-207; supports 205; turning vanes 23, 114, 161, 201-207
- Flow model testing 11, 35-36, 78, 79, 203
- Flow pulsation 76, 146-147
- Flow resistance, flow distribution device design 203
- Flow velocity 113
- Flow-related phenomena 35-36
- Flue gas desulfurization system *see* Scrubber
- Flue-gas 26, 94; conditioning 28; continuous emission monitoring system 27; monitoring instruments 44
- Flue-gas ducts (flues) 7, 13, 15, 17, 104; dead legs 43; flow distribution devices 203
- Fluidized bed boiler system 11-12
- Flux cored arc welding (FCAW) 232
- Flyash 26; ash load 111-114, 154, 167; deposition 76-77, 275; flow velocity 113; removal 13, 15, 27; thermal load 117, 166
- Flyash collection hoppers 5, 19, 69; insulation 255; stiffener sizing 182-183; vibration 76
- Forced draft fans 8-14, 29
- Forced draft system 8
- Foundations 164
- Fracture 123-124
- Framing 133-134, 138
- Free body diagram *see* Structural models
- Friction forces 117
- Friction loads 165
- Furnace 27
- Gas metal arc welding (GMAW) 232
- Gas recirculation ducts 15
- Gas recirculation fans (GRF) 15, 29
- Gaskets 31
- Girder web design 162
- Glass fiber, insulation 245
- GMAW *see* Gas metal arc welding
- Graphitization, steel 91
- Gravity supports 47, 48
- GRF fans *see* Gas recirculation fans
- Guides 19-20, 59; damage 276-277; location of 47-51
- Guillotine dampers 21, 40, 41
- Gunitite 246
- Handling 142, 235-238
- Handrails 31, 44
- Hanger rods 165, 191-192
- Hangers 20-21, 59-62, 165; damage 277; material selection 99; rigid hangers 21, 63; spring hangers 20, 61, 165, 191-192
- Hazardous materials, duct examination 266
- Heat recovery steam generator (HRSG) 11, 27
- High temperature ducts 92-94, 96
- Hoop stresses 143-144
- Hoppers *see* Flyash collection hoppers
- Hot gas ducts 17, 99, 253
- HRSG *see* Heat recovery steam generator
- ID fans *see* Induced draft fans
- Indeterminate structures 56-58, 164, 187
- Induced draft fans 8, 10, 13, 29
- Industrial boilers, operating conditions 107
- Infra-red surveying 271
- Inorganic glass fiber, insulation 245
- Inspections; construction 240; during fabrication 233-234; *see also* Structural examination
- Instrumentation ports 31
- Insulating mortar *see* Mortar insulation
- Insulation 22, 96, 108-109; construction 249-257; damage, 273, 276; installation 249-253; purpose 243-245; types 245-247
- Interface boundary conditions 37-44; duct to hopper interface 166, 182-183; structural models 164-166; thermal loads 170
- Interior walkdowns 270
- Internal bracing, damage 277
- Internal insulation 252, 253
- Internal struts 70-74, 196
- Internal trusses 22, 155; location and layout 70-74; rectangular ducts 185-191; thermal gradients 78; vibration 74
- Isolation, equipment and accessories from ductwork 38
- Isolation dampers 21

- Maximum expected transient pressure 108
- Mechanical failure *see* Fatigue
- Mechanical properties 84-91, 103-104
- Meridional stress 142-143
- Metal expansion joints 45, 77, 115, 165
- Minimum loads, static loads 210
- Models *see* Computer modeling, Structural models
- Modulus of elasticity 85-86
- Moment connections 184, 185
- Mortar insulation 246, 252, 276
- Mufflers 245
- Natural frequency 207
- Net uplift 170
- Nil ductility temperature (NDT) 91, 123
- Non-combustion wool, insulation 245-246
- Non-metallic expansion joints 38, 45, 115, 165
- Normal allowable stress 121-122
- Off-line loading combinations 125
- OL *see* Operating loads
- Operating conditions 104-108, 264-265, 280; *see also* Service conditions
- Operating loading combinations 125, 127
- Operating loads 110-114
- Operating pressure 11, 15-16, 23, 104-107
- Operating temperature 24-25, 104-107; distribution 138; loading combinations 125-126
- PA fans *see* Primary air fans
- Passivation 234
- Perforated plates 22-23, 201-203, 205, 209
- Pinned connections 183, 185
- Plate design 130-148; circular ducts 142-145; plate and stiffener composite action 140-141; rectangular ducts 132-140; stiffeners 174
- Plate fit-up 229-230
- Plate stresses 132
- Plates, damage 278
- Platform loads 110
- Platforms 31
- Pollution control 28
- Ponnet dampers 41
- L/d *see* Low support spacing to diameter ratio (L/d)
- Ladder vanes 202
- Ladders 31
- Lagging 22, 96, 108-109; attachment 256; damage 273; design 248; installation 249-253; purpose 243-245; types 247
- Lap type joint configurations 223
- Large deflection theory 136-137
- Lateral loads 197
- Lateral ties 197
- Lifting lugs 235-236
- Liners 93, 98-99, 239; damage 274; refractory lining 246
- Live loads 110
- Load interactions 156-157
- Load paths 152-156; circular duct 143, 144, 155; structural models 166-168
- Loading combinations 125-127, 131; member internal forces 169-170; stiffeners 177-180
- Loads 131; ash load 111-114, 154, 167; construction loads 118; dead load 109-110, 167, 170, 248; environmental load 110; friction load 165; lateral load 197; live load 110; member internal forces 169-170; operating load 110-114; platform load 110; pressure load 109; primary load 109; seismic load 110; shear load 162; sludge load 114; snow load 69, 110, 111; spring load 115; static load 209-210; stiffeners 177-180; system load 114-117, 154; thermal load 109, 138, 170, 188; wind load 110, 111, 154, 155, 163, 248-249; *see also* Design loads
- Louver dampers 40-42
- Low support spacing to diameter ratio (L/d) 143
- Materials *see* Structural materials
- Mating flange 37
- Maximum expected excursion temperature 108
- Maximum expected operating pressure 104
- Maximum expected operating temperature

- Precipitators 13, 15, 28
- Pressure; ductwork 15-16; dynamic unbalanced pressure 24, 115; operating conditions 104-108; operating pressure 11, 15-16, 23, 104-107; static pressure 74-75; transient pressure 24, 105-108, 111; unbalanced pressure 24, 75, 114-116, 154, 168
- Pressure loads 109
- Pressure profiles 15, 16
- Pressurized industrial boilers 107
- Pressurized power plant 8, 9, 105
- Primary air 25
- Primary air ducts 13
- Primary air fans 8-14, 29
- Primary loads 109
- Primary stress 137
- Project site conditions 221
- Pulverized coal-fired boiler system 13, 14
- Rail shipment, ductwork components 217, 219
- Rain water 69
- Rappers 76
- Recirculated gas 26
- Rectangular ducts 67-68, 131; corner configurations 141; end connections 183-185; load path 153; plate design 132-140; stiffeners 174-183; structural element design 174-193; structural models 160-162; struts and trusses 185-191; support elements 185-193; vertical support elements 191-193
- Refractory insulation 252, 276
- Refractory lining 246
- Reheat air fan 29
- Repairs 279
- Retrofitting 65
- Reverse air fan 29
- Rigid hangers 21, 63
- Ring stiffeners 193-196
- Rolled shapes, material availability 83
- Rolled steel 220
- Roller duct supports 52, 117
- Safety, duct examination 266
- Sagging 274
- Salt cake 26
- SAW *see* Submerged arc welding
- Scrubber sludge 26, 114, 275
- Scrubbers 13, 15, 28; duct degradation 263; liners 98; material selection 94; materials 84; outlet duct coatings 97
- Secondary air 25
- Secondary air ducts 12-13
- Secondary air fan 29
- Secondary stress 137-139
- Seismic loads 110, 168
- Selective catalytic reduction (SCR) 28
- Service conditions 23-25; corrosion allowances 96, 109, 205; dynamic unbalanced pressure 24, 115; erosion allowance 109, 205; excursion temperature 25, 105-108, 127, 138; indoor vs. outdoor service 103; material selection 83-99; mechanical properties 84-91, 103-104; operating pressure 11, 15-16, 23, 104-107; operating temperature 24-25, 104-107, 125-126, 136; site location 103; thermal gradient 25, 77-79; transient pressure 24, 105-108, 111; unbalanced pressure 24, 75, 114-116, 154, 163; *see also* Operating conditions
- Shear, structural models 161-162
- Shear keys 165
- Shear load 162
- Shell hoop stress 143
- Shielded metal-arc welding (SMAW) 232
- Shipping 215-216, 235-238
- Shop inspection, during fabrication 233-234
- Shop pre-assembly 220-221
- Shotcrete 246
- Shut-off dampers 41-42
- Site location 103
- SL *see* System loads
- Slide bearing plates 20, 51-52, 117, 165; damage 276-277; thermal movement 170
- Sludge 26, 114, 275
- Sludge loads 114
- Small deflection analysis 136, 137
- SMAW *see* Shielded metal-arc welding
- Snow loads 69, 110, 111
- Soil 164
- Specifications 226-228
- Speed clips 250

- 209; supports 205
- Spring hangers 20, 61, 165, 191-192
- Spring loads 115
- Square ducts 66
- Stack 29-30
- Stainless steel 85, 93-95
- Static loads, flow distribution device design 209-210
- Static pressure 23, 74-75, 154
- Steel; availability 83-84; carbon steel 244-245; coefficient of thermal expansion 85; corrosion prevention 244; creep 88-91; creep stress 89, 90, 122-123; creep-rupture strength 89; fatigue stress 123-124; fracture 123-124; graphitization 91; laboratory test samples 272; material selection 92-94; modulus of elasticity 85-86; normal allowable stress 121-122; properties 84-91; rolled steel 220; stainless steel, 85, 93-95; tangential shear stress 145; temper embrittlement 91; temperature reduction 244-245; ultimate strength 87, 88; yield strength 86, 87; yield stress 122
- Stiffener framing 134-135
- Stiffeners 66, 156, 178, 180-183; banded stiffeners 133; circular ducts 68, 220; composite action 140-141, 176-178; damage 277; design loads 177-180; duct corners 141; end connections 183-185; fit-up 229; framing 134, 135; insulation considerations 248; loading combinations 177-180; location 131-148; near fans 76; perforated plates 203; placement 176; rectangular ducts 174-183; ring stiffeners 193-196; shape selection 217, 220; truss design 188
- Stiffness 157; circular ductwork 162; ductwork 65; flow distribution device design 206-207; rectangular ductwork 160-162; stress ratio 182; support structures 63-64; trusses 74
- Stratification 78
- Stress ratio, stiffeners 182
- Stress rupture 123
- Stresses; combined stresses 139-140; fatigue 123-124, 146-147; hoop 142-143; normal allowable stress 121-122; primary stress 137; secondary stress 137-139; shell hoop stress 143; tangential shear stress 145; *see also* Design stress
- Strip analysis 137
- Structural determinacy 56-59, 157, 164
- Structural element design; circular ducts 193-196; flow distribution devices 201-211; insulation and lagging 247-249; lateral ties 197; rectangular ducts 174-193; vibration 189-190
- Structural examination; data evaluation 278-281; documentation 272-273; field examination techniques 265-273; need for 261-265; potential damage areas 273-278
- Structural materials 83; availability 83-84; bolts 95; hangers 99; plate thickness and stiffener spacing 134-136; properties 84-91; selection 92-95; surface protection 96-99, 234
- Structural models; ash loads 167; circular ductwork 162; dead load 167; displacements 170; interface boundary conditions 164-166; load development and application 166-168; load paths 166-168; member forces and reactions 169-170; model validation 169; modeling strategy 163; rectangular ductwork 160-162; seismic loads 168; shear 161-162; support structures 159; thermal gradients 168; unbalanced pressure 168
- Struts 22, 70-74; internal struts 196; rectangular ducts 185-186
- Subgirts; insulation 250-251, 257; lagging 256
- Submerged arc welding (SAW) 232
- Supports; eccentricities 52-53; fit-up 229; flow distribution devices 205; *see also* Duct supports
- Surface protection 96-99, 234
- Sustained loading combinations 126
- System loads 114-117, 154
- Tangential shear stress 145
- Temper embrittlement 91
- Temperature 15-16; excursion

- flue-gas 17; monitoring 270-271;
operating conditions 104-108;
operating temperature 24-25, 104-
107, 125-126, 136
- Temperature differential *see* Thermal gra-
dients
- Tempering air 25
- Tempering air duct 13
- Temporary bracing 236-237, 239
- Tension elements, truss design 187
- Tertiary air 25
- Tertiary air fan 29
- Test ports 31, 97
- Thermal efficiency, insulation 243-244
- Thermal expansion 45-54; clearances
52, 62; duct supports 52-53; hanger
rotation 61
- Thermal gradient loading combinations
126
- Thermal gradient loads 117-118
- Thermal gradients 25, 77-79; cold items
attached to ducts 53-54; expansion
joints 45-46; plate stresses 138;
structural models 168; supports 52-
53, 77-79; truss design 190; trusses
72
- Thermal loads 109, 117-118, 138;
interface boundary conditions 170;
truss design 188
- Time-to-failure 88
- TL *see* Thermal gradient loads
- Toggle duct 17-18
- Toggle duct sections 17-19, 43, 47, 137
- Tolerances 228, 229, 240
- Trailing edge liquid collectors 201
- Trams 267
- Transient loading combinations 126
- Transient pressure 24, 105-108, 111
- Transition duct sections 69
- Truck shipment, ductwork components
216-218, 238
- Trusses 22, 70-74, 157; design 187-190;
end connections 190-191;
rectangular ducts 185-191; thermal
gradients 78; Vierendeel trusses 74,
156
- Turbine exhaust ducts 11, 245
- Turning vanes 23, 114, 161, 201, 202,
203-209
- Ultimate strength 87, 88
- Unbalanced pressure 24, 75, 114-116,
154, 168
- Variable support hangers 21, 277
- Vibrations 5, 75-80; equipment isolation
38; fans 76; flow-induced 206;
internal trusses and struts 74;
resonance 207; truss design 189-
190
- Vierendeel trusses 74, 156
- Virtual anchor point 50
- Vortex shedding 76, 146-148, 189
- Waffle framing 134
- Water related damage 60
- Weld 140
- Weld quality 233
- Welding 230-233; codes and standards
231-232; design drawings 225, 226;
end connections 183; field welding
239; metal liners 98; thermal stress
139
- Welding electrodes 95-96, 98, 232-233
- Wet ducts, material selection 94-95
- Wind loads 110, 111; equivalent wind
load 163; insulation and lagging
248-249; load path 154, 155
- Yield strength 86, 87
- Yield stress 122