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 to 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.

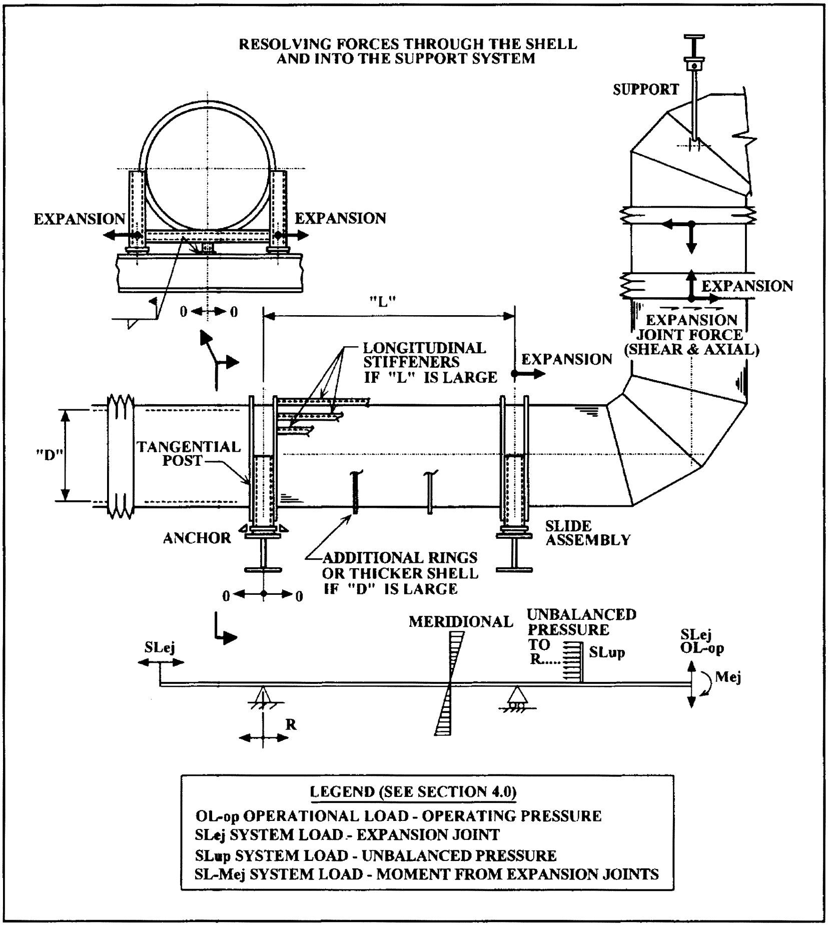

Figure 6.4
Example of Circular Duct Loading Considerations

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

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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.