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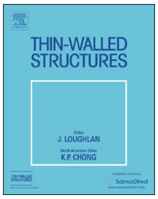

Full length article

Structural design of stiffened plates of industrial duct walls with relatively long panels undergoing large deformations

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ABSTRACT

Structural design of stiffened plates of the walls of rectangular-sectioned industrial ducts is currently based on the strip method that follows the linear flexural beam theory. The current design method assumes that the displacements generated in the plate are small and the membrane forces that generate in the plate are negligible. This paper addresses the current design method and discrepancies associated with it to present a new design approach that takes into account the effects of large displacements on the load-deformation and load-stress behavior of stiffened plates. Two different sets of formulas are presented based on Finite Element analysis of rectangular plates with relatively long aspect ratios that estimate the maximum stress and deformation in the typical and edge panels of stiffened plates. These formulas are then used to establish design equations for stiffened plates. Based on the findings of this paper, a reduction of 30–40% in the plate thickness could be achieved if the new design approach is selected over the conventional design method.

1. Introduction

Many industries require transferring large amounts of air and flu gas between different points as part of their production or treatment procedures. Depending on the nature of flu gas and the volume of transfer, ducts with different shapes and sizes are used in various parts of a given industry. Most duct line assemblies consist of various segments connected to each other to form a conduit line that transfers large amounts of air or flu gas in industrial facilities. A segment of a duct line assembly forms a straight line or an elbow with circular, rectangular or transfer cross-sections. A typical rectangular duct segment consists of four plates sealed together to form the walls of a rectangular section resting on supporting frames at two ends. The wall plates are stiffened by rib elements at certain intervals throughout the length of the duct segment as shown in Fig. 1 to form stiffened plates with relatively long rectangular panels. This paper studies the structural design of the stiffened plates of the walls of large rectangular sectioned industrial ducts.

ASCE [4] defines various loads that apply to duct line assemblies considering the duct segment geometry, the method of application, environmental conditions, the indoor or outdoor location, the nature of flue gases transferred, the flow temperature and position of duct segment in the flow system. Although there are various external loads (dead, live, wind and earthquake loads) applicable to the duct segment, the main load acting on duct walls is the internal hydrostatic pressure that transfers the air or flu gas inside the ductline. The hydrostatic pressure inside the duct is positive if the fans that generate the flow are installed upstream but in most cases the pressure is negative (suction) since the fans are installed at the outlet of the flow [4].

Structural design of duct walls consists of two stages namely, local and global design [4]. In the local stage, the plate thickness and stiffener arrangements are designed under the internal pressure whereas in the global stage the whole duct segment is designed for the external loads.

One of the major aspects in the analysis and design of industrial ducts and similar structures is the load-displacement behavior of the stiffened plates. Although the effects of large deformations (i.e. geometrical nonlinearities) on the load-displacement behavior of rectangular plates are well known, the design of plates in ductwork industries is mainly based on linear analysis without consideration of large deformations effects. ASCE [4] briefly mentions the membrane forces induced in the plate as a result of large deformations without giving any further technical guidance. Since then, the effects of large deformations on the failure criteria of long rectangular plates have been studied by several researchers. Young and Budynas [25] presented nonlinear load-deformation curves of rectangular plates for various plate boundary conditions and aspect ratios considering large deformation effects. More recently, Thanga et al. [20] studied the case of stiffened plates of duct walls while considering large displacements and allowing for partial yielding of the plate within an acceptable limit. They

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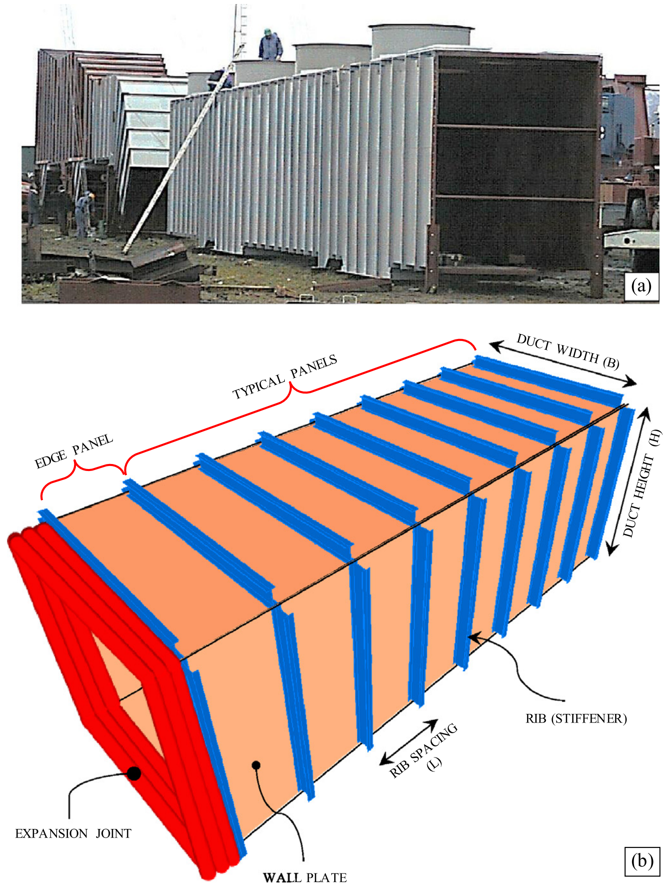

Fig. 1. (a) Large industrial rectangular duct segments under construction (courtesy of fives-solios Inc.). (b) Schematic view of a typical rectangular duct segment.

concluded that a design approach that is based on large deformation analysis would be more economic than the linear method stated in ASCE [4] guideline. Following these findings, the load-displacement and load-stress relations for long rectangular plates were then formulated by El-Aghoury and Galal [8] using Bezier equations. Similar findings were reported by Liu [15] for ducts with wall plate thicknesses ranging between 3/16" and 3/8". From the above, it can be noted that there is a need for developing design equations that takes into account the effect of large deformations using boundary conditions that represent stiffened plates of duct walls.

The duct line segments are supported against the external loads by means of structural frames and footings or through connections with other segments. The term “structural design of duct walls” in this paper refers to the local design of duct wall plates. After the design of duct walls and segments, the duct line assembly shall be checked for thermal expansion. Thermal expansion might cause destructive axial force if restrained and should be released along the duct line by using expansion joints and elbows. It is practical in the design of duct lines to use expansion joints at one or both ends of straight segments [4]. An expansion joint may transfer shear, moment, torsion or a combination of all of them between two adjacent segments of the duct line but it generally provides full release of axial forces. Thus the boundary conditions at the edge panel (see Fig. 1-b) at the location of the expansion joint are different from those of the typical panels of the wall plate. Therefore, this paper focuses on evaluating the linear and nonlinear behavior of stiffened plates of duct walls considering the large deformation effects as well as the effects of expansion joints at the ends of the duct segment on the boundary conditions.

2. Analysis and design of long-spanned rectangular plates

The current procedure of the design of long-spanned plates with aspect ratio greater than 2.0 is based on the application of flexural beam analogy by using a “unit-width strip” at the middle of the plate as shown in Fig. 2. The analysis of this unit-width beam element (design strip) could be linear or nonlinear depending on the nature of design.

2.1. Linear analysis of long rectangular plates under uniform lateral pressure

The principal assumption in the linear analysis of plates under uniform lateral pressure is that the deformations are small and strains are infinitesimal compared to the plate thickness so the classic beam bending equations apply to the design strip of the plate as a beam element.

Using the unit-width beam analogy, the cross-sectional properties of the plate are calculated based on the plate thickness, t, as shown in Eq. (1).

$$\begin{cases} I = t^3/12 \\ S = t^2/6 \end{cases} \tag{1}$$

where S is the section modulus and I is the moment of inertia of the unit-width strip. Applying the beam bending analogy to the unit-width strip of the plate for the three boundary condition combinations shown in Fig. 2, results in the elastic stresses and deflections as shown in Table 1. In this table, q is the lateral uniformly distributed load, σ is bending stress, δ is the plate deflection and λ is the plate length-to-thickness ratio (L/t). The boundary conditions indicators “S” and “C” represent the simply-supported (hinged) and clamped (fixed) ends respectively. The design stresses and deflections in Table 1 are calculated by applying the section modulus and moment of inertia in the classical bending moment equations, respectively.

The formulas presented in Table 1 are useful for the linear analysis of long (i.e. $S > 2.0$) rectangular plates based on the unit-width strip method. These equations could be interpreted in conventional design formulas in forms of Eq. (2) and Eq. (3) for the three applied boundary conditions combinations.

$$(q/F_y)\lambda^2 = \begin{cases} 1.33(\sigma_{\max}/F_y);\ (S-S) \\ 2(\sigma_{\max}/F_y);\ (C-C) \\ 1.33(\sigma_{\max}/F_y);\ (C-S) \end{cases} \tag{2}$$

$$(q/E)\lambda^4 = \begin{cases} 6.4(\delta/t);\ (S-S) \\ 32(\delta/t);\ (C-C) \\ 15.42(\delta/t);\ (C-S) \end{cases} \tag{3}$$

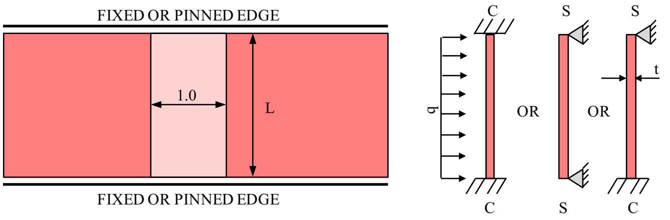

Fig. 2. Unit-width strip and beam analogy.