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Design of rectangular industrial duct plates subjected to out-of-plane pressure considering nonlinear large deformations

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ABSTRACT

Large industrial steel ducts are often rectangular and are built-up of stiffened plates. The plates along with stiffeners act to resist the pressure loads and transfer these loads to the supports. Parallel wide flange steel profiles, usually beams, are used as transverse stiffeners that are spaced perpendicular to the longitudinal axis of duct. The design process involves determining the load carrying capacity and deflection of the plate based on the plate thickness and the spacing between stiffeners. The current analysis and design method for industrial ducts is based on the elastic large deflection plate theory using standard tables.

A nonlinear finite element parametric study was conducted on dimensionless parameters to investigate the behavior of laterally loaded long plates. Through-thickness yielding of the plate and formation of partial plastic hinges at the ends is allowed. The results are presented in terms of a proposed dimensionless Normalized Load Factor (NLF) representing the applied pressure, the Normalized Deflection Factor (NDF) representing the out-of-plane deflection and the Normalized Maximum Stress Factor (NMSF) representing the maximum stresses induced in the plates. Design equations for deflection and stresses of plates are established with the aid of Bezier curves. A simple design procedure allowing for large deflection and partial yielding of edges is proposed. A limiting value for pressure has been found where it becomes irrelevant to check deflection. Results show that the proposed design procedure is simple and can lead to economic plate thicknesses and spacing of stiffeners in industrial ducts in ambient temperatures.

1. Introduction

A series of large rectangular duct systems is required to transport large amount of air and flue-gases in many industrial processes such as coal power stations, industrial boiler applications and furnace off-gas systems. Duct systems are air tight conduits needed to transport air or flue gases under positive or negative pressure. They are also exposed to high temperatures due to the fact that the air or flue gases are transported at elevated temperatures. The large industrial ducts are often rectangular having dimensions that may range from 5 m to 15 m, sometimes even larger. Fig. 1 shows a schematic of typical components of a large rectangular industrial duct.

The design of large industrial ducts is not yet covered by any design standard; however, most practitioners follow the *guidelines* of the ASCE [1]. One of the difficulties facing engineers in the analysis and design procedures of this particular structure is the uncertainty of how the components should be designed, especially that the plates exhibit large deformations which make the analysis process completely different than using the regular small deflection theory. Very few technical information and design guidelines have been published describing analysis and design techniques for such structures such as ASCE [1]. These guidelines require that the duct system should be designed to resist the following loads: (a) internal positive or negative pressure (operating or transient), (b) weight of the duct including insulation and lugging, (c) live loads such as ash weight, wind, snow and seismic (d) other loads such as thermal expansion or support reactions. Usually, the stiffener design is generally governed by the combination of transient internal pressure and wind load [2].

The behavior of the components of large industrial ducts is significantly different from those of regular plate girders. The design process of the large rectangular ducts generally involves local structural analysis of stiffeners and plates, and a global analysis of the whole duct structure. Although the plate is the most important structural element, it cannot be designed in isolation of the stiffeners supporting it. Typically, the design process involves determining the duct plate thickness, stiffener spacing, and proportioning of the stiffener section by considering one structural element at a time. In reality, the steel plate and the stiffeners act as one composite section resisting the lateral pressure. As such, the duct cross section, plate and stiffeners, act together to provide the necessary flexural stiffness for resisting transverse bending stresses. On the other hand, the side panels of the duct segment transfer the gravity loads to the supports by shear.

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Nomenclature

b	span of the plate between stiffeners [mm]
F_y	yield stress of the steel plate [MPa]
E	elasticity modulus of steel [MPa]
NDF	Normalized Deflection Factor [dimensionless]
NLF	Normalized Load Factor [dimensionless]
NMSF	Normalized Maximum Stress Factor [dimensionless]
t	thickness of the plate [mm]
p	lateral uniform pressure on the plate [MPa]
w	width of the plate strip [mm]
X_{Pn}	X coordinate of Bezier curve control point n [dimensionless]
Y_{Pn}	Y coordinate of Bezier curve control point n [dimensionless]
β	dimensionless factor representing plate slenderness [dimensionless]
Δ	deflection of plate [dimensionless]
λ	width-to-thickness ratio (b/t) [dimensionless]
σ	general term representing normal stresses in the plate [MPa]
σ_{max}	maximum stress induced in the plate (bending+membrane) [MPa]
ψ	dummy variable used to determine deflection of the plate [dimensionless]
ζ	dummy variable used to determine the maximum stress in the plate [dimensionless]

There is limited reported research work on large industrial ductworks, which resulted in the delay in development of updated guidelines and up-to-date design codes. The solutions for large deflections theory in plate design are complicated. The analysis of rectangular plates subjected to uniform lateral pressure and undergoing large out of plane deflection received increasing attention in 1940s and several successful attempts were made by Levy [3,4]. However, the outcome was a series of lengthy mathematical formulas that were difficult to use in regular design procedures. Young [5] has provided tabulated numerical values for dimensionless coefficients for the relations among pressure load, deflection and stresses for rectangular plates under uniform load producing large deflections. Unfortunately, these tables are limited to relatively low values of pressure. More recently, Wang et al. [6] proposed a simpler, yet still lengthy, mathematical procedure for an exact large-deflection mathematical analysis of rectangular plates with both fixed and simply supported edges. Such tables or solutions for the rectangular plate analysis are useful for design of the large industrial ductworks. Thanga et al. [2] carried out a comprehensive work on large industrial ductworks and proposed several dimensionless factors governing the behavior and strength of stiffened panels.

The objective of this study is to establish relations between loads, plate thickness and stiffener spacing for large industrial ducts. In order to achieve this goal, a nonlinear finite element model was developed to accurately simulate the plate behavior in both the elastic and plastic ranges. The model was validated using results from theoretical solution and the values from "Roark's Formulas" by Young [5] and the work done by Thanga et al. [2]. Another objective is to identify the fundamental parameters that dictate the behavior of laterally loaded plates for the numerical study. This necessitates a method of analysis that can trace the behavior of plates after undergoing large deflection. This study considers only plates subjected to static pressure loading and under ambient temperature.

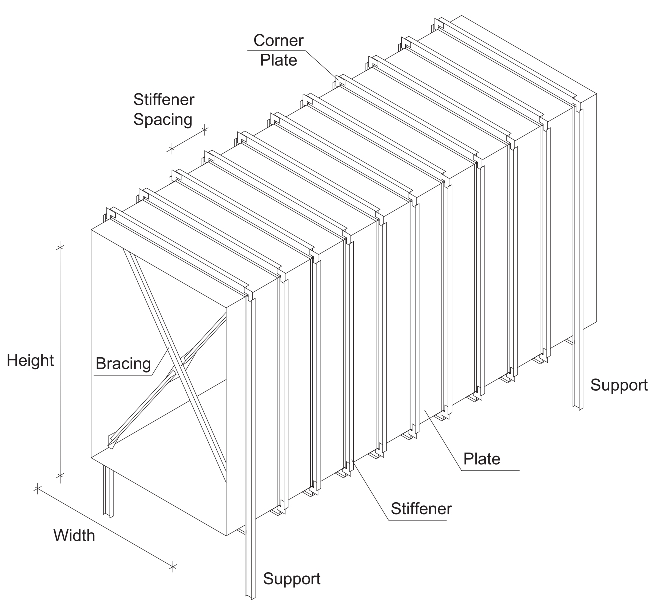

Fig. 1. Schematic of large rectangular ducts and its main structural components.

2. Large versus small deflection theories

The classic theory of laterally loaded plate bending is often classified as *small* or *large* deflection plate theory, based on the ratio of the out-of-plane deflection, Δ, to the plate thickness, t. The small deflection theory does not consider the membrane stresses that develop in the plate when deflection to plate thickness ratio becomes large and when the plate edges are restrained from pulling-in. Hence, the relationship between pressure and deflection will be linear during small deflection [7].

Large deflection response occurs when the magnitude of the out-of-plane deflection becomes equal to or greater than half the thickness of the plates subjected lateral pressure [7]. The large out-of-plane deflection causes stretching of the plate resulting in membrane stresses in addition to bending stresses. If the edges are prevented from pulling in, membrane action becomes more significant and the overall behavior becomes nonlinear; this is what is referred to as nonlinear large deflection plate theory.

Deformation predictions based on the small deflection theory lead to excessive thickness or smaller spacing between the stiffeners. The plate between the stiffeners in large industrial ducts can undergo large deflections while performing safely and satisfying the serviceability limit. Such larger deflections would cause higher membrane stresses and, consequently, a higher proportion of the acting pressure will be supported through the development of membrane stresses rather than by bending stress. This illustrates that membrane action requires relatively higher deflections to be triggered. Therefore, it is anticipated that allowing partial yielding in the plate edges near supports will increase the deflection, hence increasing the membrane stresses.

In the past, the analysis and design of the plate thickness, i.e., the stiffener spacing, was done in accordance with pure plate bending behavior known as the elastic small deflection theory. Currently, many engineering firms determine the spacing of stiffeners based on elastic large deflection plate theory. Based on