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Elastic buckling behavior of rectangular plates with holes subjected to partial edge loading

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ABSTRACT

Cut-outs or openings are inevitable part of steel structural systems since they are required as access ports for mechanical and electrical systems or to reduce the amount of material that is used. When such perforated plates experience compression loads, they may buckle or show instability due to axial compression. In this study, the buckling of perforated square and rectangular plates subjected to in-plane compressive edge loading is investigated using the finite element method. To analyze the behavior of the plates the following four edge loading cases were applied; concentrated edge loading, asymmetric partial loading at the opposite edges, partial loading at the center of the opposite edges and partial loading at the two ends of the opposite edges. The plate aspect ratio, the length and location of the edge loading and diameter of the circular hole are taken as the variables that have a buckling effect on the behavior of the plate. The results show that the square plates are highly sensitive to buckling when the loading at the center of the plates.

1. Introduction

In the literature there are a number of studies reporting the linear buckling behavior of rectangular plates, however, limited in depth work has been published on perforated plates under in-plane uniform loading [1–8] and linearly varying in-plane loading [9, 10]. The studies concerning perforated plates show that the presence of holes change the buckling mode shape and may reduce the elastic buckling load capacity of perforated steel plates.

Deolasi and Datta [11] investigated the elastic buckling and vibration behavior of rectangular plates without holes using the finite element method based on ordinary first order shear deformation theory (FSDT). They concluded that the plates are less susceptible to buckling when partial edge loading is located near the supported edges. Srivastava et al. [12] used the finite element method to investigate the buckling and vibration characteristics of stiffened plates subjected to in-plane partial and concentrated loading at the opposite edges. They stated that the stiffened plate is less prone to buckling when the loading is located near the supported edges and near the stiffeners. Mariorana et al. [13–15] conducted a series of investigations which generally were concerned with the elastic buckling of behaviors of perforated plates under axial compression and bending moment and localized symmetrical loads. The localized symmetrical loads were applied at the short edge of the plate with different ratios of load length to short edge length. Ikhenazen et al. [16] investigated the linear buckling of simply supported thin plates subjected to patch compression using the finite element method. They determined the buckling coefficient for two different load cases applied to a range of plate with various edge ratios ($a/b = 1, 2,.., 10$). Recently, Singh et al. [17] undertook a buckling analysis of thin rectangular plates with cutouts subjected to partial edge compression using the finite element method. In their work, the diameter of circular hole numerically set to 0.2 of the short edge of plates is taken as the constant in all kinds of plates, They showed that square plates are significantly affected by partial edge loading in comparison with rectangular plates having aspect ratios $a/b = 1, 2, 3, 4$.

Since there are few studies that are available in the literature related to the linear buckling behavior of perforated plates subjected to partial edge loading cases the present study aims to fill that gap. The buckling behavior of perforated plates under in-plane different partial edge loading was investigated and in addition the effects of the hole size on buckling load was analyzed. The plate aspect ratio, the length and location of the edge loading and diameter of the circular hole are considered to be the variables that affect the behavior of the perforated buckling plate. The finite element method was used to determine the plate buckling load of the perforated plates. The aim of this study is to determine the variation of elastic buckling load of rectangular plates subjected to partially edge loading as the plate aspect ratios and the diameter of the circular holes were changed.

2. Description of the problem

Fig. 1 shows a sample rectangular plate with a circular perforation having a width b, length a, thickness t and a circular cut-out with diameter d located at the center of plate. All the four plate edges are simply supported in the out-of-plane direction.

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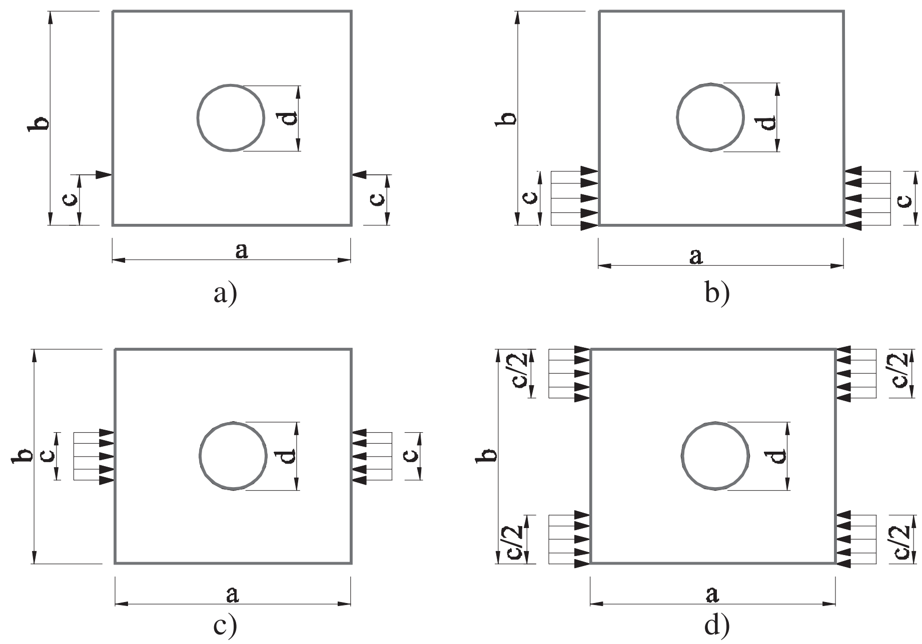

Fig. 1. Partial edge loading patterns of perforated plates: (a) concentrated loading at the opposite edges, (b) partial loading at one end of the opposite edges, (c) partial loading at the center of the opposite edges (d) partial loading at the two ends of the opposite edges.

In order to investigate the effect of partial loading on the perforated plates, they are subjected to localized edge loading of four different types. The external loads are placed on the short edge of plates as shown in Fig. 1. For the concentrated edge loading case in Fig. 1a, the load is moved along the short edge and c denotes the distance between the load and the lower left corner of plate. In the other cases shown in Fig. 1b to d, c denotes the length of the partial load.

This study reports on the investigation of the elastic buckling behavior of perforated plates subjected to partial edge loading. Two different aspect ratios $a/b = 1$ and $a/b = 2$, different normalized partial loading ($c/d = 0.0, 0.05, 0.1, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50$) and a different normalized hole size ($d/b = 0, 0.1, 0.2, 0.3, 0.4, 0.5$) were selected.

3. The finite element model and buckling analysis

The maximum load carrying capacity of a structure can be obtained by performing either nonlinear analysis or buckling analysis. In nonlinear analysis, the externally applied load is divided into smaller load steps, then these smaller loads are applied at each increment and an equilibrium state is found through iteration. Hence, the maximum load carrying capacity or instability point(s) of the structure is determined. The second method is the buckling analysis in which not only is the critical loads obtained but also the corresponding deformation shapes of the modeled structure. The linear buckling analysis (or eigenvalue analysis) consists of two stages. First, a unit load or stress which has same load pattern as a given external load is applied to determine the internal stresses in structure due to externally applied loads. In the second stage, based on the initial stress, the geometric stiffness matrix is obtained in order to perform the eigenvalue analysis. In the linear buckling analysis, it is assumed that the deformation is small and the material obeys the Hook's Law. When one of these assumptions is violated, the nonlinear buckling analysis must be performed. In the present study, the material behavior was assumed to be linear elastic and the deformations compared with the overall dimensions of plate were assumed to be small. Based on these assumptions, a linear buckling analysis was carried out to investigate the buckling behavior of the perforated plates.

3.1. Finite element modeling

All the necessary computations of the plate buckling were performed using ANSYS; a commercial finite element analysis program [18]. The SHELL63 element used for modeling and analyzing the perforated plates has four nodes and six degrees of freedom at each node since the flexural behavior and membrane action can be taken into consideration using this element. The material of the plates was assumed to be homogeneous, isotropic and elastic. The material properties for Young's modulus $E = 210$ GPa and Poision's ratio $= 0.3$ were selected. The dimensions of the square plate were set to 100×100 and thickness of plates was taken as 1 mm.

The typical meshed plates and boundary conditions are given in Fig. 2. The maximum size of the shell elements was selected $b/20$. The shell element size along the hole perimeter was set to the smaller of $b/50$ or $d/40$ [5, 9, 17]. All the edges of the plates were modeled as simply supporting the out-of-plane direction. Three roller supports along the edge at $y = -b/2$ were used in order to prevent the plate from exhibiting a rigid body motion.

After concentrated or partial edge loads were applied to the plates as shown in Fig. 1, the linear buckling analysis was carried out to investigate the buckling behavior of the perforated plates. The lowest critical buckling load parameters for distributed and concentrated in-plane loading were calculated according to the following dimensionless form:

$$N^*_{cr} = \frac{N_{cr} b^2}{D} \text{ for distributed loading}$$

$$N^*_{cr} = \frac{P_{cr} b}{D} \text{ for concentrated loading} \tag{1}$$

where N_{cr} is the intensity of the buckling load per unit length and P_{cr} is the concentrated buckling load. D is the flexural rigidity of the plate defined by:

$$\mathrm{D} = \frac{\mathrm{E}t^3}{12(1-\upsilon^2)}. \tag{2}$$