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Strengthening of perforated plates under uniaxial compression: Buckling analysis

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ABSTRACT

This paper focuses on the cutout-strengthening of perforated steel plates subjected to uniaxial compressive loads. The square plates considered each has a centrally placed circular hole and four simply supported edges in the out-of-plane direction. Four types of stiffeners named ringed stiffener (*RS*), flat stiffener (*FS*), longitudinal stiffener (*LS*) and transverse stiffener (*TS*) are mainly discussed. The finite element method (FEM) has been employed to analyse the elastic and elasto-plastic buckling behaviors of strengthened and unstrengthened perforated plates. The results show that the strengthened perforated plates have higher buckling strengths than those of the unstrengthened ones, while the elevations in elastic buckling stress and elasto-plastic ultimate strength are closely related to stiffener types (i.e., *RS*, *FS*, *LS* and *TS*) as well as plate geometric parameters (i.e., a plate slenderness ratio and a hole diameter ratio). Furthermore, comparisons of strengthening efficiency considering the variations of buckling stress with stiffener weight are carried out, and recommendations on the most efficient cutout-strengthening methods for the uniaxially compressed perforated square plates with centric circular holes are proposed.

1. Introduction

Cutouts are often provided in plate structures such as cold formed steel members, plate and box girders, box pylons and ship grillages for the purposes of access, services and even aesthetics. The presence of holes in such structures results in a redistribution of the membrane stresses accompanied by a change in mechanical behaviors of the plates. Concretely, a significant reduction in elasto-plastic ultimate strength, when compared to solid plate (i.e., imperforated plate), has always been found in perforated plates notwithstanding the occasionally occurring increase in elastic buckling critical load as reported in previous articles. When the cutout is inevitable for the plates under high working stress, the reduced buckling strength of the perforated plate may be insufficient to meet the requirements of normal serviceability and structural safety. It is necessary, hence, to adopt an appropriate cutout-strengthening method to improve the buckling behaviors (including elastic buckling critical stress and elasto-plastic buckling ultimate strength) of perforated plates in these situations.

A large number of researches have been undertaken on the buckling behavior of perforated plates and the main concerns in published articles can be classified into two categories, i.e., elastic buckling and elasto-plastic buckling. For elastic buckling, Shanmugam and Narayanan [1] and Sabir and Chow [2] firstly used the finite element method (FEM) to predict the elastic buckling stress of perforated square plates with different loadings and edge conditions. The conjugate load/displacement method (CLDM) was then successfully applied by Yettram, Brown and Shakerley [3–6] to the elastic buckling analysis of square plates with centric/eccentric rectangular perforations, accompanied by design guidance about geometric size, location and orientation of the rectangular hole. El-Sawy and Nazmy [7] investigated the effect of aspect ratio on the elastic buckling critical loads of uniaxially loaded rectangular plates with eccentric circular and rectangular (with curved corners) holes. El-Sawy and Martini [8] employed the finite element method to determine the elastic buckling stresses of biaxially loaded perforated rectangular plates with longitudinal axis located circular holes. Moen and Schafer [9] developed closed-form expressions for approximating the influence of single or multiple holes on the elastic buckling critical stress of plates in bending or compression. As for elasto-plastic buckling, Narayanan and Rockey [10] described the ultimate strength tests on thin-walled webs containing a circular hole and presented a method to approximately predict the ultimate capacity of plate girders with perforated webs. Azizian and Roberts [11] carried out the geometrically nonlinear elasto-plastic analysis using finite element method for axially compressed square plates with centrally placed square and circular holes. Narayanan and Chow [12] presented an approximate method of

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predicting the ultimate load carrying capacity of simply supported perforated plates under uniaxial compression, whose reliability was validated by comparing with test results. Curves suitable for the use of designers have also been proposed in the paper to determine the ultimate capacity of square plates with centrally placed holes. Shanmugam et al. [13] proposed a design formula, on the basis of the results from the finite element analyses, to determine the ultimate load carrying capacity of perforated square plates with square or circular holes for the cases of different boundary conditions and uniaxial or biaxial compression. El-Sawy et al. [14] focused on the elasto-plastic buckling of uniaxially loaded square and rectangular plates with circular cutouts by the use of the finite element method, including some recommendations about hole size and location for the perforated plates of different aspect ratios and slenderness ratios. Paik [15–17] investigated the ultimate strength characteristics of perforated plates under edge shear loading, axial compressive loading and the combined biaxial compression and edge shear loads, and proposed closed-form empirical formulae for predicting the ultimate strength of perforated plates based on the regression analysis of the nonlinear finite element analyses results. Maiorana et al. [18,19] dedicated to the linear and nonlinear finite element analyses of perforated plates subjected to localized symmetrical load. In summary, the elastic and elasto-plastic buckling behaviors of perforated plates with different aspect ratios (square and rectangular), slenderness ratios, hole shapes (square, circular, rectangular and rectangular with curved corners) and hole locations (centric and eccentric) have been systematically studied in previous researches, and conclusions, suggestions and formulations beneficial for practical engineering design have also been presented. However, most of them focused on the changes in buckling behavior of perforated plates due to the presence of cutouts. The cutout-strengthening methods used for improving the degraded buckling behavior of perforated plates have not been investigated in published literatures.

Herein, this paper is dedicated to the bucking analyses of strengthened perforated steel plates under uniaxial compression. The studied square plates with centric circular holes are considered to be simply supported on all edges. Four types of stiffeners, i.e., ringed stiffener, flat stiffener, longitudinal stiffener and transverse stiffener, are taken into account. A series of profound investigations of both elastic and elasto-plastic buckling behaviors for strengthened and unstrengthened perforated plates are carried out by the use of the ANSYS finite element method, since the elastic buckling stress and elasto-plastic ultimate strength are useful for the serviceability limit state (SLS) and ultimate limit state (ULS) design purposes, respectively. In addition, recommendations on the most efficient cutout-strengthening methods for the uniaxially compressed perforated square plates with different slenderness ratios and circular hole diameter ratios are proposed on the basis of contrastive analyses of strengthening efficiency considering varying stiffener weights (i.e., stiffener sizes) for each stiffener type.

2. Perforated square plates

2.1. Geometry

The perforated square plates, with a centric circular hole for each one, are employed as research objects in this paper. The following two geometric parameters have been considered:

- plate slenderness ratio b/t, varying from 20 to 100 with increment of 10,
- hole diameter ratio d/b, varying from 0.1 to 0.5 with increment of 0.1,

where b and t are the width and thickness of the square plate, and d is the diameter of the circular hole, as shown in Fig. 1.

Four types of stiffeners named ringed stiffener (*RS*), flat stiffener (*FS*), longitudinal stiffener (*LS*) and transverse stiffener (*TS*) are considered in the present paper due to their wide applications in practical engineering. The details of the strengthened perforated plates are shown in Fig. 2:

(1) For the *RS*-strengthened plate, a strengthening stiffener with thickness of t_a and width of h_a is symmetrically welded to the perforated plate at their circular intersections after being rolled into a ring with outer diameter d.
(2) For the *FS*-strengthened plate, three fabricating steps are normally suggested. Firstly, a circular hole with diameter of $(d+2t_b)$, where t_b is the thickness of square flat stiffener with width of L_b, should be perforated in the center of the stiffener. The perforated stiffener, then, is tightly attached to the surface of the plate strengthened with two circles in the plate and the stiffener being concentric. The welding is finally carried out along the inner (hole) edge and the four outer edges of the flat stiffener.
(3) For the *LS*-strengthened or *TS*-strengthened plate, the two stiffeners with thickness of t_c or t_d and width of h_c or h_d are parallel or perpendicular to the load direction after being welded to the perforated plate, and the smallest distance between hole edge and stiffener's surface, as used for welding, is selected as the same value of stiffener thickness (t_c or t_d).

Considering the common situations of practical engineering, the geometric sizes (interpreted in Fig. 2) of stiffeners selected in the following analyses take the values as follows:

- For ringed stiffener (*RS*), $t_a=0.5t$, $h_a=10t_a$.
- For flat stiffener (*FS*), $t_b=0.5t$, $L_b=1.8d$, $\theta_b=90^\circ$.
- For longitudinal stiffener (*LS*), $t_c=0.5t$, $h_c=8t_c$.
- For transverse stiffener (*TS*), $t_d=0.5t$, $h_d=8t_d$.

Note that there is another layout of flat stiffener where the stiffener's outer edges and plate's edges are skew (e.g., $\theta_b=45^\circ$). But it has been proved by the authors' analyses that the buckling stresses (including elastic and elasto-plastic) of $\theta_b=45^\circ$ are slightly smaller than those of $\theta_b=90^\circ$ (with result differences being no more than 4%). Therefore, this article only considers the case of $\theta_b=90^\circ$.

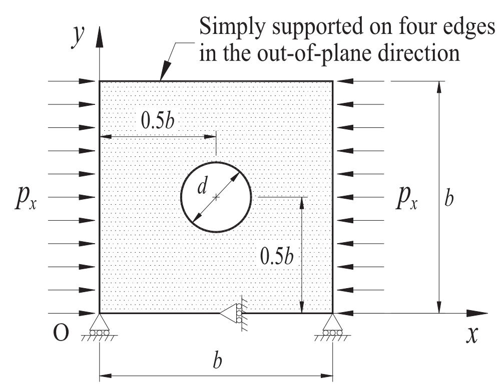

Fig. 1. The unstrengthened square plate with a centrally placed circular hole.