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Opening reinforcement for box-section walls containing continuous elliptical holes in steel pylons

Bin Cheng [a,b,*], Peng Shi [a], Jianlei Wang [a], Chun Li [a]

[a] Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT

This paper focuses on the reinforcing methods used for improving the compression behaviors of perforated box-section walls as provided in the anchorage zones of steel pylons to hold the cables. The rectangular plates investigated each have single-row continuous elliptical holes and are simply supported on four edges in the out-of-plane direction. Two types of reinforcing stiffeners named flat stiffener (FS) and longitudinal stiffener (LS) are considered. Uniaxial compression tests are first conducted for 46 specimens, of which 10 are unreinforced plates and 36 are reinforced plates. The mechanical behaviors such as stress concentration, out-of-plane deformation, failure pattern, and elasto-plastic ultimate strength are experimentally investigated. Finite element models are further developed to predict the ultimate strengths of plates with various dimensions. The FE results are validated by the test data. The influences of non-dimensional parameters including plate aspect ratio, hole spacing, hole width, stiffener slenderness ratio, as well as stiffener thickness on the ultimate strengths are illustrated on the basis of numerous parametric studies. Comparison of reinforcing efficiency shows that the continuous longitudinal stiffener is the best reinforcing method for such perforated plates. The simplified formulations used for estimating the compression strengths of reinforced plates are finally proposed.

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1. Introduction

In box-section steel pylons of cable-stayed bridges, cutouts in the outer walls are inevitable in the anchorage zones to hold the cables. The openings are usually of elliptic shapes arising from the oblique angles between the cables and the pylon, and multiple holes are often continuously provided corresponding to the number of cables and the anchorage locations. No out-of-plane loading occurs to the perforated plates through which the cables run, because the gaps between the cables and the hole edges are always reserved for deforming. Instead, due to the collaboration of sectional walls, the perforated plates are uniaxially compressed in the in-plane direction despite that the cables are commonly anchored onto the other non-perforated plates perpendicular to the perforated ones, and evidently, the lower plates bear higher compressive stresses than the upper plates. These perforated plates, commonly act as flanges of a box section, are more prone to compressive failure than those non-perforated web plates for the following reasons: (1) additional compressive stresses caused by significant sectional moments of the tower in the longitudinal plane of the bridge may occur on the flanges (i.e., perforated plates); (2) sectional areas of the plates are reduced because of the holes; and (3) the out-of-plane rigidity of the non-perforated web plates is improved since they are laterally connected with and thus supported by the rigid anchor systems.

The presence of continuous holes in such structures is expected to result in a significant increase in stress concentration and a remarkable reduction in ultimate bearing capacity of the compressed plate when compared to the non-perforated one. If the degraded ultimate strength of the perforated plate fails to meet the requirement of structural safety, an appropriate cutout-reinforcing method should be adopted to improve the behaviors. Unfortunately, there is no usable reference in existing literatures including current design codes for the reinforcement of such holes.

The studies on the stress concentrations of perforated plates were firstly carried out for infinite plates by Muskhelishvili [1], Savin [2], and Peterson [3], followed by the work concerning finite plates conducted by Zhang et al. [4], Yang et al. [5], She and Guo [6], Li et al. [7], and Yu et al. [8]. More efforts were devoted to the ultimate strengths by considering the elasto-plastic buckling of the plate. Narayanan and Rockey [9] carried out 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 [10] performed 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 [11] presented an approximate method of predicting the ultimate load carrying capacity of simply supported perforated plates under uniaxial

* Corresponding author at: Room A508, Ruth Mulan Chu Chao Building, 800 Dong Chuan Road, Shanghai 200240, China.

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compression, whose reliability was validated by comparing with test results. Curves suitable for the use of designers have also been proposed in their study to determine the ultimate capacity of square plates with centrally placed holes. Shanmugam et al. [12] 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. [13] 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 [14–16] 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 analysis results. Maiorana et al. [17,18] performed the linear and nonlinear finite element analyses of perforated plates subjected to localized symmetrical load. Moen and Schafer [19] described the elastic buckling behaviors and proposed closed-form expressions for critical elastic buckling stresses of plates with single or multiple perforations including slotted holes under bending and compression. Cheng et al. [20,21] experimentally and numerically investigated the influences of slotted holes and continuous elliptical holes on the stress concentrations and ultimate strengths of the compressed plates in steel pylons, with enclosed formulae having been proposed for the strength estimation. Cheng and Zhao [22,23] investigated the cutout-strengthening of uniaxially compressed shear loaded square plates containing single circular hole by the use of finite element method. In summary, behaviors of perforated plates considering various parameters have been comprehensively investigated in previous researches, and some recommendations and formulations beneficial for practical engineering design have also been presented. However, very few of them are related to the continuous elliptical holes or to the reinforcement of holes.

Therefore, as a continued work for the paper [21], this research further focuses on the reinforcing methods as used to improve the compression behaviors of plates perforated by continuous elliptical holes. Besides the longitudinal stiffeners (LS) that have been noted in current design codes [24–27] to be commonly used to reinforce the solid thin-walled plates so that the local buckling could be avoided, another type of reinforcing stiffeners called flat stiffener (FS) is also considered for the perforated plates due to simple detail and easy construction. The studied plates are supposed to be simply supported in the out-of-plane direction on their four edges. The single row of elliptical holes is centrally located in the center line of the plate, and uniaxial in-plane compression is considered according to the practical stress distribution of plates in pylon. Compression test of both unreinforced and reinforced plates is carried out by the use of a self-balanced loading device, followed by a large number of parametric numerical studies concerning various dimensions of plates, holes, and stiffeners using finite element method. Behaviors such as stress concentrations, out-of-plane deformations, failure patterns as well as elasto-plastic ultimate strengths of the plates are investigated. The influences of non-dimensional parameters including plate aspect ratio, hole spacing, hole width, stiffener slenderness ratio, as well as stiffener thickness on the ultimate strengths are obtained. Comparisons in reinforcing efficiencies of stiffeners are also made, and the simplified formulations used for estimating the compression strengths of reinforced plates are finally proposed for engineering applications.

2. Test setup

2.1. Test specimens

A total of 46 perforated rectangular plates were fabricated, of which 10 were unreinforced plates and 36 were reinforced plates.

For the unreinforced (UN) plates perforated by continuous elliptical holes, three non-dimensional parameters, that is, plate aspect ratio a/b, hole width/plate width d/b, and hole spacing/length l/h, were mainly considered, and the selected values were $a/b = 0.9$, 1.8, 2.4 and 3.6, $d/b = 0.1$ and 0.2, and $l/h = 2$, 3 and 4, respectively. Here, a, b, d, h, and l correspond to the plate length and width, and the hole width, length, and spacing, respectively (Fig. 1). The plate slenderness ratios, i.e., b/t, of all specimens were selected as 30. As a result of the oblique angles between the stayed cables and the pylon, the length of elliptical hole was always selected as 1.5 times its width, that is, $h/d = 1.5$.

For the reinforced plates, two types of reinforcing stiffeners named flat stiffener (FS) and longitudinal stiffener (LS), as shown in Fig. 2, were investigated.

(1) For the FS-reinforced plate, three fabricating steps were adopted. Firstly, one row of continuous elliptical holes each with width of $(d + 2t_f)$ and length of $(h + 2t_f)$ was perforated in the rectangular flat stiffener with length of a_f, width of b_f, and thickness of t_f, with the hole spacings equal to those of holes provided in the compressed plate. The perforated stiffener, then, was tightly attached to the surface of the plate to be reinforced, with elliptical holes in the plate and the stiffener being concentric. The welding was finally carried out along the inner (hole) edge and the four

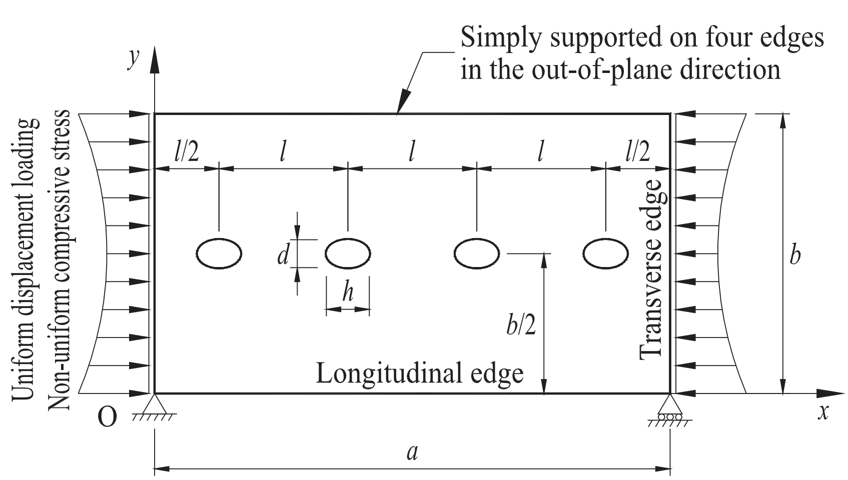

Fig. 1. The unreinforced perforated plate containing continuous elliptical holes.

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