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Elastic stability of uniformly compressed plates perforated in triangular patterns

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Critical elastic buckling load of uniformly compressed isotropic plates perforated in equilateral triangular patterns was investigated using FEM. Stiffened and unstiffened square and rectangular elements with wide ranges of hole diameter-to-spacing ratio and plate slenderness were studied. The effect of perforations on the critical elastic buckling load was determined. Design formulas for predicting critical elastic buckling stress based on reduction coefficient approach and equivalent thickness approach were developed using multiple nonlinear regression analysis of FEM results. The obtained critical elastic buckling stress reductions and developed formulas were verified by comparison with results available in literature and with an extensive database of FEM results.

1. Introduction

Cold-formed metal decks are frequently used in building construction for roofing and flooring. In addition to the structural effectiveness due to their strength and lightweight, metal decks can also provide a finished ceiling with sound absorption capabilities when the decks are perforated and combined with a sound absorbing material. Such decks are usually referred to as acoustic or acoustical. The perforations are typically in the form of periodic small round holes located either in webs or flanges of the deck. Fully perforated decks are used as well.

Individual elements of cold-formed metal decks have large width-to-depth ratios, which make them vulnerable to local buckling at stress level lower than the yield point of steel when they are subjected to compression. Perforations reduce stiffness and critical elastic buckling stress of the plates and make analysis of the perforated plates even more complicated. A number of studies were dedicated to the stability of plates with one hole or with an array of holes [1–8]. There are also publications on analysis of multiperforated thick plates, commonly referred to as tube sheets, used in heat exchangers and pressure vessels [9]. Results of those studies cannot be used for analysis of thin plates with multiple periodic holes because of either significantly different arrangements of holes or significantly different plate thickness. The sheet thickness-to-hole spacing ratio was usually greater than three in the tube sheet studies.

Eurocode 3 [10] contains equations for effective thickness of sheeting perforated in equilateral triangular patterns. The effective thickness is the thickness of an equivalent non-perforated sheeting reduced based on the hole diameter-to-spacing ratio. The effective thickness in Eurocode 3 [10] is different for membrane and bending stiffness. The equations are based on numerical investigations by Schardt and Bollinger [11] and address only stiffness, but not stability of perforated plates.

Misiek and his co-authors [12–14] analytically and numerically investigated stiffness and stability of thin plates perforated with round holes arranged in triangular or quadratic patterns. Two quadratic patterns were considered: with rows of holes parallel and inclined at 45° to the direction of applied load. The plates were fully and partially perforated. Results of the study were presented in the form of graphs of the reduction factors for stiffness and buckling coefficient. Misiek and his co-authors [12–14] obtained very interesting and useful information that sheds light on stability of multiperforated plates. Their study, however, covered only square plates simply supported on four sides, commonly referred to as stiffened elements. Rectangular plates and plates simply supported on three sides, so-called unstiffened elements, were not studied.

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Nomenclature

a	is plate length;
a_1, a_2, a_3, and a_4	are regression coefficients;
b	is plate width;
c	is spacing of holes;
d	is diameter of holes;
E	is elastic modulus;
f_{cr}	is critical elastic buckling stress of perforated plate;
$f_{cr,solid}$	is critical elastic buckling stress of solid plate;
k	is buckling coefficient;
k_p	is critical elastic buckling stress reduction coefficient due to the perforations;
k_s	is plate slenderness coefficient;
P_{cr}	is critical elastic buckling load of perforated plate;
$P_{cr,solid}$	is critical elastic buckling load of solid plate;
$P_{cr,perf}^{Eq.(7)}$	is critical elastic buckling load of perforated plates with k_p calculated using Eq. (7) for stiffened square and rectangular elements;
$P_{cr,perf}^{Eq.\ (8)\ or\ Eq.\ (9)}$	is critical elastic buckling load of perforated plates with k_p calculated using Eq. (8) for unstiffened square elements or Eq. (9) for unstiffened rectangular elements;
$P_{cr,perf}^{Eq.\ (10)}$	is critical elastic buckling load of perforated plates with k_p calculated using simplified design formula (Eq. [10]);
$P_{cr,perf}^{FEM}$	is critical elastic buckling load of perforated plates from FEM;
$P_{cr,perf}^{IPA\ Handbook[17]}$	is critical elastic buckling load of perforated plates calculated using equivalent stiffness concept published in [17];
$P_{cr,perf}^{Misiek\ etal.}$	is critical elastic buckling load of perforated plates calculated with the method proposed by Misiek et al. in [12–14];
R^2	is coefficient of determination;
t	is plate thickness;
t_{eq}	is equivalent plate thickness reduced due to the perforations;
w_{cr}	is distributed critical elastic buckling load of perforated plate;
α	is plate aspect ratio;
ν	is Poisson's ratio.

AISI-S100 [15] contains limited provisions for determination of the effective width of uniformly compressed stiffened elements with circular holes, which are based on study conducted by Ortiz-Colberg and Pekoz at Cornell University on cold-formed steel columns [16]. The provisions cannot be applied to multiperforated plates discussed in this paper.

The IPA Handbook [17] presents the equivalent solid material concept, where equivalent strength or stiffness of the perforated material is used in place of strength or stiffness of the solid material. Effective elastic modulus and Poisson's ratio given in [17] are functions of percent open area for the in-plane loaded plates perforated in equilateral triangular patterns. The effective elastic properties could be used for calculation of the critical elastic buckling stress of perforated plates. However, no justification on the applicability of this approach for critical elastic buckling stress calculation was found.

In the present work, elastic buckling of uniformly compressed isotropic plates perforated with round holes in equilateral triangular patterns was studied using the finite element method (FEM). Stiffened and unstiffened square and rectangular plates with wide ranges of hole diameter-to-spacing ratio and plate slenderness were studied. A series of design formulas for predicting critical elastic buckling stress of perforated plates based on two approaches was proposed. Applicability of the effective elastic properties given in IPA Handbook [17] for critical elastic buckling stress calculation was evaluated.

2. Scope of study

Elastic buckling of isotropic plates with round holes in equilateral triangular patterns subjected to uniaxial compression was analyzed using FEM. In an equilateral triangular perforation pattern, three adjacent holes are centered on the tips of equilateral triangles as shown in Fig. 1. This pattern was selected for the study because it is the most effective packaging arrangement and the most popular pattern due to its inherent strength and wide range of open areas it provides [17].

Preliminary calculations showed that critical elastic buckling load of the perforated plates is affected by the hole diameter-to-hole spacing ratio, d/c, irrespective of the absolute values of the hole diameter and spacing. Therefore, only one hole diameter of 12.7 mm (0.50 in.) was used in the study. Spacing of the holes ranged from 101.6 mm (4 in.) to 13.4 mm (0.526 in.), resulting in the d/c ratios from 0.125 to 0.950 and in the percent open areas from 1.4% to 81.8%, respectively, which cover most of the practical cases.

Square and rectangular plates with the aspect ratio of nine were analyzed. Stiffened elements represented by plates simply supported on four sides and unstiffened elements represented by plates simply supported on three sides, while the unloaded fourth side remained free, were studied. The plate slenderness, b/t, ranged from 20 to 80. The plates were assumed to be made from cold-formed steel with elastic modulus of 2.03×10^5 N/mm^2

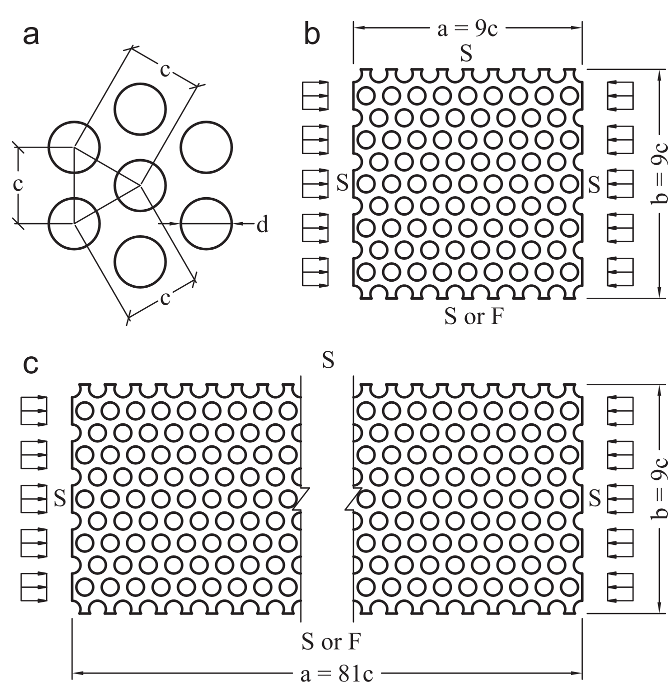

Fig. 1. Studied perforated plates. (a) Equilateral triangular perforation pattern; (b) Square plates; and (c) Rectangular plates. S=simply supported side; F=free side.