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Local buckling of aluminium and steel plates with multiple holes

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ABSTRACT

This paper considers local buckling of perforated square aluminium plates. Plates of various slenderness with simply supported edges and subjected to uniaxial compression are studied using the finite element method. Different perforation patterns are investigated, from a single circular hole to 25 circular holes distributed over the plate. A number of aluminium alloys are considered and compared to steel grade A36. Results show that the resistance of the plates containing a single central cut-out is higher than that of plates with more holes and of equal total cut-out size. A further refinement beyond 5 holes does not influence the resistance.

1. Introduction

Aluminium plates containing a single hole or multiple holes in a row are used in many applications, for example for window cut-outs in airplane fuselages and ships or inspection holes in webs of steel box girder bridges, offshore platforms and ships. Aluminium plates with multiple holes are also applied in building structures for a number of reasons:

- They allow for a weight reduction;
- They allow light from outside to enter the structure or vice versa;
- They allow for ventilation of storage buildings;
- They ease fastening to other structural elements;
- They enhance sound insulation when combined with proper insulation materials.

Because of the slenderness of these plates, instability should be considered in their design. Local buckling of steel plates with one hole has been studied before, [1–17], as well as local buckling of steel plates with a number of holes in a row, [18–21]. The results of these studies will be discussed below. Some inconsistencies in the results of these studies appear to be related to unclear definitions of the limit loads or limit stresses. The definitions used throughout this paper are explained in Fig. 1, which provides the force versus out-of-plane deformations of a slender (Fig. 1a) and a stocky (Fig. 1b) plate. Symbols F_E and σ_E indicate the Euler or critical elastic buckling load and stress, respectively. For a plate of linear elastic material, increasing force causes increasing out-of-plane deformations, starting at F_E. For a plate with non-linear material properties, the plastic squash load, F_{pl}, indicates yielding at zero out-of-plane deformations. The plastic squash load is thus equal to the yield stress σ_y multiplied by the plate cross-sectional area A. For an imperfect plate containing out-of-plane deformations, a moment develops upon loading and this causes a decreasing plastic force for increasing out-of-plane deformations. The failure load F_{fail} is bounded by the buckling curve and the plasticity curve. For slender plates, Fig. 1a, the deformations become large at reaching F_{fail} and this may give rise to problems such as web breathing in the serviceability limit state. For this reason, the extra strength in the post-buckling region is often not fully exploited and the resistance, F_u, is defined as the minimum of F_{fail} and F_E, i.e. it is equal to F_E for slender plates, Fig. 1a, and equal to F_{fail} for stocky plates, Fig. 1b. This definition is in agreement with most previous studies into buckling of steel plates with holes. In the conversion from force to stress, the gross area without deduction for holes is used and the stress presented is the average stress over this gross area: $\sigma_u = F_u / A_{full}$.

Several studies have been carried out on local buckling of steel plates containing holes. Many of these consider only one hole. The critical elastic buckling load of plates with a hole is extensively

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Nomenclature

A	area of the gross cross-section
E	Young's modulus
N	number of holes
P	perforation ratio
b	plate width
d	hole diameter
f	reduction factor
k	buckling factor
n	hardening exponent in the Ramberg–Osgood relationship
t	plate thickness
α, β	buckling coefficients
ε	strain
ν	Poisson ratio
σ	stress

Subscripts

$_E$	Euler
$_{fail}$	failure
$_{full}$	full plate
$_{pf}$	perforation
$_{pl}$	plastic
$_{tan}$	tangential
$_u$	resistance
$_y$	yield

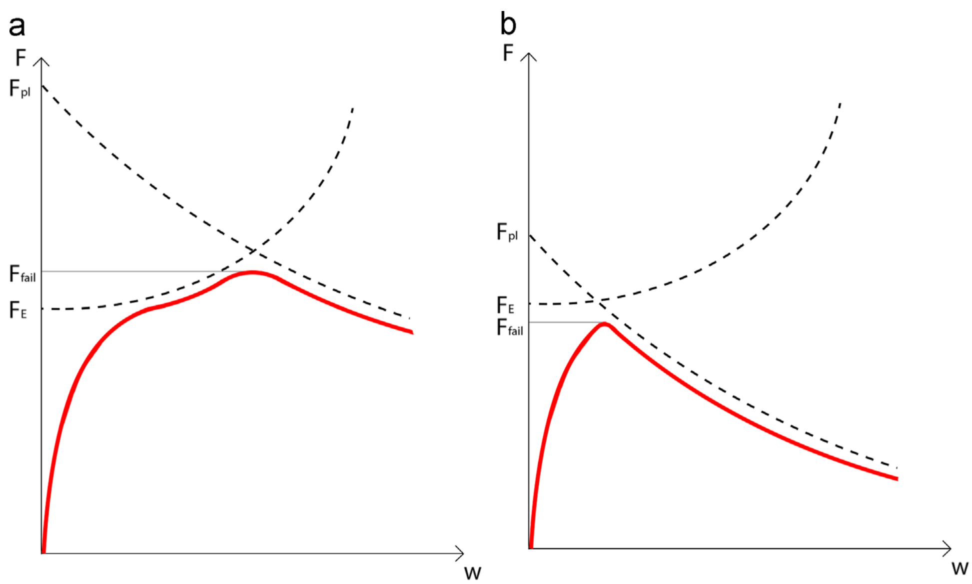

Fig. 1. Force versus out-of-plane deformation. (a) Slender plate, where $F_u = F_E < F_{fail}$. (b) Stocky plate where $F_u = F_{fail} < F_E$.

studied and reported in many papers, of which the first ones were published in the 1960's and 1970's, [1–3]. The first studies providing failure loads were based on experiments, [4–8], but this method has been replaced by finite element analyses in more recent studies, and these are discussed here. Roberts and Azizian [9,10] determined the resistance of a square plate with a central hole subjected to uniaxial or biaxial compression or shear. El-Sawy et al. [11] studied the change in failure mode from elastic buckling to failure of square and rectangular plates with central and non-central holes of materials with various yield stresses. Maiorana et al. [12] investigated the influence of a localised load on the resistance. Aydin Komur [13] considered the resistance of plates with elliptical cutouts. Shanmugam et al. [14] developed a design equation to approximate the failure load of perforated steel plates, which was based on a curve fit of results using the finite element method. Paik [15–17] developed empirical formulas for the failure load of perforated plates under combined biaxial and shear loading.

Moreover, a limited number of studies was performed on local buckling of plates with more than one hole. Moen and Schafer [18,19] and Moen [20] have considered elastic buckling of long plates with multiple holes, all in one row. Smith and Moen [21] considered elastic buckling of long cold-formed columns with multiple holes in one to three rows. The main parameters influencing the buckling behaviour of steel perforated plates loaded in uniaxial compression are derived from these studies and discussed below.

An important parameter is the aspect ratio. The resistance of rectangular, full plates with an integer aspect ratio is known to be equal to that of a square full plate. For plates containing central holes, however, a rectangular plate with an integer aspect ratio has larger values of F_E and F_{fail} as compared to an equivalent square plate, [22], [12–13]. Moen and Schafer [18] demonstrated that the presence of a hole can even increase F_E in case of relatively short plates with one hole or with multiple holes in a row. This is due to the fact that the hole influences the wavelength of the buckles. For longer plates, the increase is lost.

Plate slenderness is another important parameter. The thickness over width ratio has been considered in all mentioned studies. As for plates without holes, the resistance, σ_u, always decreases as the thickness over width ratio decreases and the governing criterion for the resistance changes from F_{fail} to F_E. The reduction of F_{fail} caused by the presence of a single hole is larger than the reduction of F_E.

The critical elastic buckling load is almost independent of the hole size, e.g. [11] and [23]. Some studies even conclude that F_E increases with increasing hole size, which is attributed to redistribution of membrane stresses towards the edges of the plate,