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Effect of hole reinforcement on the buckling behaviour of thin-walled beams subjected to combined loading

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ABSTRACT

In this study, the effect of hole reinforcement on the buckling behaviour of thin-walled structures mostly used in aircrafts is investigated under combined loads. A fuselage floor beam with real dimensions is used for the buckling analysis, and a parametric study based on several loading scenarios is considered. Investigated structures include different ratios of hole diameter to reinforcement width (d/w), ratios of reinforcement height to web plate thickness (h/t), and the aspect ratio of the web plate (a/b). The material of the thin walled structure is Al 7075 series. The commercial finite element analysis program, ABAQUS, is used for buckling analysis. The loading scenarios such as compression, shear, and bending, as well as combined loading are considered using a validated finite element model. For the selected range of geometrical parameters, buckling loads and allowable buckling stresses are computed. Furthermore, compression, shear and bending rates are calculated, and the interaction curves are plotted with the help of data obtained from the finite element studies. The effect of loading scenario on the buckling strength is compared for beam without a hole, with a hole and with a hole plus reinforcement cases. The main goal of this study is to provide engineers graphical data that can be used to check whether or not a structure will fail under several defined load cases including combined loading.

1. Introduction

Thin-walled structures are widely used in aerospace and defense industry applications. Since the reserve factor is kept low in this type of structure, it tends to show easy buckling. Moreover, due to various design requirements such as power cables, hydraulic tubes, fresh and waste water pipes, a web of open holes need to be created in the structure [21,26]. A structure weakened by open holes can be reinforced by local support around the hole [3,8,16]. Thus, it becomes stronger with respect to buckling and has a lighter design than a perforated plate.

Different hole types such as rectangular [2,17], hexagonal [31] or circular [11] and different number of holes [23–25] have been used in the literature [1]. One circular hole on web is considered for this study.

Many researchers have studied the buckling behaviour of beams [20,29] or plates [33]. Some of these studies have been undertaken for thin plates with holes using specific technical methods such as theoretical hand calculations, the Finite Element Method (FEM) and testing procedures. Moen and Schafer [19] focused on closed-form expressions for approximating the influence of single or multiple holes on the critical elastic buckling stress of plates in bending or compression. They have created a parametric buckling formula for plates simply supported on 3 or 4 sides and validated their formula using FEM and classical engineering approximations. Panedpojaman et al. [22] have developed a practical approach for estimating the shear strength of non-composite symmetric and asymmetric cellular beams, based on failure by local web-post buckling. They investigated the influence on buckling strength and buckling mechanisms of geometric web-post parameters, such as section size, opening depth ratio, spacing ratio and tee depth with a validated finite element (FE) web-post model. Tsavdaridis and D'Mello [28] have presented an experimental and analytical study on the behaviour of perforated steel beams with closely spaced web openings to investigate the failure mode and load strength of a web-post between two adjacent web openings. They developed numerical test specimens and verified their analyses using FEM and compared their results with full-scale experiments. They considered the effects of web opening depth and web thickness in order to understand the stability of a web post subjected to vertical shear load.

Cheng and Zhao [5] studied the cut out-strengthening of perforated steel plates subjected to uniaxial compressive loads. They considered that each of the square plates that have a centrally placed circular hole and four simply supported edges in the out-of-plane direction. They

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used FEM to analyze the elastic and elasto-plastic buckling behaviours of strengthened with different types of stiffeners and unstrengthened perforated plates. They found out that the inelastic buckling stress and elasto-plastic ultimate strength are closely related to stiffener types as well as plate geometric parameters. Eiblmeier and Loughlan [9] investigated the influence of cut-out diameter and circular reinforcement ring width on the buckling stability of square panels under pure shear or under pure compression loads. The results of their study showed the influence of cut-out diameter and reinforcement ring width on the buckling stability of simply supported panels.

Although, in the literature, there are many buckling loads types studies performed on beams such as plates under only compression [4,6,33], only pure shear load [7,12,30], pure bending loads [34,19], both of each pure loads [32] or lateral torsional [13,21], combined loading applications have not been considered. The most important feature that makes this article different from the previously published studies is that the study is conducted under combined loads (compression, shear and bending).

This paper is organized as follows: parametric geometry criteria [10] and material properties are provided in Section 2. In Section 3, we presented the validation of the finite element model using the result of experimental [28], finite element analysis [22] in the literature and theoretical hand calculations [14]. Buckling analysis results and the critical buckling stress curves with respect to the geometric parameters are given for pure compression, shear and bending loads in Section 4. More than 400 models were analyzed with the validated finite element model to determine the buckling interaction curves. Section 5 provides a parametric buckling analysis study conducted under combined loading using the variables mentioned above. A numerical example for usage the interaction curve so that engineers can use our graphical data to check whether their system buckles or not is given in Section 6. Finally the conclusion drawn from this study is presented in Section 7.

2. Floor beam

2.1. Geometry

The structural body of an aircraft consists of three parts: the skin, the frame and the longitudinal beams (longeron and stringer). The structures subjected to passenger weight are called floor beam and floor panels, as shown in Fig. 1. There are many holes in web section of the beam because of various design principles and the need to alleviate the overall structure weight. Structures weakened by hole opening can be strengthened by two different methods. If a beam is produced by the sheet metal method, it is reinforced with a bending sheet on the perimeter of the hole. If a beam is produced by CNC machining, the weakened regions can be reinforced using the cutout-strengthening method. The aerospace industry primarily uses the second method for hole reinforcement. The geometry used in this study is an I-type floor beam with a circular hole produced by a CNC machining method. Three

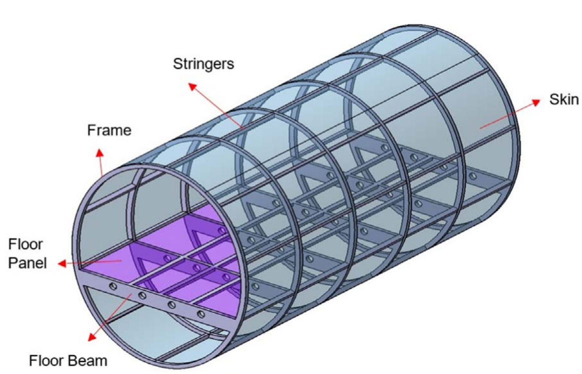

Fig. 1. The skeleton of the aircraft and floor beam structure.

different geometrical parameters are considered. The ranges of the geometrical parameters are selected as:

(i) Ratio of reinforcement width to hole diameter w/d, $0.033 \leq w/d \leq 0.150$.
(ii) Ratio of reinforcement height to web thickness h/t, $1.5 \leq h/t \leq 4.5$.
(iii) Ratio of web length to web height (aspect ratio) a/b, $1.5 \leq a/b \leq 7.0$.

The increments for the parameter ranges are designated to be 0.0167, 0.5 and 0.5 for w/d, h/t, and a/b, respectively. Web thickness, t, flange thickness, t_f, flange width, w_f, hole diameter, d, and web height, b are fixed at 2, 5, 48, 60 and 120 mm respectively. Web length, a, is taken to be 330 mm as a reference value. The geometry investigated in the study and parameters w, h, a, b, t, t_f and w_f can be seen in Fig. 2.

2.2. Material properties

In general aerospace structures, aluminum 2000 series is chosen for skin elements and aluminum 7000 series is preferred for frames, stringer, and beam components. Following these practices, 7075 T651 aluminum alloy material is selected for the aircraft fuselage floor beam used in this study. Details of the material properties are taken from Military Handbook [18], and required details are tabulated in Table 1. The plastic strain value to be used in non-linear buckling for finite element study is determined from the stress-strain curve displayed in Fig. 3. Values of stress-strain between yield and ultimate stress are imported to the FEA program's non-linear material properties module.

3. Validation of the finite element model

In this section, the value of the critical buckling stresses obtained from the finite element model are compared with those from theoretical hand calculations for plate structures under several loading conditions (such as pure compression, pure shear and pure bending loadings). The second validation step is conducted by comparing FEA results by studies of Panedpojaman et al. [22] and Tsavdaridis and D'Mello [28].

3.1. Flange support test

The buckling stress formulas taken from J. Huet [14] can be applied only for the plate structures. If the flange supports the web in a beam, the flange can be removed and the structure can be modeled as a four-sided, simply supported plate. This flange support test can be checked using the following inequality:

$$2.73\frac{I_t}{h_a e_a^3} - \frac{A_t}{h_a e_a} \geq 5, \tag{1}$$

where I_t is the moment of inertia of the flange, A_t is the cross-sectional area of the flange, h_a is the web height and e_a is the web thickness. In our reference geometry, the left-hand side of inequality Eq. (1) becomes approximately 60, which is much higher than the required value of 5. Therefore, theoretical hand calculations can be applicable for this study under different loading conditions.

3.2. Theoretical hand calculations

The reference plate geometry values given in Section 2.1 are used in the theoretical hand calculations. The allowable stress formulas under pure compression, pure bending and pure shear loading conditions can be computed as follows [14]:

$$F_{ccr} = K_c E_c \left(\frac{t}{b}\right)^2 \leq F_{cy}, \tag{2}$$