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Buckling and post-buckling of a composite C-section with cutout and flange reinforcement

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ABSTRACT

This paper presents an investigation into the effect of cutout and flange reinforcement on the buckling and post-buckling behaviour of a carbon/epoxy composite C-section structure. The C-section having a cutout in the web is clamped at one end and subjected to a shear load at the other free end. Three different stiffener reinforcements were investigated in finite element analysis by using MSC Nastran. Buckling load was predicted by using both linear and nonlinear FE analysis. Experiments were carried out to validate the numerical model and results. Subsequently post-buckling analysis was carried out by predicting the load–deflection response of the C-section beam in nonlinear analysis. Tsai-Wu failure criterion was used to detect the first-play-failure load. The effect of circular and diamond cutout shape and effective flange reinforcements were investigated. The results show that the cutout and reinforcement have little effect on the buckling stability. However an L-shape stiffener to reinforce the C-section flange can improve the critical failure load by 20.9%.

1. Introduction

Carbon reinforced composite materials are being increasingly used in primary airframes due to many advantages over the traditional metallic alloys. Research efforts have been made to further improve the structural design and mechanical performance in application. In this paper attention was focused on the buckling and post-buckling behaviour and design improvement of a composite C-section beam. This configuration may represent part of a typical wing or tail-plane spar structure. Since cutouts on the web are part of the structure features for weight saving or system access, their effect on the structural load carrying capability is one of the primary concerns in airframe design. Another concern is the buckling stability of the C-section especially the flange that is subjected to compressive force. The influence and reinforcement of the cutout on the C-section web on the flange buckling and failure should be quantified for this type of thin-walled structures.

Extensive research has been carried out for stress analysis around flat composite panels by analytical or numerical methods [1–4]. Studies were also performed in finding optimised cutout shape, e.g. Falzon et al. [5] showed that for a quasi-isotropic panel under in-plane shear load the optimum cutout shape was a diamond rather than the conventional circular. From the results of Kumar and Singh [6], quasi-isotropic laminate under combined in-plane loads with elliptical vertical cutout has the maximum buckling load and post-buckling strengths, whereas the laminate with elliptical-horizontal cutout has the minimum strengths. With the same composite laminate and loads, the effects of flexural boundary conditions on buckling and post-buckling responses with and without a central cutout of various shapes was carried out using finite element method [7]. Various cutout edge reinforcements were investigated to reduce stress concentration and increase buckling strength [8]. This result was further investigated for the C-section beam in a previous study [9] and relevant to this current research.

Cutout location and size also influence a composite panel's buckling stability. A comprehensive review on bucking and post-buckling behaviour of composite plates was published by Nemeth [10]. The review includes many influential factors, such as the cutout size, shape, eccentricity and orientation, plate aspect and slenderness ratios, loading and boundary conditions, and plate orthotropy and anisotropy. A further study on the post-buckling behaviour was conducted by Bailey and Wood [11], in which the influence of cutout diameter to panel length ratio (up to 0.65) on the load carrying capability was investigated. The study has shown that a ratio greater than 0.35 will result in higher buckling load that is even greater than that of a panel without a cutout. This is due to the change in load paths and stress redistribution. In a panel without a cutout a great portion of the pre-buckling axial load is centrally located; therefore the bending stiffness of the central part of the panel is of paramount importance. Research has shown that

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Nomenclature

E_i	ply modulus in the *i*-direction
G_{ij}	ply shear modulus in the *i*–*j* plane
ν_{12}	ply Poisson's ratio in the 1–2 plane
X_t, X_c	tensile/compressive strength in fibre direction
Y_t,Y_c	tensile/compressive strength in transverse direction
S	shear strength
ρ	density of the composite
σ_1	maximum principal stress

bending stiffness and buckling resistance are reduced when relatively small cutouts are introduced. However, when a relatively larger cutout is present, the load path is no longer centrally located but directed towards the edges of the panel. This explains why the buckling stability is greater for panels with larger cutouts. In this regard, Eiblmeier and Loughlan studied the buckling response of a composite laminate panel with reinforced circular cutout under different loading and boundary conditions [12,13].

Lateral buckling is one of the most important mechanical behaviour of composite beams subjected to certain external loads. The effects of hole diameter and hole location on the lateral buckling behaviour of woven fabric laminated composite cantilever beams were investigated by Eryigit et al. [14]. Pasinli [15] studied the similar cantilever beams but having two square or two circular holes by using theoretical, experimental and numerical methods. It was concluded that the circular holes are advantageous compared to the square ones in terms of lateral buckling behaviour. Cylindrical shell is one of the important structures used widely in engineering applications. Buckling and post-buckling of these shells is a necessary fundamental problem and has been attracted attention of many researchers [16]. Shi et al. [17] investigate the local and global buckling responses of composite grid stiffened cylindrical shells with unreinforced or reinforced cutouts under axial compressive loading. The results indicated that the grid reinforcements can reduce or eliminate the risk of local buckling response near the cutout areas and increase the critical load more effectively than the skin reinforcements.

Research on the fibre tow placement (or fibre tow steering) technique has been conducted recently in order to reduce cutout stress concentrations. Jegley et al. [18] demonstrated the effectiveness of fibre tow steered panels in reducing the stress concentration and improving the overall panel load carrying capability under both compressive and shear loads. Lopes and Gürdal [19] carried out a study on the post-buckling progressive damage behaviour and final structural failure of tow-placed composite panels with a central cutout. Panels with fibre tow reinforced cutout showed up to 56% higher strength compared with the straight fibre laminates. Initiation of damage and final structural failure were also delayed significantly for the fibre tow reinforced panels.

Apart from the aforementioned studies on flat plates, buckling behaviour of composite C-section beams has also been reported in the open literature. For example, Razzaq et al. [20] focused on the effect of load position and warping on the buckling of a simply supported C-section beam under two point loads applied symmetrically about the beam's mid-span. It was found that the warping effect was most severe when the load was applied thought the centroid; stresses due to warping were over 20% higher than the flexural stresses. Lee and Kim [21] developed a finite element model to study the lateral buckling of a composite C-section beam. The effects of fibre orientation, location and type of applied load on critical buckling load were studied. The results showed that, for a simply supported beam, the warping effect was reduced by rotating the fibre angle off-axis up to 45°. This material layup has increased the critical buckling load of relatively long beams, but decreased the buckling stability of short beams (in which the optimal fibre direction was 0°). Shan and Qiao [22] derived a total potential energy method for a composite cantilever beam and conducted an analytical study of buckling due to bending and torsion considering various parameters such as the load location, fibre orientation and fibre volume fraction.

However, few studies have been published to address the cutout influence on the buckling and post-buckling behaviour of C-section composite beams. This current paper presents a study on cutout effect and flange reinforcement to improve bucking and post-buckling stability of a C-section beam. An experiment was conducted to validate the finite element model and analysis. Different cutout and reinforcement effects on the C-section buckling and post-buckling behaviour were studied and flange reinforcement was presented to improve the structure stability and strength.

2. Model and methodology

2.1. Material and geometry

Three constant C-section beams with and without a web cutout were studied. The beam is 650 mm in length, 200 mm in web depth and 100 mm in flange width, as shown in Fig. 1a. It is made of 16 plies of the M21/T800S carbon–epoxy prepreg in a symmetric layup $[\pm45/0/\pm45/90/\pm45]_s$ for both the web and flanges. The ply thickness is 0.25 mm resulting in 4 mm thick laminate. Mechanical properties of the laminate are given in Table 1. One of the C-section has a circular cutout on the web and another with a diamond shape cutout. Three different cutout reinforcements were considered. Detailed geometry and dimension of the cutouts and reinforcements are shown in Fig. 1b. The steel reinforcement rings of 1.5 mm thick and 20 mm wide were made of T300 series stainless steel. The laminate rings were 2 mm thick and 20 mm wide cut from an eight-ply laminate made of the same material as the beam with stacking sequence $[0/\pm45/90]_s$. The fibre tow rings were made of six plies of 0.25 mm thick fibre tape.

In order to improve the buckling and post-buckling performance of the C-section beam, three flange reinforcements of L-shape stiffeners (Re1–Re3) as shown in Fig. 2 were designed. They are made of the same material and layup as the beam and have the same weight. However the cross section, length and bonding position are different. The cross section of stiffener Re1 is twice of Re2, but half the length. The vertical stiffener Re3 has the same geometry size as Re1, but different bonding direction from the horizontal stiffeners Re1 and Re2. For each reinforcement design, only one of these stiffeners was used.

2.2. Numerical model and analysis

The C-section beam was numerically modelled and analysed by using the commercial package MSC Patran/Nastran. The beam and reinforcement rings were modelled by quadrilateral shell elements (QUAD4) with composite laminate properties. The offset command was used to model the separate surfaces representing the beam