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Experimental and numerical investigation of buckling behavior of composite cylinders with cutout

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ABSTRACT

This manuscript employed experimental and numerical procedures to investigate the effects of initial geometric imperfection on the buckling behavior of the perfect and perforated composite cylinders. In the numerical part, linear eigenvalue analysis of the perfect cylinder showed a large discrepancy in comparison to the NASA SP-8007 guideline from 1968. However, results were considerably enhanced by performing a nonlinear analysis where initial geometric imperfection was simulated using Single Perturbation Load Imperfections (SPLI) and Linear Buckling Mode-shaped Imperfections (LBMI) techniques. Numerical analyses were performed for three different groups of the perforated cylinders to evaluate the effect of the growing cutout size on the buckling behavior. In addition, the mutual effect of the cutout and the initial geometric imperfection on the buckling analysis were investigated. Results confirmed that cutout effect is dominant, for the cylinder under consideration, so considering initial geometric imperfection has a negligible effect on the predicted buckling load. In the experimental part, perfect and perforated glass/epoxy composite cylinders with a stacking sequence of [90/+23/−23/90] were manufactured using filament winding technique and tested under compressive axial loading. Buckling test data of the perfect and perforated cylinders showed an acceptable correlation with the numerical results obtained using the nonlinear analyses methods.

1. Introduction

Fiber-reinforced composites are widely used in aerospace structures due to their outstanding properties as, high strength and stiffness to weight ratios compared to traditional materials. The traditional approach to design thin walled structures subjected to compressive loading is to use deterministic analysis to predict buckling load and then empirical knock-down factors as NASA SP-8007 were applied to reduce the load [1]. NASA guideline curve was introduced as a knock-down factor in terms of radius to the thickness ratio, (R/t), in the isotropic cylindrical shell as shown in Fig. 1. However, these factors are inappropriate for buckling evaluation of cylinders manufactured using composite materials, so, new analysis procedures are under investigation by taking into account the properties of composite materials. As well as, most aerospace structures are introduced with cutouts which are necessary for maintenance and inspection of internal mechanisms. Cutouts presence made these structures more vulnerable to compressive loading and necessitate to update the current analysis methods. So far, many analytical solutions have been developed to predict buckling load of the cylindrical shell by considering the effect of initial geometric imperfections as Flugge [2], Donnell [3] and Koiter [4]. Ravenhall [5] offered a correction factor to resolve the discrepancy between experimental and numerical results of cylindrical shells. Readers are referred to Tannyson [6] for detailed information.

Hutchinson and Koiter [7] investigated the effect of imperfections on the buckling behavior of cylindrical shell. Khot [8] employed the non-linear Donnell's theory, and Card [9] used Koiter's theory along with the energy method to consider the effect of imperfection on the buckling analysis of composite cylindrical shells. They defined imperfections as an initial displacement in their procedures. The method of Linear Buckling Mode-shape Imperfections (LBMI) was proposed by Khot and Venkayya [10]. They used axially symmetric mode-shapes obtained through linear eigenvalue buckling analysis as the initial geometric imperfections in their nonlinear analysis.

Hilburger et al. [11] examined manufacturing signature causes geometric imperfections and compared results with LBMI method. Hühne et al. [12] proposed a method to obtain buckling load by considering a local distortion in a local area of the shell structure. In their procedure, local perturbation was simulated by applying a lateral load and buckling was continued by applying the axial load. They found that after reaching to a certain lateral load which is named P1, cylinder lost sensitivity to the lateral load, the corresponding axial load to P1 is

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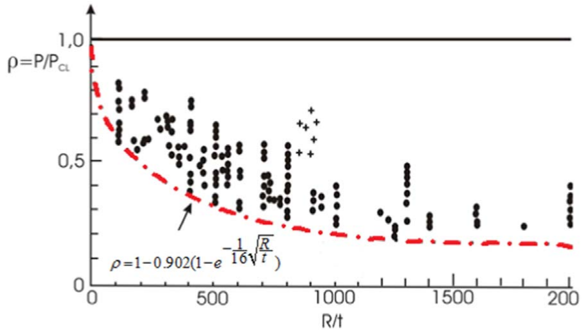

Fig. 1. NASA SP-8007 guideline curve [1].

assigned as the buckling load of the cylinder. This method is called Simple Perturbation Load Imperfections (SPLI) also is classified as a ‘worst’, ‘realistic’ and ‘stimulating’ imperfection by classification of Winterstetter and Schmidt [13]. Degenhardt et al. [14] proposed a probabilistic stability analysis via Monte Carlo simulation and examined various imperfections associated with geometric, loading and material properties. They found that geometric imperfections have the most important effect on the axial buckling capacity of the shell structure. In a comprehensive numerical investigation performed by Castro et al. [15], several imperfections modeling methods were simulated numerically and results were compared and discussed.

Hilburger et al. [16,17] developed an analytical solution to predict buckling load of the composite cylinder with cutout. Their analytical predictions showed good correlation with STAGS software results and experimental data. Later, Tafreshi [18] showed Hilburger's results were well matched with Abaqus software results. Orifici and Bisagni [19] have used the SPLI method to predict buckling load of composite cylinders with various sizes of square cutouts and stacking sequences.

Arbelo et al. [20] numerically examined the combination of the effect of imperfections caused by SPLI method and cutout on composite cylindrical shells. They concluded, in the small cutout the effects of imperfections on the buckling load are dominant and after a specified cutout size this effect is negligible in comparison with the effect of the cutout. Also in large cutout, a combination of both effects are responsible for the buckling behavior. They did not verify their numerical findings with experiment.

To the best knowledge of the authors, there is no published data regarding experimental evaluation on the effects of a circular cutout on the bucking behavior of composite cylinders. In the present manuscript, the effect of initial geometric imperfections on the buckling load of a cylindrical shell with and without circular cutout is investigated by employing experimental and numerical techniques. In the numerical part, initial geometric imperfections are simulated by using SPLI and LBMI methods in Abaqus software. In the experimental part, perfect and perforated glass/epoxy composite cylinders are fabricated and tested to evaluate the numerical findings. The major concern of this paper is to experimentally evaluate the combination effect of initial geometric imperfection and cutout on the buckling capacity of the composite cylinder for the present study case.

2. Experimental consideration

2.1. Specimen fabrication

Cylindrical specimens were fabricated using E-glass fiber (1200 tex direct roving) and Araldite LY 556 epoxy resin and HY917 hardener using filament winding method and were cut to the required size as shown in Fig. 2. The nominal laminate thickness of all the cylinders was approximately 2.2 mm, with a nominal inner diameter of 378 mm and an overall length of 700 mm. Table 1 shows geometric properties of the fabricated cylinders. The stacking sequence of all cylinders was [90/23/−23/90], where each layer had a thickness of 0.55 mm. In the current research, 4 perfect cylinders and 6 perforated cylinders were fabricated and tested to verify the numerical findings.

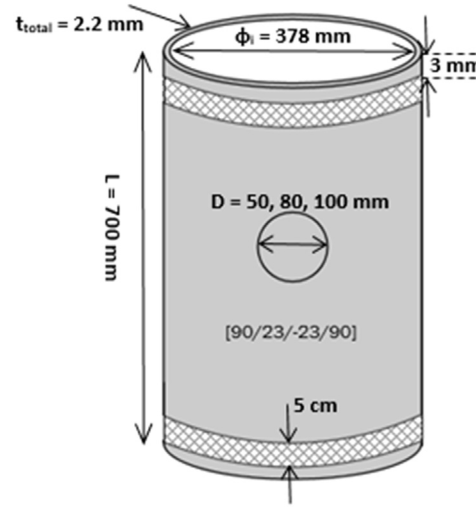

Fig. 2. Composite cylinder dimensions and layup.

Table 1
Geometrical properties of samples (dimensions are in mm).

Code	Cutout diameter	Length	Total thickness	Inner diameter	Number of samples
A3	–	700 ± 2	2.1 ± 0.1	378	4
B50	50 ± 1	700 ± 2	2.1 ± 0.1	378	2
B80	80 ± 1	700 ± 2	2.1 ± 0.1	378	2
B100	100 ± 1	700 ± 2	2.1 ± 0.1	378	2

The ends of the specimens were machined parallel and flatted to assure proper load introduction during testing. Fig. 2 shows the perforated cylinder schematically. During machining of the cylinders to the required length and drilling the circular cutouts a metallic mandrel was left inside the cylinder to prevent local damages around the cutting area. Also, a hole saw cutter was used to create perforations on the cylinders.

2.2. Mechanical properties reduction

In order to extract mechanical properties of materials used in cylinder fabrication, a group of specimens was fabricated and tested according to ASTM standard. Young's modulus in fiber and matrix directions, $E_x = 35.5$ GPa and $E_y = 5.4$ GPa, Poisson's ratio, $\upsilon_{xy} = 0.28$ and in-plane shear modulus, $G_{xy} = 4.085$ GPa were obtained by testing five specimens in each case according to ASTM D3039 [22] and ASTM D7078 [23], respectively. In addition, Fiber volume fraction of samples prepared from cylinders and coupon specimens were between 55% and 57% according to burn out test performed based on ASTM D3171 [21].

2.3. Testing procedure

Buckling tests were performed using Zwick Roell 50 t universal testing machine under displacement control conditions at a crosshead speed of 0.01 mm/s. In order to monitor the uniformity of loading, two orthogonal electrical strain gauges were mounted on both sides of the cylinder close to the edge also two dial gauges rotated 90 degrees diametrically with respect to SG1 and SG3 were installed on top of the testing fixture as shown in Fig. 3a. In addition, three strain gauges on the perfect side and five strain gauges on the perforated side of the cylinder with cutout were installed to study deformation pattern during buckling as shown in Fig. 3b. Data logger TMR-211 provided by TML