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Structural behavior of shells with different cutouts under compression: An experimental study

Tohid Ghanbari Ghazijahani *, Hui Jiao, Damien Holloway

School of Engineering and ICT, University of Tasmania, Hobart, TAS 7001, Australia

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ABSTRACT

A considerable volume of literature is found regarding the effect of an opening in thin cylindrical shells under different loading. Among these, quite a few of the references are directly related to the cutouts along the length of the shells in the form of entrance doors. The main focus of this study is the tubes with door-shaped cutouts under axial loading. Different buckling modes as well as the effect of geometric parameters of a cutout were examined in this study. A stiffening method was also used to decrease the effect of the cutout on the capacity of such structures.

1. Introduction

Cylindrical shells as important structural elements are often found with various local geometric non-uniformities, among which are different forms of openings. Such openings are widely used as the entrances of the steel towers for maintenance and any other accessibility purposes. These cutouts are also employed for the attachment of electrical devices to such structures.

Many researchers have investigated the structural behavior of such structures with various openings. Tennyson [1] investigated the effects of unreinforced circular cutouts on the buckling behavior of circular cylindrical shells subjected to axial compression. A membrane stress distribution and isoclinic patterns were defined around the edge of the opening in this research. Numerical and experimental methods were used by Jullien and Limam to investigate the stability of cylindrical shells with openings [2]. The analysis showed that the buckling load was quite sensitive to the opening angle or circumferential size of a cutout. An area replacement method (ARM) of strengthening the circular cutouts in a cylindrical shell on the buckling strength of such shell was studied analytically and experimentally by Bennett et al. [3]. Buckling of steel cylindrical shells with elliptical cutouts was studied by Shariati and Rokhi [4]. It appeared that the buckling load decreased when the width of cutouts was constant and height of them increased. Simple design rules were proposed by Eggwertz and Samuelson considering theoretical analyses and experimental data for shells with rectangular cutouts [5]. Aluminum cylindrical shells with rectangular cutouts in different locations along the specimens were studied by Han et al. [6], who showed that the location and the size of an opening significantly affect the buckling load of such structures. Steel shells with elliptical cutout under axial compression were studied numerically and experimentally by Shariati and Rokhi [7]. They showed that longer shells were much more sensitive to the position of a cutout.

The present study investigates the effect of different longitudinally located cutouts at the end zone of the shells, which may represent different entrances or doors in steel hollow section, e.g. towers (see Fig. 1). The main objectives of this study are to address: (i) experimental modeling of the entrance-shaped cutouts, (ii) compression tests of different shapes of such perforated shells, (iv) evaluation of the effect of different shapes of the cutout, and (iii) comparison of the results with the available data.

2. Experimentation

2.1. Test rig

An AVERY machine was employed for the experimental program of this study (Fig. 2). The machine was calibrated by Australian Calibration Service (ACS) to ensure the accuracy of the function of the machine. The AVERY machine was capable of applying a static loading with a controllable loading rate.

Test specimens were mild steel tubes with D/t ratio of 47.6 ($D = 76.2$ mm, $t = 1.6$ mm, and $H = 400$ mm, see Fig. 3). Both ends of the specimens were machined to allow the top and bottom plates to contact the specimens uniformly. A CHEVALIER 2040 VMC, three axis CNC cutting machine was utilized to cut the cutouts in different shapes. As

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* Corresponding author. Tel.: +61 469 311 896.
E-mail addresses: tohid.ghanbari@utas.edu.au, tohidghanbari@gmail.com (T. Ghanbari Ghazijahani).

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Fig. 1. Entrance door of a wind turbine tower [8].

mentioned earlier, the main objective of selection of such cutouts are to assess the structural behavior of the shells when they act as entrance-shaped cutouts. Cutouts in five different forms were adopted: (i) rectangular cutouts with two semi-circular ends (RCSC), (ii) semi-RCSC cutouts with the same shape as RCSC yet half height (SRCSC), (iii) elliptic shapes (FOVA), (iv) semi-oval-shaped openings (SOVA), and (v) rectangular cutouts with filleted corners (RECT). An intact specimen was also included as a control specimen. Stress–strain relationship and the material properties of the specimens were obtained through tensile coupon tests, as presented in Table 1 and Fig. 4.

Geometric features of the cutouts are seen in Figs. 5 and 6. A constant ratio of $b/a = 0.4$ was applied for all specimens so that different specimens revealed proper results corresponding to the different geometries. For all of the specimens, a distance of 50 mm from the bottom end was taken as the lower boundary limit of the cutout. Note that the cutout was made at the area opposite to the seam weld of the specimens to avoid any possible influence of the residual stresses caused by the welding. Three different values for "a" were considered representing small, medium and large cutouts (see Table 2). Sharp corners were avoided in all cutout designs to minimize/limit stress concentration.

End shortening of the specimens while loading was accurately recorded by the AVERY machine. CEA-06-240UZ-120 Micro-Measurements strain gauges were used and attached to the most critical points (side edge of the cutout and near the bottom edge; further details are given in Section 3.3) to record the strain values and evaluate the load-strain behavior of such areas.

3. Results and discussions

3.1. Observations

3.1.1. Intact specimen

Fig. 7 shows the intact specimen after the buckling, displaying a symmetric ring-shaped bulging wave near the base commonly referred to as "elephant foot" buckling. This mode of buckling occurred at around 15 mm from one end of the intact specimens and encompassed the whole circumference of the buckled section. A gradual decrease of the axial load was seen after initiation of the buckling. Loading was continued until the buckling wave covered the whole hoop direction of the tube, which was eventually accompanied by a significant drop in the loading.

3.1.2. Specimens with cutout

The present specimens with a cutout showed a unique buckling mode in which the edge area of the tubes together with the cutout was influenced by the buckling phenomenon. To the best of the authors' knowledge, this mode of buckling has not been reported by other investigators. In this mode, buckling was initiated at the edge of the cutouts with outward sine waves in a symmetric arrangement. As the load increased, the waves deepened and developed to the adjacent area while at the same time buckling of the opposite side of the tubes was detected in an *elephant foot* mode (see Fig. 8). It should be mentioned that the *elephant foot* mode of buckling developed only nearly up to the half of the section (see Fig. 9) such that the area below the cutout was not affected whatsoever. Fig. 9 also shows the buckling in RCSC.3 specimen around the cutout and the edge area.

It is interesting to note that buckling in the specimens RCSC.3 and RECT.3 (which had the largest cutout) was initiated near the top of the cutout whereas with the decrease in the size of the cutout the initial buckling wave approached the center of the opening. Fig. 10 shows the buckling waves occurring in the three different RECT and RCSC specimens in which RECT.3 experienced the buckling wave initiation at around 0.23a from the top of the cutout, RECT.2 at 0.32a and for the smallest cutout, the buckling wave initiated at the middle of the height of the hole. Fig. 11 shows FOVA, SRCSC, and SOVA specimens after buckling, in which for FOVA and SRCSC the buckling waves occurred in the mid-height of the cutout. In Fig. 11, the compressive areas of the buckling waves showed a kind of paint flaking over the surface of the tubes. Progress of buckling is seen in Fig. 12 for the specimens RECT, RCSC and FOVA at three different stages of loading.

3.2. Capacity of the specimens

Table 3 shows the ultimate capacity and the ratio of the capacity of the specimens with cutouts to the ultimate load of the intact specimen. The decreasing trend of the capacity was plotted in Figs. 13 and 14 for the present specimens. Parameter "b" is the width of the cutout, which is the most important geometric parameter of the cutout area since for high values of "b" the cross section has lost more material so that the tubes were weaker against the buckling. A parameter μ was also defined as $\mu = \frac{D\,ab}{t}$ in which the D/t ratio was included as well as the two major geometric parameters of the cutout, "a" and "b".