Thin-Walled Structures 80 (2014) 13–21

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Experimental study on damaged cylindrical shells under compression

Tohid Ghanbari Ghazijahani*, Hui Jiao, Damien Holloway

School of Engineering, University of Tasmania, Hobart, Australia

ARTICLE INFO

Article history:
Received 23 January 2014
Received in revised form
25 February 2014
Accepted 26 February 2014
Available online 18 March 2014

Keywords:
Thin-walled cylindrical shells
Tests
Compression
Initial damage
Dent

ABSTRACT

Sensitivity to initial imperfections under compressive loading has been extensively studied in shell structures. However, due to the existence of a wide range of imperfections with various shapes and amplitudes, the real behavior of such structures needs to be further investigated when they face with a damaged area. This study presents an experimental program in which buckling and failure response of damaged shell specimens are analyzed. The results of this study can be generalized for many kinds of cylindrical shells to full scale of applications with similar D/t ratios.

1. Introduction

Axial compressive stresses in cylindrical shell structures arise from various causes such as in towers and chimneys caused by the weight of the structures [1]. Such structures are often vulnerable to physical contacts of the other elements during their service life. A wide range of references can be found in the literature in regard to the buckling and failure response of cylindrical shell structures with normal fabrication-related imperfections under compressive stresses, e.g. [2–9].

However, quite a few studies reflect such structures with large imperfections caused by a collision. Local bulges, dents and unilateral corrugations were studied and it was found that local dents significantly reduced the critical load [10]. The effect of localized imperfections on the buckling of cylindrical shells under axial compression was studied and a considerable reduction of the critical load due to the imperfections was observed [11]. Two new approaches were proposed for the numerical and analytical stability analyses of imperfect shells [12]. Theoretical buckling stress of such shells was defined by Eq. (1), [1]. In this equation E is Young's modulus and "ν" is Poisson's ratio. "t" and "r" are respectively the thickness and the radius of the shells. This equation mostly overestimates considerably the buckling load of thin shell due to the occurrence of local deformations resulted from the geometric imperfections in experimental models. It should be noted that, the number of full buckling waves around the circumstance and half-wavelength of the buckling waves were also defined theoretically by Eqs. (2) and (3) respectively [1].

$$\sigma = \frac{Et}{r\sqrt{3(1-\nu^2)}} \simeq 0.605\,E\frac{t}{r} \tag{1}$$

$$n = \left(\frac{3}{4}(1-\nu^2)\right)^{0.25}\left(\frac{r}{t}\right)^{0.5} \simeq 0.909\left(\frac{r}{t}\right)^{0.5} \tag{2}$$

$$\lambda = \frac{\pi}{(12(1-\nu^2))^{0.25}}(rt)^{0.5} \simeq 1.728\sqrt{rt} \tag{3}$$

Analytical methods were developed for the estimation of the upper critical loads for non-reinforced cylindrical shells with axisymmetric dents (bulges) located on the shell structures. An investigation has been conducted on the buckling of steel cylindrical shells with a single local dent [13,14]. It was found that even a single dent strongly influences the magnitude of the critical load.

Refs. [15,16] are highly relevant papers to this work. Axial compression was applied to the damaged specimens and the buckling behavior was studied [15]. It was found that damaged shells reached almost half of the capacity of the intact specimens in the case of eccentric loading. For undamaged specimens failure was quite abrupt and without warning whereas the damaged structures had a phase of stable growth of a dent before the catastrophic failure ensued. Parametric study on the buckling behavior of dented short carbon steel cylindrical shell subjected to uniform axial compression was conducted [16]. Cylindrical shells with longitudinal dents were believed to have higher buckling strengths than cylindrical shells with circumferential dents.

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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).

http://dx.doi.org/10.1016/j.tws.2014.02.029
0263-8231

Table 1
Specifications of the specimens.

	Specimen	d (mm)	Orientation of the dent	HD (mm)	HD/H	WD (mm)
$\boldsymbol{D/t=607.08}$, $\boldsymbol{t=0.25}$ **(mm)**, $\boldsymbol{L/D=1.44}$	LCC.1	–	–	–	–	–
	LCC.2	–	–	–	–	–
	LCC.3	0.45	Horizontal	110	0.5	19
	LCC.4	2.3	Horizontal	110	0.5	39
	LCC.5	3	Horizontal	110	0.5	63
	LCC.6	6.2	Horizontal	110	0.5	75
	LCC.7	3	Diagonal	110	0.5	60
	LCC.8	6.5	Diagonal	110	0.5	75
	LCC.9	2	Vertical	110	0.5	75
	LCC.10	3.3	Vertical	110	0.5	90
	LCC.11	3.2	Horizontal	55	0.25	56
	LCC.12	8	Horizontal	55	0.25	72
	LCC.13	1.8	Horizontal	20	0.09	35
$\boldsymbol{D/t=339.52}$, $\boldsymbol{t=0.25}$ **(mm)**, $\boldsymbol{L/D=1.36}$	SCC.1	–	–	–	–	–
	SCC.2	–	–	–	–	–
	SCC.3	0.4	Horizontal	15	0.130	14
	SCC.4	0.8	Horizontal	15	0.130	21
	SCC.5	1.2	Horizontal	15	0.130	26
	SCC.6	1.8	Horizontal	15	0.130	30
	SCC.7	2.5	Horizontal	15	0.130	38
	SCC.8	0.5	Horizontal	30	0.260	16
	SCC.9	0.9	Horizontal	30	0.260	26
	SCC.10	2.1	Horizontal	30	0.260	32
	SCC.11	1	Horizontal	57.8	0.5	22
	SCC.12	2.7	Horizontal	57.8	0.5	37
	SCC.13	1.2	Vertical	57.8	0.5	44
	SCC.14	1.2	Diagonal	57.8	0.5	42

The present study was performed on 27 locally dented shell specimens as very limited experimental data are found on the dented shells under compression. Dent imperfections of different depths, locations and orientations were modeled. This paper focuses on the following points:

- Experimental modeling of dented shells;
- Buckling of intact and damaged specimens;
- Failure modes of such structures;
- Capacity assessment of dented shells and;
- Comparison of the results with other works and existing standards.

2. Experimental program

2.1. System set-up

2.1.1. Apparatus

The test apparatus for the present experimental program was a MTS-810 machine. Two end plates were fabricated in which the specimen ends were placed in grooves with a slight tolerance in order to restrain the specimens in the radial direction while allowing rotation of the walls about the circumferential line. End plates were gripped by two jaws of the MTS machine. Before the tests the two top and bottom plates were calibrated accurately to ensure that the axial loading was uniformly applied. The vertical distance between the two plates before the tests was adjusted such that no additional weight of the plates was applied to the top portion of the specimens.

Fig. 1. Test set-up for cylindrical shell specimens.

2.1.2. Specimens

In this study, 27 precisely-fabricated specimens with two different D/t ratios were tested (see Table 1 and Fig. 1). LCC.1 to LCC.13 ($D=151.77$ mm, $L=218.55$ mm and $t=0.25$ mm), were the specimens with higher D/t ratio and SCC.1 to SCC.15 were the specimens with lower D/t ratio ($D=84.88$ mm, $L=115.44$ mm and $t=0.25$ mm). The Young's modulus as the main material property in buckling tests of thin shells and Poisson's ratio were obtained from a tensile coupon test as 210 GPa and 0.3 respectively.

The specimens had top and bottom circular caps to simulate the practical instances of the tanks with two end caps. Fig. 2 presents two practical instances of the steel tanks with circular flat roofs and local geometric defects on the surface of such structures.

2.1.3. Indentation and measurements

Indentation was conducted by means of a steel indenter with a circular sharp end (see Figs. 3–5). Indentation was made through closely moving the indenter over the body of the shell specimens to achieve a dent with the desired depth and corresponding width. A finger LVDT was utilized in order to have accurate recordings of the dented area (Fig. 5). A small ball-shaped tip of this LVDT made it capable to move along and/or across the dented region and accurately detect the geometric depressions of the dent. CEA-06-240UZ-120 Micro-Measurements USA made strain gauges were employed in order to record the strain values in the critical areas of the test samples. End shortening of the specimens was recorded by the MTS machine.

3. Test results

3.1. Buckling and failure

3.1.1. Intact specimens

Intact specimens in this study are considered as control specimens against which the other locally imperfect specimens were