Thin-Walled Structures 98 (2016) 558–564

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Buckling behavior of axially compressed cylindrical shells: Comparison of theoretical and experimental data

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ARTICLE INFO

Article history:
Received 28 July 2015
Received in revised form 30 October 2015
Accepted 30 October 2015
Available online 9 November 2015

Keywords:
Buckling
Cylindrical shell
Axial compression
ABAQUS simulation
Theoretical prediction

ABSTRACT

This paper examines the buckling of short mild steel cylindrical shells subjected to axial compression. Cylinders were joined together using Metal Inert Gas (MIG) welding process with radius-to-thickness ratio, R/t, ranging from 25 to 100. The axial length of the specimens were assumed to be 111.8 mm. Past result on axially compressed cylinder machined using Computer Numerically Controlled (CNC) machining is compared with fresh experimental results on MIG manufactured axially compressed cylinder. The paper contains a comparison between theoretical predictions, ABAQUS FE results and experimental data for axially compressed cylinder. Details about material testing and collapse test are provided. As compared to the CNC machined specimen, results indicates that there is a good agreement between theoretical prediction, ABAQUS FE results and experimental data for MIG manufactured cylinder with radius-to-thickness ratio, R/t ranging from 25 to 100, with difference ranging between −7% and +2%.

1. Introduction

Thin-shell structures find applications in many branches of engineering. Typical examples include aircraft, spacecraft, cooling towers, nuclear reactors, steel silos and storage tanks of bulk solids and liquids, pressure vessels, pipelines, offshore platforms, Ref. [1]. Cylindrical shells are the most commonly used thin-shell structure geometry. This is due to its simple geometry and relative ease of manufacture. Thus, it is not surprising that over the years, large amount of research work has been carried out for this shell geometry.

When in use, cylindrical shells are often subjected to various loadings such as external pressure, internal pressure, axial compression, bending, torsion etc., or combined loading, i.e., axial compression and torsion, axial compression and external or internal pressure, torsion and external or internal pressure, etc. For such application, their failure behavior is of great importance. For thinner cylinders, primarily used in aerospace application, the failure is limited by elastic buckling. Whereas, for thicker cylinders usually used in marine and offshore application, the failure mode is largely due to plastic buckling. In fact, the first theoretical shell buckling problem to be solved was the cylindrical shell subjected to axial compressive loading [2]. However, early test on cylindrical shells reveals that real cylinder fails at much lower load, with experimental values even below 30% of the theoretical load [1].

The search for this major difference in both the theoretical prediction and experimental data has led to numerous researches in the area of imperfection sensitivity of cylinder subjected to axial compressive loading, such as initial geometric imperfection in Refs [3–5], non-uniform axial length in Refs [6–8], non-uniform loading in Refs [9–13], etc. However, the problem is far from being solved. In fact, the axially compressed cylinder has been considered one of the last classical problems in homogenous isotropic structural mechanics where it remains difficult to obtain close agreement between theoretical prediction and experimental results [1]

In this paper, investigation into comparison between theoretical prediction and experimental results of buckling load of short mild steel cylindrical shells subjected to axial compression is presented. Cylinders were joined together using Metal Inert Gas (MIG) welding process with radius-to-thickness ratio, R/t, ranging from 25 to 100. The axial lengths of the specimens are assumed to be 111.8 mm. Predictions based on the ABAQUS FE code [14], are compared with theoretical predictions. Finally, comparison were made between the result obtained from experiment in this paper and past experiment of axially compressed cylinder machined using computer Numerical Controlled (CNC) machining.

2. Background: buckling of axially compressed cylinders

2.1. Theoretical background

The failure/buckling behavior of cylindrical shell is mainly characterized by the radius-to-thickness ratio of the shell. Thin-shell cylinder usually buckles elastically, so failure by buckling

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http://dx.doi.org/10.1016/j.tws.2015.10.027
0263-8231/

controls the design criterion. Whilst, thick cylinder fails in the elastic–plastic range, so failure is govern by collapse. If a cylinder is subjected to uniform axial compression, the following buckling modes can be experienced: (i) axisymmetric mode, where the cylinder develops a corrugated appearance, with waves only in the axial direction, (ii) asymmetric mode, where the cylinder develops inward and outward displacement of the shell wall with several full waves around the circumference, and usually several waves up the height (note that the number of waves falls progressively as the shell becomes thicker), and (iii) symmetric mode, where the cylinder forms a single bulge around the circumference.

The classical buckling analysis of cylinder is based on the hypothesis of membrane pre-buckling state, i.e., bending stresses are neglected, and of Donnell shallow shell theory. From the above hypothesis, the classical elastic critical buckling load for axially compressed cylinder with axisymmetric mode is given by:

$$F_{cyl} = \frac{2\pi E t^2}{\sqrt{3(1-\nu^2)}} \quad (1)$$

However, for relatively thick cylinder that fails within the plastic region, the reference buckling load, F_{ref}, is taken as the load required to cause the cylinder to yield and it is designed according to Ref. [15] as Eq. (2):

$$F_{ref} = \pi D t \sigma_{yp} \quad (2)$$

where

F_{cyl} is the cylinder classical elastic critical buckling load

F_{ref} is the cylinder reference buckling load required to cause yield

E is the Young's Modulus of the material

σ_{yp} is the yield stress of the material

v is the Poisson's ratio of the material

D is the diameter of the cylinder

t is the wall thickness of the cylinder

2.2. Modeling details

Consider a circular cylinder with diameter, D, radius, R and uniform wall thickness, t, having an axial length, L, as sketched in Fig. 1a. It is assumed that the cylinder is subjected to axial compression. The cylinder is assumed to be fully clamped at one end, and at the other end, the cylinder is only allowed to move in the axial direction. Fig. 1b shows the photograph of the experimental set up of the cylinder, taking a close look at the top edge after spring-back/unloading. The cylinder is assumed to be made from mild steel with the material properties shown in Table 1.

Table 1
Set of material data obtained from uni-axial tensile tests on mild steel plate (E=young's modulus, UTS=ultimate tensile strength). Note: The upper yield for 0.5 mm thickness specimen was taken from 0.2% proof stress.

Specimen thickness (mm)	Sample	E (GPa)	Upper yield (MPa)	Lower yield (MPa)	UTS (MPa)
0.5	1	201.7	210.8	–	313.6
	2	172.8	192.9	–	295.1
	3	206.5	205.6	–	308.8
1.0	1	204.7	255.9	242.9	329,5
	2	199.2	253.4	249.0	333.5
	3	238.1	259.2	249.3	336.6
2.0	1	256.2	311.7	289.2	363.6
	2	227.3	322.8	312.4	384.0
	3	240.8	331.9	287.9	375.6

The specimens were modeled using four-node three-dimensional doubly curved shell elements with six degree of freedom (S4R). The material is modeled as elastic perfectly-plastic. Nonlinear static analysis was carried out using the modified Riks method algorithm which is implemented in ABAQUS.

3. Experimentation

3.1. Cylinder geometry and material properties

For this experiment, five mild steel cylinders with three different thickness (t=0.5, 1.0, 2.0 mm) as shown in Fig. 2, were tested. All cylinders were assumed to have nominal diameter, D=100 mm. The axial lengths for all cylinders were kept at 111.8 mm. To ensure repeatability of experimental data, two specimens with nominal thickness of 1 mm and 2 mm respectively were manufactured. This would provide two experimental data values for cylinder with nominally the same geometry. Specimens were designated as: CY1_t0.5. The number following 't' indicates the thickness of the cylinder. For example, CY1_t0.5 implies

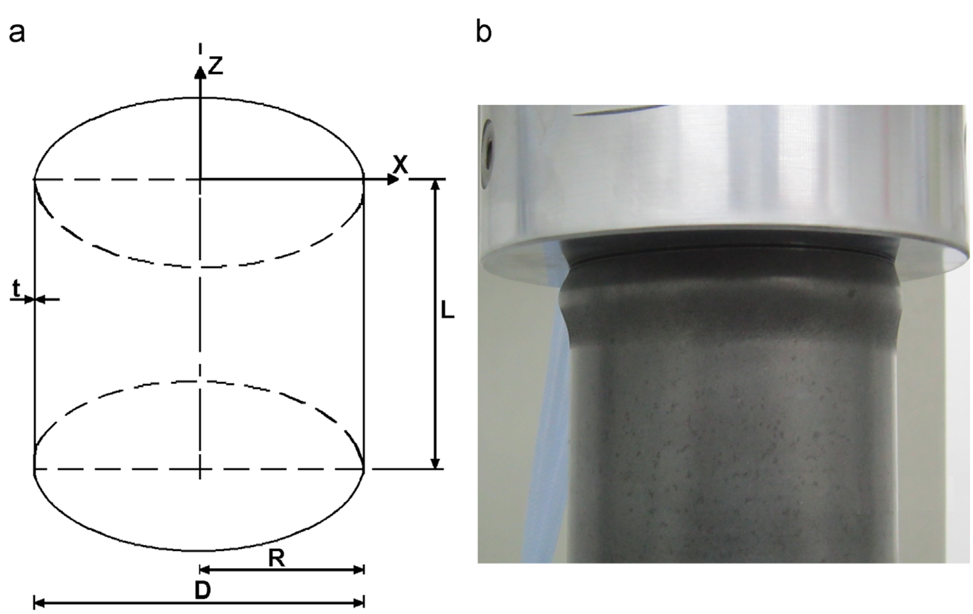

Fig. 1. Geometry of analyzed cylinder (a), a close look of the top edge after spring-back/unloading during experimentation (b).