BUCKLING EXPERIMENTS OF AXIALLY COMPRESSED CIRCULAR CYLINDER WITH IMPERFECT LENGTH

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ABSTRACT: Buckling experiment on the effect of imperfect length on the buckling load of axially compressed circular cylinder is presented in this paper. Seven cylindrical specimens with different wave number ranging from 0 to 12 were manufactured using advanced manufacturing process. Specimens were cut from 1 mm mild steel plate using waterjet machining and weld using Metal inert gas welding. During the cutting process sinusoidal waves were introduced. The magnitude of the waves is assumed to be a fraction of the axial length of the cylindrical shell structure. The ratio of axial imperfection-to-axial length of the cylinder (2A/L) was taken to be 0.1. Repeatability of experimental buckling load for two nominally identical pairs with no waves (perfect) and 12 waves (imperfect) was good. The error within each pair were: 3% and 4%. Furthermore, experimental results indicate that the imperfect length in the form of sinusoidal waves strongly affect the load carrying capacity of circular cylinder [(58.62 kN; 60.47 kN) for perfect cylinders; (32.38 kN) for cylinder with 4 waves; (20.23 kN) for cylinder with 8 waves; (28.59 kN) for cylinder with 10 waves and (30.48 kN; 31.79 kN) for cylinders with 12 waves]. Also, it was revealed that the buckling load of the cylinder reduces as the axial imperfection amplitude of the cylinder increases.

KEYWORDS: *Buckling; Circular Cylinder; Axial Compression; Imperfect Length; Imperfection Sensitivity*

1.0 INTRODUCTION

Cylindrical shells are used mainly in many engineering practice such as civil, mechanical, pressure vessel, marine, offshore industries and in the collision kinetic energy dissipation system of ships, motor vehicle and aerospace [1]. For example, in offshore industries, they are used for onshore and offshore pipelines as a means of transporting petroleum products from one location to the others. When used for this application, they cover a wide range of distance spanning over several kilometers. Hence, there is a need to connect several cylinders together using different joining process such as welding and fastening. However, when the load acting on the cylindrical structures is axial compression, the interaction between the connecting junctions becomes very important. Then, the axial length of the cylinder must be uniform/even as this will likely affect the buckling load of the structure.

The buckling strength of axially compressed cylindrical shells has been adjudged to be particularly sensitive to imperfections in the shells [2]. This sensitivity to imperfection on the actual buckling load of axially compressed cylindrical shell structure is however, strongly dependent on the form of imperfection approach adopted. This imperfection could exist in different forms such as initial geometric imperfection, non-uniform length, non-uniform loading, inaccurate modeled boundary conditions, influence of pre-buckling deformation and material discontinuity/crack. A state-of-the-art survey of the buckling and post-buckling of thin-walled geometrically imperfect cylinders of various construction when subjected to destabilizing loads was presented in [3-4].

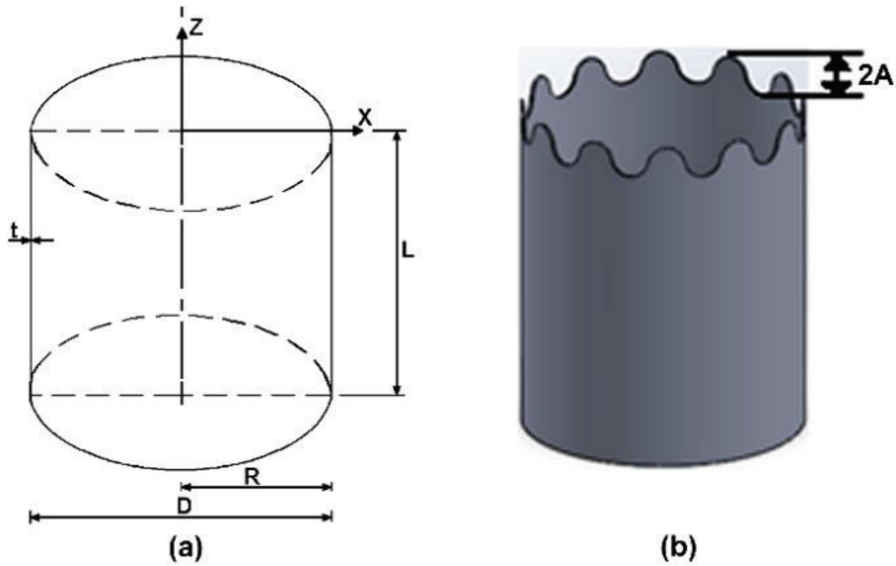
Research into imperfection sensitivity of cylinder can be found in [5-22]. Sample of references on initial geometric imperfection can be found in [5-8]. In references [9-17], buckling behavior of cylinders with the presence of crack/material discontinuity were considered. References [18-20] were devoted to axially compressed cylinder with non-uniform loading. Whilst, in references [21-22], the buckling behavior of axially compressed cylinder with non-uniform axial length were investigated. The imperfection shape had a sinusoidal profile along compressed edge with the cylinder having variable length at one ends with sinusoidal profile. In [21], finite element code was used to compute the load carrying capacity of the axially compressed cylinder with imperfect length. The geometrical parameter for cylinder considered were taken to be: radius-to-thickness ratio, R/t, ranging from 165 to 100, axial amplitude of imperfection-to-thickness ratio, A/t, ranging from 0 to 6.0 and length-to-radius ratio, L/R, was taken to be 2.4. Moreover, in [22], experimental data on the buckling behavior of eighteen axially compressed mild steel cylinders with imperfect length was presented. The nominal thickness of the cylindrical model was assumed to be 0.4 mm. The length-to-radius ratio, L/R was taken to be 2.4, and the radius-to-thickness ratio, R/t = 185. The magnitude of axial imperfection-to-thickness ratio, 2A/t, was varied between 0.05 and 1.0. Cylinder were machined from 11.0 mm thick BS 4360 mild steel tube with the outside diameter of 168.3 mm using computer numerically controlled ((CNC) machining.

Motivation for the present work originates from the conclusion of [22] where it was stated that; (i) the wall thickness of CNC machined cylindrical models were not as good as was hoped for, the uniform wall thickness of 0.4 mm was difficult to achieve using this manufacturing process. Hence the use of alternative advanced manufacturing process is required, and (ii) some additional tests of models with larger amplitude of imperfection would be desirable in order to have better understanding of the role of wave number on the collapse load.

This paper presents additional tests of models on the buckling behavior of mild steel cylinder subjected to axial compression having uneven length with larger amplitude of imperfection using advanced manufacturing process. The use of advanced manufacturing process is important in order to account for variation in thickness of imperfect cylinder presented in [22] using CNC machining. In order to produce the specimen with uniform thickness for this experimental work, cylinders were cut from flat mild steel plate using waterjet machine and joined together using Metal Inert Gas (MIG) welding process. The effect of increasing the number of waves and the ratio of axial imperfection amplitude to the cylinder axial height, 2A/L = 0.1, on the buckling load of axially compressed cylindrical shell is presented.

2.0 METHODOLOGY

Seven circular cylinders with uneven axial length having different number of sinusoidal waves were subjected to axial compression. Circular cylinder with diameter, D, radius, R and uniform wall thickness, t, having an axial length, L, as sketched in Figure 1a. Cylinder has nominal thickness of 1 mm and the following geometrical parameter: R/t = 50; L/R = 2.24. The cylinders were assumed to have axial imperfection-to-axial length ratio, 2A/h of 0.1). The choice of 2A/h = 0.1, was based on the suggestion by [22], that cylinder with larger imperfection amplitude should be considered to provide a better understanding of the subject matter. The cylinders were cut from mild steel plate using waterjet machining, rolled using conventional rolling machine and weld using Metal inert gas welding (MIG). During the cutting process sinusoidal waves with different wave number of 0, 0, 4, 8, 10, 12, and 12 were introduced as illustrated for the case of cylinder with twelve waves in Figure 1b. The specimens were designated as CY1, CY2 (perfect), CY3 (4 waves), CY4 (8 waves), CY5 (10 waves) and CY6, CY7 (12 waves). Perfect cylinder with 0 wave and cylinder with 12 waves were fabricated in pair with nominally the same geometry. This is done to confirm repeatability of the experimental data. The material properties from which the cylinders were made is obtained from uniaxial tensile test of 3 dog bones samples at the rate of 1 mm/min. The average values of material data obtained from tensile test are: Young's Modulus E = 196.1GPa, Poisson ratio, ν = 0.3 and the yield stress based on 0.2% offset, σ_{yp} = 205 MPa.



(a) (b)

Figure 1: (a) Section through conical shell and (b) illustration of sinusoidal waves region

2.1 Specimen Manufacturing

The cylindrical models were manufactured using three different manufacturing processes which are: (i) cutting process, (ii) rolling process and (iii) welding process (see reference [16] for details). During the cutting process, specimens were sketched using AutoCAD software which was then imported to waterjet machine for the cutting of the specimen to the required dimensions and number of waves introduced on one ends of the cylinder. The use of the waterjet machine is assumed to be one of the best advanced manufacturing cutting process in order to obtain perfect dimension and shape of the sinusoidal waves. After the cutting process, the shape of the samples was transformed to cylinder using the conventional rolling machine. Special care was taken during this process to ensure that the desired shape is produced. Lastly, the rolled cylinders are joined together using the Metal Inert Gas (MIG) welding process.

2.2 Collapse Test

Prior to testing, several geometrical measurements of the cylinder were taken. They are: (i) wall thickness, (ii) inner and outer diameter, and (iii) axial length. This is done to confirm the appropriateness of the manufacturing process employed in this paper as compared to that adopted in [22]. The wall thickness was measured using micrometer screw gauge while the other geometrical parameters were measured using digital Vernier caliper. Table 1 presents the measured average, minimum, maximum and standard deviation of the cylinder wall thickness. From Table 1, it is apparent that cylindrical model (CY4) has the lowest deviation from the nominal thickness, while cylindrical model (CY2) has the largest deviation. Then, the measurement of cylinder outer and inner diameters and axial length were taken. Details of measured mid-surface diameter and the average axial length of the cylinders are given in Table 2 and Table 3, respectively.

Table 1: Data of measured cylinder wall thickness

Model	No. of waves	tmin	tmax	tave	tstd
		(mm)			
CY1	0	0.96	1.01	0.977	0.0117
CY2	0	0.96	1.01	0.978	0.0119
CY3	4	0.96	1.01	0.977	0.0103
CY4	8	0.97	0.99	0.974	0.0056
CY5	10	0.96	0.99	0.972	0.0069
CY6	12	0.96	0.99	0.972	0.0068
CY7	12	0.96	0.99	0.971	0.0065

Table 2: Data of measured cylinder mid-surface diameter

Model	No. of waves	Mid-surface diameter (mm)	
		Top	Bottom
CY1	0	102.25	102.23
CY2	0	101.87	102.18
CY3	4	102.26	101.94
CY4	8	102.36	102.18
CY5	10	102.23	102.48
CY6	12	102.27	102.17
CY7	12	102.33	102.31

Table 3: Data of measured cylinder axial length

Model	No. of waves	Axial length	
		Max.	Min
CY1	0	112.52	-
CY2	0	112.58	-
CY3	4	117.61	106.79
CY4	8	117.57	106.77
CY5	10	117.60	106.85
CY6	12	117.49	106.88
CY7	12	117.56	106.79

All cylinders were subjected to axial compression using INSTRON machine. An incremental axial load was applied from the moveable end of the compression machine at the rate of 1 mm/min while the other end was fixed. In providing the desired boundary condition, the specimen is fixed at one end while allowing rotation and axial movement on the other end. The specimen is placed between platens of the INSTRON machine without any covering plate, as shown in Figure 2. During the experiment, the axial shortening of the specimen was recorded using the machine controller.

Figure 2: Experimental set-up for cylinder subjected to axial compression

3.0 RESULTS AND DISCUSSION

During the experiment, the buckling load of the cylindrical specimen corresponding to the different number of waves was recorded using the machine controller. Figure 3 shows a typical plot of load against axial shortening for perfect cylinder, CY2 (N = 0) and imperfect cylinders, CY4, CY5, CY7 (N = 8; N = 10; N = 12, respectively). From Figure 3 it is evident that the compression load versus axial shortening has an initial linear shape until the maximum load. Then, a gentle fall in the graph. However, for imperfect cylinder with 4 waves, the behavior is different. In this case, prior to the collapse load, there was an initial drop in the buckling load of the imperfect cylinder at relatively low load (14.7 kN). After the initial drop in the buckling load, the cylinder continues to support more load until it reaches the collapse load (32.375 kN) as shown in Table 4. According to Blachut [22], this behavior can be attributed to the development of first buckles in the neighborhood of the top edge of the cylinder. After which the cylinder continue to support addition load until a new set of buckles begins.

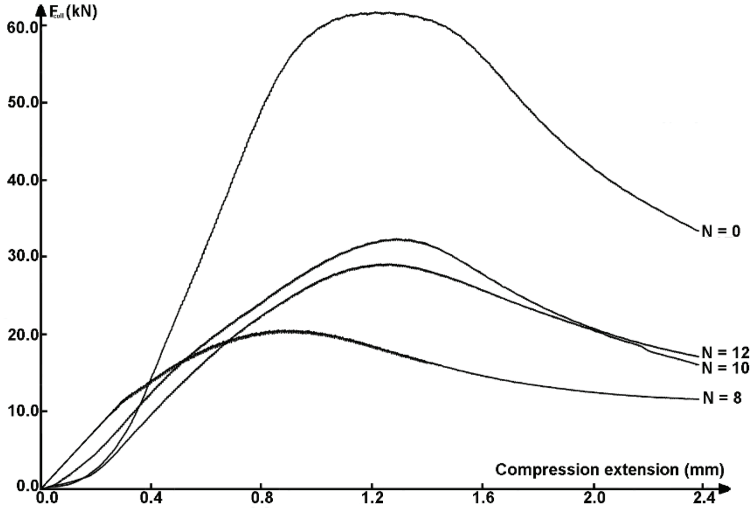


Figure 3: Comparison of experimental load versus compression extension for different number of waves

Table 4 provides the corresponding magnitudes of the buckling loads for all the tested cylinder. It can be seen from Table 4, that repeatability of experimental data (for both perfect and imperfect cylinder was good. The errors within each pair are 3% (for perfect cylinder) and 4% (for imperfect cylinder).

Moreover, it can be observed from Figure 3 that there was a drastic drop in the buckling load of the cylinder passing from perfect cylinder to imperfect cylinder with 8 waves. Then a gradual increase as the wave number increases. Again, there is a good visual comparison of the collapsed shape for perfect and imperfect cylinder as presented in Figure 4. For perfect cylinder, the collapsed shape shows that there was bulging in the neighborhood of the load application region. Similar observation can be seen for imperfect cylinder with 12 waves.

Table 4: Magnitude of buckling load obtained for cylinder with different wave number

Model	No. of waves	Buckling load (kN)
CY1	0	58.617
CY2	0	60.473
CY3	4	14.7 & 32.375
CY4	8	20.233
CY5	10	28.591
CY6	12	30.478
CY7	12	30.790

Figure 4: (a) Photograph of deformed perfect cylinders after test and (b) photograph of deformed imperfect cylinder with 12 waves after test

Figure 5 depicts the plot of buckling load corresponding to different number of waves for axial-imperfection amplitude-axial length ratio (2A/L) of 0.1. The vertical axis is normalized by the buckling load for the perfect cylinder. It can be seen from Figure 5 that there was an initial drop in the load carrying capacity of the perfect cylinder as a result of imperfection due to uneven cylinder length passing from 0 wave to 8 waves - reduction of average buckling load for perfect cylinder from 59.545 kN to 20.233 kN for imperfect cylinder with 8 waves. This reduction amount to 66% drop in the load carrying capacity of the cylinder. Then, moving from 8 waves to 12 waves, there is a gradual increase as the wave number increases. It is obvious that increasing the wave number of the cylinder has a minimal effect on the buckling load of the imperfect cylinder after a certain waves number – here at wave number, N = 8. This behavior may not be generally true for smaller imperfection amplitude, since the failure mode for imperfect length cylinder with small imperfection amplitude is characterized by buckling failure. Whilst, the failure load for imperfect length cylinder with large imperfection amplitude is controlled by the localized failure of the sinusoidal wave as seen in Figure 4. However, it will be interesting to find out what happen with cylinder with 2 and 6 waves, and what happens to the contact interaction behavior on the cylinder having different imperfection amplitude.

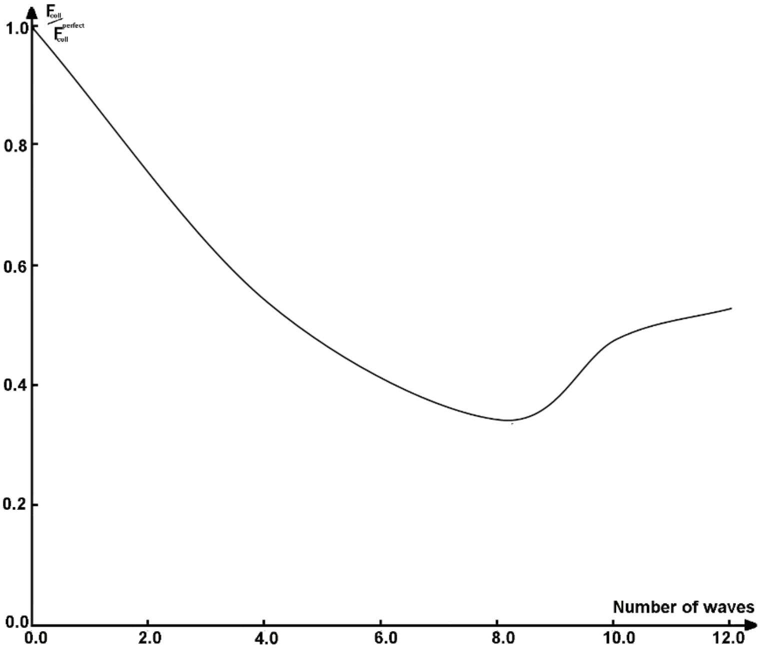


Figure 5: Plot of cylinder buckling load versus the number of waves for axial imperfection-to-cylinder axial length ratio, 2A/L = 0.1

4.0 CONCLUSION

The paper provides additional experimental results into the buckling behavior of imperfect cylindrical shell with uneven axial height subjected to axial compression. Two nominally identical cylinders (perfect and imperfect) failed at a close magnitude of buckling load, hence confirming repeatability of experimental data and also validating the suitability of the advanced manufacturing process employed in this experiment. However, this may not be appropriate for smaller amplitude of axial imperfection because of the diameter of the water jet. From this experiment, it can be concluded that the role of uneven axial length with sinusoidal waves on the buckling behavior of axially compressed cylinder is severe. It will be interesting to check what will happen if other axial imperfection shape in the cylinder axial length is considered.

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