The Effect of Axial Crack on the Buckling Behavior of Axially Compressed Cylinders

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Abstract**-- It is a general believe that the introduction of crack on a shell structure will considerably reduce the buckling load of the structure. This paper seeks to examine the effect of axial crack of a percentage of the axial length on the buckling and post-buckling behavior of axially compressed cylindrical shell structure. This is an experimental study involving six mild steel specimens with radius-to-thickness ratio, R/t = 50. The mild steel specimen is assumed to have a nominal thickness of 1 mm and the axial length-to-thickness ratio, L/R = 2.2. Cylinders had axial crack introduced to a fraction of the cylinder axial length. The magnitude of the crack length-to-cylinder axial length is varied between 0.05 and 0.5. Experimental results reveal that the load carrying capacity of the cylindrical shells is strongly dependent on the crack length, i.e., increasing the crack length leads to a decrease in the buckling load of the cylindrical shells. As an example, cylinder with axial crack extending by 20% of its axial length is enough to cause maximum reduction in the load carrying capacity of the shell (about 37% reduction).**

Index Term**-- Axial compression, axial crack, buckling, steel cylinder, imperfection sensitivity**

I. INTRODUCTION

Cylindrical shells structures are widely used in many branches of engineering such as aircraft, nuclear reactors, storage tanks, pressure vessels, pipelines and offshore drilling rigs etc. In many real life applications, cylindrical shells are often subjected to axial compressive load. As an example, in storage tanks with the cylinder axis vertical, the loads on the roof cause axial compression in the shell wall. For offshore drilling rigs, the weight of the legs of the drilling rigs cause axial compression on the member.

The buckling strength of cylindrical shell under axial compression has been adjudge to be particularly sensitive to imperfection in the shell, [1]. This sensitivity to geometric 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. The most widely considered imperfection types are the initial geometric imperfection i.e., eigenmode imperfection, axisymmetric imperfection, simple perturbation load imperfection, linear buckling mode shape imperfect and geometric dimple-shaped imperfection. Sample of references on initial geometric imperfection can be found in Refs [2 – 4].

Imperfection sensitivity of cylinder under axial compression is not a new problem but it is far from being satisfactorily resolved. Infact, several publications has been presented on buckling of imperfect cylindrical shells under axial compression. Refs [5 – 7] are example of papers on the load carrying capacities for axially compressed cylinder with non-uniform axial length. Axially compressed cylinders with non-uniform loading have received some attention in [8 – 12]. Refs [8 – 10] were devoted to axial compressed cylinder with non-uniform axial length, while Refs [11, 12] cover combined effect of non-uniform axial length and initial geometric imperfection. In [11], initial geometric imperfection is taken as the shape of a single stress free dimple (similar to the lateral perturbation imperfection). The study of Song et al., [12] used a similar approach where four imperfection forms were considered. They are; (i) linear bifurcation mode, (ii) non-linear buckling mode, (iii) several post-buckling deformed shapes for the perfect shell, and (iv) a weld depression.

Buckling behavior of cylinders with the presence of crack has also received some attention in [13 - 19]. Refs [13 – 16] were devoted to cylinders subjected to axial compression only using finite element analysis. Whilst, [17, 18] covers cracked cylinders under combined loading. Estekanchi and Vafai [13], proposed and developed a special purpose program for generating finite element model for analyzing the buckling behavior of cylindrical shells with through cracks with varying length and orientation (longitudinal, circumferential and angled) under axial compression. In Ref. [14], linear eigenvalue buckling analysis of cylinders with single or multiple cracks subjected to axial compressive force was examined using finite element method. A similar approach was used in Refs [15, 16] to investigate the role of elastic liner on the load carrying capacity of crack cylindrical shell with special attention devoted to the effect of crack geometry (crack length and crack orientation) as well as the material properties and thickness of the elastic liner on the buckling behaviour and buckling shape of the cylinder. Vaziri and Estekanchi [17], examines the effect of crack type, size and orientation on the buckling behaviour of cracked thin cylindrical shells subjected to combined internal pressure and axial compression using linear eigenvalue analysis. Two types of crack were analyzed, (i) through crack, and (ii) thumbnail crack. In Ref. [18], ABAQUS finite element code was used to carry out linear and non-linear analyses on the effect of crack position, crack orientation and crack length on the buckling and post-buckling behavior of thick and long cracked cylindrical shells with radius-to-thickness ratio, R/t = 10.5, the axial length-to-thickness ratio, L/R, ranging from 4.76 to 11.9 and the crack length-to-circumference of cylinder ratio, $a/2\pi R$, are 0.2, 03 and 0.4. Finite element results were benchmarked by conducting several experimental buckling tests. The results show that the buckling load and buckling mode of the shells were affected by changing the position of the crack. Also, it was revealed that the load carrying capacity of the axially compressed cylinder could be affected by the orientation of the crack, with circumferential crack (0°) producing the least effect while angle crack (45°) results in the largest reduction. As a result of both numerical and experimental studies, similar conclusions on the effect of circumferential crack were reached by Ifayefunmi and Hap [19] for the case of axially compressed cylinder with material discontinuity/crack on the flanges of the cylinder.

It is evident, from literature survey, that there is little experimental data available on the effect of axial crack (longitudinal crack) on the buckling behavior of cylindrical shells subjected to axial compression, and the available data is limited to crack length-to-circumference of cylinder ratio, $a/2\pi R$, of 0.2, 0.3 and 0.4. Therefore, this paper present experimental study on the effect of axial crack length on the buckling and post-buckling behavior of relatively thick and short cylinder subjected to axial compression. The ratio of crack length-to-axial length considered is of the range 0.05 to 0.5. This will highlight some important happenings within the region of crack length-to-axial length ratio, between 0.05 and 0.2, which were not considered in [18]. This is an experimental study representing initial result of a wider study – results of which are to be published separately.

II. BACKGROUND - BUCKLING OF AXIALLY COMPRESSED CYLINDER

Cylindrical shells structures are susceptible to buckling when under loading conditions. Axially compressed cylinder can fail/buckle through two distinct mechanisms: (i) axisymmetric collapse and (ii) asymmetric bifurcation buckling, [6]. These buckling modes are usually characterized by the value of the radius-to-thickness ratio of the cylinder. Thick cylindrical shell structures with low value of radius-to-thickness ratio usually fail by plastic buckling (axisymmetric collapse). Whilst, for thinner cylinder with relatively high value of radius-to-thickness ratio, the failure is usually limited to elastic buckling (asymmetric bifurcation buckling).

Fig. 1a and Fig. 1b depict photograph of axisymmetric collapse and asymmetric bifurcation buckling for axially compressed cylinder, with radius-to-thickness ratio of 50 and 100, respectively. From Fig. 1, it can be seen that for axisymmetric collapse (Fig. 1a), a single bulge around the circumference that is symmetric with respect to the axis is observed. Whereas, for asymmetric buckling mode (Fig. 1b), there is alternatively inward and outward displacement of the shell wall.

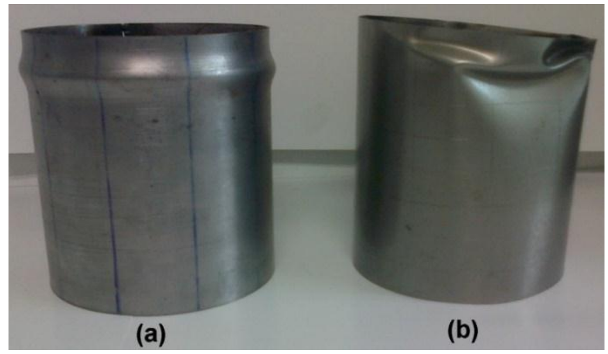

Fig. 1. Photograph illustrating axisymmetric collapse mode (Fig. 1a) and asymmetric bifurcation mode (Fig. 1b) for axially compressed cylinder

III. EXPERIMENTATION

A. *Model geometry and mechanical properties of the cylindrical shells*

Consider a steel cylinder with radius, R and nominal wall thickness, t, having the axial length, L, and crack length, 2a, as sketched in Fig. 2. Six cylindrical specimens C1, C2, C3, C4, C5 and C6 were manufactured from flat mild steel plate grade A36 and axial crack of various lengths were introduced in the specimen during the manufacturing process. The nominal geometry of the models was the same, and it is given by $R/t = 50$, $L/R = 2.2$, and the wall thickness $t = 1$ mm. Cylinders were joined together using Metal Inert Gas (MIG) welding process. All cylinders are to be subjected to axial compression.

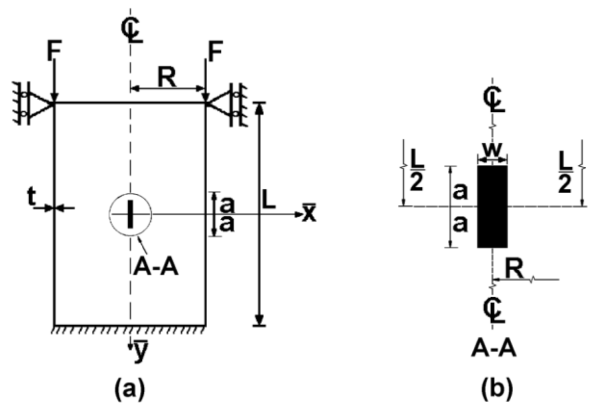

Fig. 2. Section through cylindrical shell (Fig. 2a). The insert illustrates the crack region (Fig. 2b).

The material properties of the mild steel plate were obtained by testing three flat tensile specimens under uni-axial tensile test using INSTRON testing machine. The tensile specimens were machined according to British Standard BS EN 10002-1:2001, [20]. Table I presents the summary of the material properties data which were obtained from uni-axial test. The shells and tensile specimens were not stress relieved at any stage of their manufacture.

TABLE I
Set of material data obtained from uni-axial tensile tests on mild steel plate (E = young's modulus, UTS = ultimate tensile strength)

Sample	E (GPa)	Upper yield (MPa)	Lower yield (MPa)	UTS (MPa)
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
Average	214.0	256.2	247.1	333.2

B. Test Specimen manufacturing

To manufacture the cylindrical shell, several process were carried out, they are: (i) cutting of the flat plate to the required dimension, (ii) rolling the flat plate into the desired shape and (iii) welding the meridional axis of the rolled specimen. Fig. 3 illustrates the overview of the manufacturing process.

First, the flat plate is cut into the desired dimension (i.e., length and circumference of the cylinder) as shown in Fig. 3a using abrasive waterjet machine. Then, the flat plate is rolled into the desired shape using the conventional rolling machine as depicted in Fig. 3b. Special care was taken during the rolling process until the desired cylindrical shape is achieved. Fig. 3c depicts the photograph of all specimens after the rolling process. The rolling process only transform the flat plate into hollow cylindrical shape but the meridional axis of the hollow cylinder need to be joined together. The joining process of the hollow cylinder was achieved by using Metal Inert Gas (MIG) welding process.

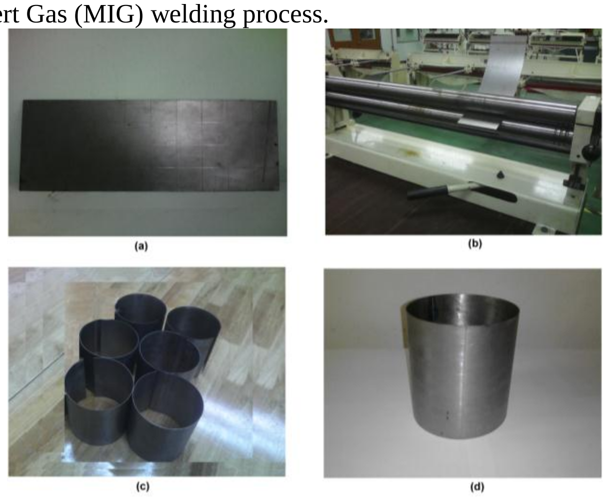

Fig. 3. Illustration of manufacturing processes of cylinders.

During the welding process, axial crack of varying length was introduced on all the specimens. The magnitude of axial crack, 2a, to the cylinder axial length, 2a/L, was varied between 0.0 to 0.5. Axial crack length introduced on specimen model C2, C3, C4, C5, and C6 were 0.05, 0.1, 0.15, 0.2, and 0.5 respectively. Whilst, cylindrical model C1 was assumed to be nearly perfect model. Since the cylinders were symmetric, it was decided to locate the crack in the middle of the cylinder axial length (Fig. 2a).

C. Test Specimen measurements

A number of measurements of the wall thickness, axial length, diameter and the introduced axial crack width were taken on all cylindrical models prior to the collapse test. The importance of conducting initial geometric measurements of shells was highlighted in [21]. First, the wall thickness was measured using micrometer gauge. The average t_{ave}, minimum t_{min} and maximum t_{max} wall thickness are provided in Table II. Then, the measurement of the cylinders axial length was carried out using digital vernier caliper and the obtained results are presented in column 5 of Table II.

TABLE II
Measured values of the wall thickness, axial length and crack width of all cylindrical models

Model	t_{ave}	t_{min}	t_{max}	L_{ave}	crack width
	(mm)				(µm)
C1	1.02	1.01	1.03	112.4	0.00
C2	1.03	1.02	1.03	111.4	13.28
C3	1.02	1.02	1.02	111.2	12.96
C4	1.01	1.00	1.02	111.4	12.97
C5	1.02	1.01	1.02	111.5	13.58
C6	1.02	1.01	1.02	111.1	13.98

Next, the inner diameters of the cylinders were measured using digital vernier caliper at five equally spaced diameters with the results given in Table III. Finally, the crack width for all cylinders was measured using inverted microscope. The results obtained are given in column 6 of Table II.

TABLE III
Measured of the diameter of cylinders C1 – C6

	Diameter of cylindrical model structure (mm)					
	C1	C2	C3	C4	C5	C6
A-F	100.13	100.21	100.08	100.03	100.08	100.08
B-G	99.97	100.18	100.12	100.15	100.12	100.06
C-H	100.04	99.98	99.98	100.13	100.07	100.11
D-I	99.96	100.13	100.18	100.14	100.15	100.10
E-J	100.01	100.11	100.13	100.12	100.03	100.09
Average	100.02	100.12	100.10	100.11	100.09	100.09

D. Collapse test

Six cylinders, C1, C2, C3, C4, C5 and C6, were subjected to axial compression. Imperfect cylinders C2 – C6 were tested with different crack length introduced. Cylinder C1 was placed between the platens of 250 kN INSTRON machine, as shown in Fig. 4. This helps to provide the desirable boundary condition, i.e., the cylinder is fixed at one end, i.e., $u_x = u_y = u_z = \Phi_x = \Phi_y = \Phi_z = 0$. The same boundary condition was applied at the other end except for $u_z \neq 0$. Though it is practically impossible to achieve fully clamped condition without rotation, but the effect of rotation on the magnitude of buckling load of cylindrical shell has been proven to be marginal, [22].

The load was applied to the bottom end of the cylinder. Incremental axial load was applied at the rate of 1.0 mm/min from the bottom of base plate.

Fig. 4. Compression test arrangements of cylindrical model C1.

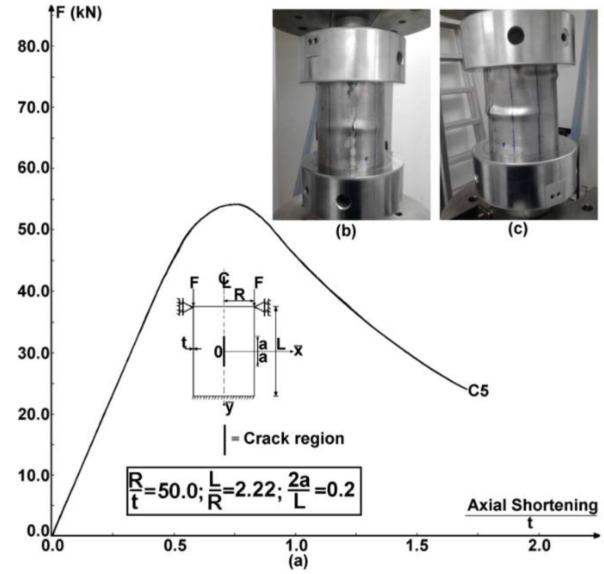

Fig. 6. Plot of experimental axial compressive force, F, against axial shortening for imperfect cylinder C5 (i.e., cylinder with the ratio of crack length to axial length of 0.2).

During the experiment, the axial shortening of the cylinder were recorded using the machine controller. Fig. 5 depicts the plot of axial compressive force against axial shortening for cylinder C1 (i.e., assumed perfect cylinder with no crack). It can be seen that the load versus axial shortening curve is nearly linear up to collapse load. The first linear stage in the pre-buckling path is when the structure deforms elastically after which there is a transition from elastic deformation to plastic deformation. The post-collapse/post-buckling path shows a drop in load as axial shortening continue to increase. A similar plot is presented in Fig. 6a for cylinder C5 (i.e., imperfect cylinder with the ratio of crack length to axial length of 0.2). Similarly, it can be observed from Fig. 6a that the pre-buckling path is nearly linear up to the collapse load and in the post-buckling path, the load decreases as axial shortening increases.

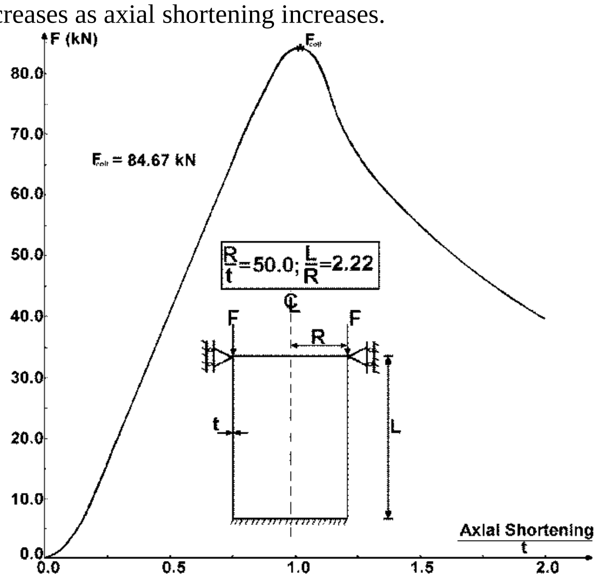

Fig. 5. Plot of experimental axial compressive force, F, against axial shortening for near perfect cylinder C1 (i.e., cylinder with no crack).

Fig. 7 presents comparisons of the load versus axial shortening for cylinders with different magnitude of axial crack length. It must be noted that the amount of compressive deformation in Figs 5, 6 and 7 are normalized by the nominal wall thickness of the cylinders. It can be seen from Fig. 7, that the load against axial shortening for all cylinders shows similar trend except for ratio of axial crack to axial length of the cylinder less than 0.1 (i.e., increasing the ratio of axial crack to axial length of the cylinder results in the increase of the stiffness of the cylinder). Also, it can be noticed from Fig. 7 that the post-buckling behavior follows the same pattern only differing in the magnitude of the buckling load. This behavior appears to be consistent with that of Ref. [18] using finite elements code.

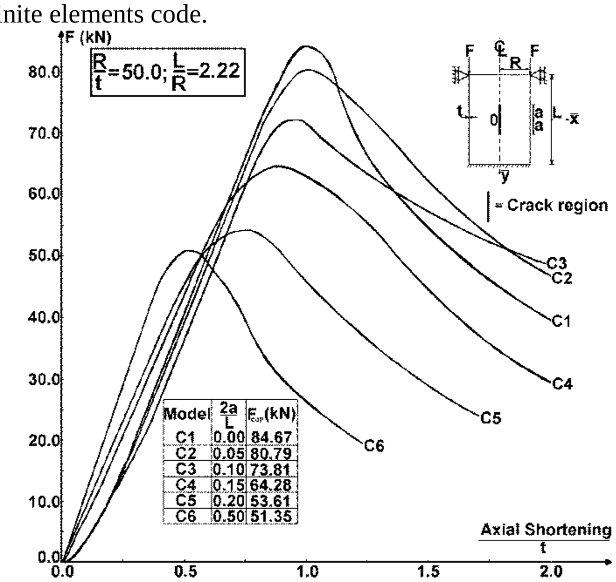

Fig. 7. Plot of experimental axial compressive force, F, against axial shortening for cylindrical shells with and without crack at various crack length.

Fig. 8 shows the collapsed shape of cylinders C1 – C6 after testing. It is apparent that all the cylinders tested fails through axisymmetric collapse. Cylinder C1, C2, C3, C4, C5 and C6 failed at 84.67 kN, 80.79 kN, 73.81 kN, 64.28 kN, 53.61 kN and 51.35 kN respectively.

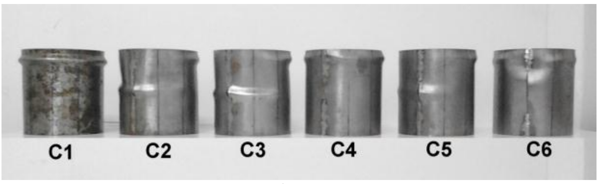

Fig. 8. Photographs of tested cylinders C1 – C6.

IV. COMPARISON OF EXPERIMENTAL RESULT WITH THEORETICAL REFERENCE LOAD

In order to validate the experimental result for nearly perfect cylindrical model C1, experimental collapsed load is compared with theoretical reference load. The theoretical reference load was obtained by calculating the buckling of a reference cylindrical shell using Eqn (1), which is designed as follows:

$$F_{ref} = \pi D t \sigma_{yp} \qquad (1)$$

where F_{ref} is the reference load (i.e., load required for the cylinder to yield).

To achieve the reference load for cylinder C1 using (1), the geometric and material properties were assumed to be the average, i.e., D is the average diameter of the cylindrical shell (D_{avg} = 100.02 mm), t is the average wall thickness of cylindrical model (t_{avg} = 1.02 mm), σ_{yp} is the average upper yield stress of the material from which cylinders are made (σ_{yp} = 256.2 N/mm^2). Then, substituting these values into (1), the magnitude of the reference load for cylinder C1, is determined, F_{ref} = 82.11 kN.

V. RESULTS AND DISCUSSIONS

From Figs 5, 6 and 7, it is apparent that prior to the collapse load, the load versus axial shortening curve is nearly linear. This indicates that the stress is uniformly distributed all over the shell, except in the region crack region as exemplified in Figs 6b and 6c. Also, from Fig. 6b and 6c, it is obvious that as the load increases the crack region increases until the collapse load is reached. In addition, contrary to the principle which state that for axially compressed shell, deformation and stress are greater at region closer to the point of load application, it can be seen that for imperfect cylinders (with crack), the buckling of the specimen begins locally around the crack region (Fig. 6b) and then the cylinder experience general failure with bulging out around its circumference (Fig. 6c). Whereas, for the perfect cylinder (C1), there is a bulging out around the circumference in the neighborhood of the region of load application (Fig. 8).

Furthermore, from Fig. 7, it can be observed that the post-buckling behavior of imperfect cylinder (C2, C3, C4, C5 and C6) is similar to each other and that they only differ in the value of the collapse load. This can be attributed to the fact that there is no interaction existing between the two crack edges while deformation of the shell and the crack opens completely, [18].

Fig. 9 depicts the plot of buckling load corresponding to different imperfect cylinders having a crack against increasing length of crack. It can be seen from Fig. 9 that increasing the crack length of the cylinder results in decrease in the load carrying capacity of the structures. This result appears to be in agreement with published work in open literatures [13 – 15], i.e., load carrying capacity of the cylindrical shell structure reduces as the axial crack length increases. Also, it appears from Fig. 9 that for $2a/L \geq 0.2$, the line remains about linear i.e., a fraction of 0.2 crack on the axial length of the cylinders is enough to cause maximum reduction in its buckling strength.

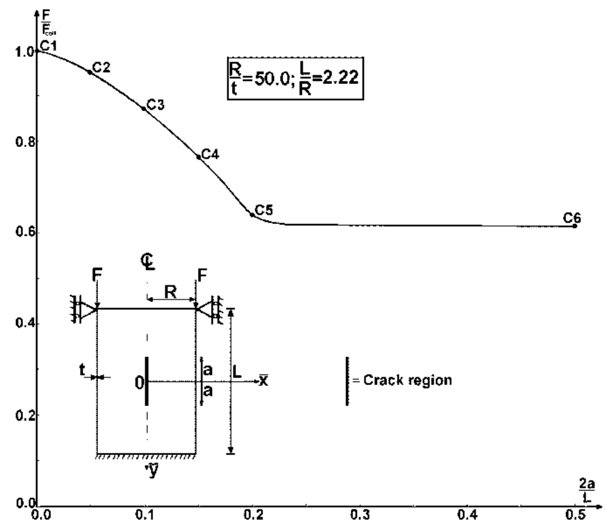

Fig. 9. The effect of crack length on the buckling strength of axially compressed cylinders.

In addition, the experimental data complement the work of Shariati et al. [18] and widen its scope by catering for axial crack length-to-axial length of the cylinder within the range 0.05 to 0.2. According to [18], it was reported that for cylindrical shells with axial crack (longitudinal crack), the change in crack length and increasing the crack length-to-circumference of cylinder ratio, has minor effect on the buckling load of the cylinder. This is only valid for ratio of axial crack length to axial length of the cylinder above 0.2. From the experimental results presented in this paper, it is apparent that changing the axial crack length and increasing the axial crack length-to-axial length of cylinder by 10% (i.e., 0.1) will cause a reasonable reduction in the buckling load of the cylinder, about 13% reduction in the load carrying capacity, while changing the crack length and increasing the crack length-to-axial length of cylinder by 20% (i.e., 0.2) will produce about 37% reduction in the load carrying capacity and changing the crack length and increasing the crack length-to-axial length of cylinder by 50% (i.e., 0.5), the buckling load remains about the same. Hence, for axial crack length-to-axial length of the cylinder ratio, less than 0.2, there is a considerable reduction in the load carrying capacity of the cylinder.

Finally, prediction of reference buckling load for cylinder C1 based on (1) gives a close result to the experimental value (82.11 kN versus 84.67 kN). It can be seen that the result are in very good agreement as the reference buckling load underestimate the experiment by 3%.

VI. CONCLUSION

This paper provides additional experimental data into the buckling behavior of relatively thick and short cylindrical shell with axial cracks subjected to axial compressive force. Contrary to Ref. [18], it can be concluded that for cylinders with axial crack, change in crack length and increasing the ratio of crack length to axial length of the cylinder will cause a considerable reduction in the load carrying capacity of the cylinders, for crack length-to-axial length of the cylinder ratio ≤ 0.2. Whilst, for crack length-to-axial length of the cylinder ratio > 0.2, changing the crack length and increasing the ratio of crack length to axial length of the cylinder has minor effect on the buckling load of the cylinder. In addition, it is revealed that the buckling mode of cylinder with axial crack changes with crack length and that the buckling deformation leads to a reasonable amplification of the load intensity around the crack region.

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REFERENCES

[1] J. M. Rotter, "Cylindrical shells under axial compression", in Buckling of Thin Metal Shells, J. G. Teng, J. M. Rotter (eds), Spon Press, London, 2004, pp. 42-87.

[2] J. C. Amazigo, B. Budiansky, “Asymptotic formulas for the buckling stresses of axially compressed cylinders with localized or random axisymmetric imperfections”, *Journal of Applied Mechanics*, 93, 179 – 184, 1972.

[3] J. Hutchinson, D. Muggeridge, R. Tennyson, “Effect of local axisymmetric imperfection on the buckling behaviour of circular cylindrical shell under axial compression, *AIAA Journal*, 9, 48 – 52, 1971.

[4] A. Khamlichi, M. Bezzazi, A. Limam, “Buckling of elastic cylindrical shells considering the effect of localized axisymmetric imperfections”, *Thin-Walled Structures*, 42, 1035 – 1047, 2004.

[5] J. Blachut, “Buckling of axially compressed cylinders with imperfect length”, *Computers and Structures*, 88, 365 – 374, 2010.

[6] J. Blachut, “Buckling of cylinders with imperfect length”, *Journal of pressure vessel technology*, 137, 011203-1 – 011203-7, 2015.

[7] L. Friedrich, H. G. Reimerdes, “Imperfection sensitivity of circular cylindrical shells of varying length subjected to axial compression”, In: 54th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference, Boston, MA, 2013.

[8] M. Cai, J. M. F. G. Holst, J. M. Rotter, “Buckling strength of thin cylindrical shells under localised axial compression”, In: Proceeding of the 15th ASCE Engineering Mechanics Conference, New York, pp 99 -100, 2002.

[9] V. Krasovsky, “Nonlinear effects in behaviour of cylindrical shells under nonuniform axial compression, Experimental Results”, In: Proceedings of the 2nd International Conference on Nonlinear Mechanics, Beijing, pp 245 – 248, 1993.

[10] A. Libai, D. Durban, “Buckling of cylindrical shells subjected to nonuniform axial loads”, *Journal of Applied Mechanics, Transactions of the ASME*, 44, 714-720, 1977.

[11] B. Kriegesmann, M. W. Hilburger, R. Rolfes, "The effects of geometric and loading imperfections on the response and lower-bound buckling load of a compression-loaded cylindrical shell", Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Material Conference (doi 10.2514/6.2012-1864), Honolulu, Hawail, 2012.

[12] C. Y. Song, J. G. Teng, J. M. Rotter, “Imperfection sensitivity of thin elastic cylindrical shells subjected to partial axial compression”, *International Journal of Solids and Structures*, 41, 7155 – 7180, 2004.

[13] H. E. Estekanchi, A. Vafai, “On the buckling of cylindrical shells with through cracks under axial load”, *Thin-Walled Structures*, 35, 255-274, 1999.

[14] B. H. Jahromi, A. Vaziri, “Instability of cylindrical shells with single and multiple cracks under axial compression”, *Thin-Walled Structures*, 54, 35 – 43, 2012.

[15] Y. T. Kim, “Buckling of a cracked cylindrical shell reinforced with an elastic liner”, Master’s Theses, Northeastern University, Boston, Massachusetts, USA, 2011.

[16] Y. T. Kim, B. Haghpanah, R. Ghosh, H. Ali, A. M. S. Hamouda, A. Vaziri, “Instability of a cracked cylindrical shell reinforced by an elastic liner”, *Thin-Walled Structures*, 70, 39 – 48, 2013.

[17] A. Vaziri, H. E. Estekanchi, “Buckling of cracked cylindrical thin shells under combined internal pressure and axial compression”. *Thin-Walled Structures*, 44, 141 – 151, 2006.

[18] M. Shariati, M. Sedighi, J. Saemi, H. R. Eipakchi, H. R. Allahbakhsh, “Numerical and experimental investigation on ultimate strength of cracked cylindrical shells subjected to combined loading”, *Mechanika*, 84, 12 – 19, 2010.

[19] O. Ifayefunmi, Lu Kian Hap, “Effect of material discontinuity on the flanges of axially compressed cylinder”, Journal of Mechanical Engineering and Sciences, 10, 2084-2097

[20] BS EN 10002-1, "Tensile testing of Metallic Materials, Part (1), Method of test at ambient temperature", British Standard Institute, London, UK, 2001.

[21] J. Singer, "Buckling experiments on shell - A review of recent development", TAE Report No. 403, pp. 1 - 81, 1980.

[22] O. Ifayefunmi, J. Blachut, “The effect of shape, thickness and boundary imperfections on plastic buckling of cones”, Proceedings of the 30th International Conference on Ocean, Offshore and Arctic Engineering, Vol. 2, OMAE2011-49055, ASSME, NY, USA, pp 23 - 33, 2011.

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