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Experimental study of SS304L cylindrical shell with/without cutout under cyclic axial loading

M. Shariati *, H. Hatami

Department of Mechanical Engineering, Shahrood University of Technology, Shahrood, Iran

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ABSTRACT

In this research, softening and ratcheting behaviors of stainless steel 304L cylindrical shells under displacement-control and force-control cyclic axial loading are studied. Experimental tests were performed by a servo-hydraulic INSTRON 8802 machine. The mechanical properties of specimens were determined according to ASTM E8 standard. Under force-control loading with non-zero mean force, ratcheting behavior is occurred on cylindrical shell and plastic strain accumulation continues up to collapse point of cylindrical shell. The rate of ratcheting strain became higher by using of the higher force amplitude. Under displacement control loading, softening behavior is observed and due to occurred buckling in compression zone, this behavior becomes more extreme. Also, cutout effect on cylindrical shells under these kinds of loadings has been studied and it has been observed that cutout causes softening and ratcheting behaviors in cylindrical shell extremely. Also effect of locations and sizes of cutouts on softening and ratcheting behavior are studies and results shows that increase of cutout radius shows more ratcheting strain than other specimens and rate of ratcheting strain is much higher than the others and reaches collapse point earlier than other specimens.

1. Introduction

Recently, shells and plates assigned a widespread part of different industrial structures to themselves. Due to their light weight and high strength, shells have wide range of usages in industries. These specifications arise from geometric and substantial nature of the shells. Shell structures are considered from the best structures by their pressure and strike load endurance as in the nature, animals and plants are covered by shell structure coverings. By getting the perception of important specifications of shell structures including load tolerance power, high consistency, and easy manufacture, engineers are always using shell structures in design and manufacture of different structures. Its use in airplane framework, wing and tail covering, rocket covering and etc. are mentioned as shell usages. Using shells and sheets in other industries like automotive industries, floating industries, oil and gas tanks in petrochemical industries, pipe lines, liquid storage tanks, seeds silos, pressured containers, and valves or caps. are prevalent. Special kind of symmetric axial shells which are known as cylindrical shells are discussed in this research.

Despite the presence of non-zero mean stress, cyclic stress-control loading leads to accumulation of residual plastic strain; this phenomenon is named as ratcheting. These stresses should be greater than yield stress. It means that under this stress, material or structure have to enter plastic zone. Ratcheting is especially important in prediction of engineering structures life time. Also under asymmetric cyclic loading if the specimens have an imperfection as cutout or crack, it occurred to crack growth of nearby the imperfection and rate of ratcheting is increased [1].

Mentioning the discussed subject about the importance of fatigue phenomenon and unknowability of low cyclic fatigue and on the one hand, daily increase of cylindrical shell usage and lack of knowledge related to their fatigue specifications, analysis of fatigue phenomenon regarding cylindrical shell is studied in this research.

In order to review the implemented works on types of materials under different cyclic loadings, studies are proposed in two parts. First part is about cyclic loading on different materials and the effect of types of loading on parameters like ratcheting strain, rate of ratcheting strain, number of needed cycles to failure of materials and other parameters. Second part is reviewing papers concerning only to cylindrical shells under cyclic loading.

A study has been done on the ratcheting behavior and fatigue of a kind of copper alloy under uniaxial loading by mean stress. They measured ratcheting strain to failure point by stress-control tests in room temperature with/without mean stress. By drawing ratcheting strain vs. number of cycles, they showed that for this alloy, the related curve is similar to creep curve and has three stages: initial, secondary and tertiary stages. The mentioned researchers

* Corresponding author. Tel.: +98 273 3395503; fax: +98 273 3391460.
E-mail addresses: mshariati@shahroodut.ac.ir, mshariati44@gmail.com (M. Shariati).

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also studied ratcheting strain rate and predicted fatigue lifetime of this alloy by using the models like Walker and SWT model [2]. Also another study has been done on low cyclic fatigue and ratcheting of CK45 steel under uniaxial loading. some strain-control and stress-control tests performed on this kind of steel. some equations achieved for fatigue lifetime predictions based on strain-control tests results and used for fatigue damage prediction in ratcheting failure [3]. A study has been done on low cyclic fatigue and strain-stress curves of carbon steel and stainless steel structures [4]. Another study has been done on axial ratcheting strain effect on torsion low cyclic fatigue lifetime of a kind of lead-free during several tests. They used multi axial strain-control loading in room temperature to find out that fatigue lifetime reduces by increasing axial strain ratcheting [5]. Several tests performed regarding fatigue properties and nitrogen steel ratcheting, under uniaxial loading. In these tests they studied stress amplitude effects, mean stress, history loading and rate of stress loading on ratcheting behavior of these steels [6]. Another test performed on kind of eutectic tin–lead solder under multi axial and uniaxial loading and studied its ratcheting behavior. Also, the effects of applied strain rate on strain ratcheting in different conditions were studied [7]. A study has been done on ratcheting effects and stainless steel SS304 fatigue in uniaxial loading under stress-control conditions at room temperature. Mean stress effects, stress amplitude and stress–ratcheting strain ratio and specimens lifetime were studied. Results of these tests show that ratcheting strain and fatigue life time of this material is highly related to mean stress, stress amplitude and stress ratio [8]. Experimental tests have been don on the behavior of polyacetal or Polyoxymethylene (POM) under uniaxial cyclic loading. They showed that the ratcheting strain and strain rate ratcheting are sensitive to the applied stress amplitude and the mean stress [9]. Also some studies have been done on predicting of hysteresis loops by isoenergy density theory for polycrystals [10,11]. Many fatigue studies were performed on standard samples of stainless steel like SS304, SS304L, SS316 and SS316L, since these samples show high resistance under cyclic loading and high strain ratcheting behavior [12–17]. A study has been done on mechanical characterization and finite element modeling of cyclic stress–strain behavior of ultra-high molecular weight polyethylene. In this study, by using symmetric strain-control tests, with/without air jet cooling, material constants (to be used in advanced models of plasticity in ABAQUS to determine isotropic and kinematic hardening behavior) were derived and used in ABAQUS for hysteresis cycles modeling [18]. Also, cyclic loading on cylindrical shell by box shaped section and behavior of these structures under cyclic loading were studied [19].

Recently, some studies are performed on cylindrical shells with circular sections under cyclic loadings. These shells are exposed to cyclic axial loadings during their lifetime and it reduces their lifetime. Earthquakes are considered of natural loadings and will be applied on these structures [20]. Because of problems in experimental tests present in cyclic axial loading of cylindrical shells, slight studies were performed on them. One of these studies is presented in which buckling strain amplitude of shells under cyclic axial loading is predicted less than monotonic pressure loading, but softening or hardening behavior of the specimens were not mentioned [21]. Another study has been done on alloy cylindrical shells under biaxial loadings and used numerical method and hardening models to simulate hysteresis curves. Loadings were done according to strain-control and were applied under tension – twist displacement on specimens simultaneously [22]. Experimental studies on cylindrical shells were done mostly by cyclic bending loadings. Many experimental results were achieved by this kind of loading on cylindrical shells [23–28]. A preformed study on tubes has shown that amount of cycles, mean stress and stress amplitude are effective parameters to collapse these specimens under cyclic axial loading with internal pressure [29]. Strain-control loading was also done on magnesium alloy cylindrical shells and amount of cycles needed to failure of specimens under the effect of strain amplitude and mean stress were studied [30]. Another study analyses buckling behaviors on monotonic and cyclic strain-control loading effects under the influence of different parameters like diameter, length and radius of cylindrical shell [31].

Only buckling behavior under compression loading was studied on cylindrical shell with cutout. A study has been done on buckling of composite cylindrical shell with cutout under compression loading and internal pressure [32]. Another study has been done on aluminum cylindrical shells with cutout under compression loading and studied the size of cutout, position of cutout and aspect ratio on buckling behavior of specimens [33]. A recent study has been done on the effect of thickness, length and diameter on buckling behavior of cylindrical shells with elliptical cutout under compression loading [34]. Also some studies are performed on buckling of cylindrical shells with cutout and cracked [35,36].

In this research, cylindrical shells were placed under force-control and displacement-control cyclic axial loading. Also the cutout effect on cylindrical shell hysteresis curves, under these kind of loadings were studied and the effect of size of cutout, position of cutout and length of specimens on hysteresis curves behavior were studied. It is observed that the cutout intensifies softening and ratcheting behavior on cylindrical shells.

2. Test device

Experimental tests in this study have been performed by using INSTRON 8802 servo hydraulic machine (Fig. 1). This device can be loaded up to 250 kN dynamically. A load cell with 25 kN capacity were used to perform standard tension tests and to obtain mechanical properties of the cylindrical shells. An extensometer was used in standard tension tests to achieve higher accurate displacement.

3. Boundary conditions

In order to perform cyclic axial loading on cylindrical shells a fixture is needed which is able to apply tension and compression loading on cylindrical shells without any rotation slip and clearance. Because specimens are thin, their two sided thread is not possible. So, part No. 2 were used to reinforce two endings of shells. These parts were threaded and each side of them was welded to cylindrical shell in order to prevent separation of shell while loading (Fig. 2). These kinds of joints samples in cyclic axial loading also are seen in articles [19,37]. To ensure no deformation in fixtures, in addition of threaded to fixture, a pin is used. In Fig. 2, part No. 1 is a fixture for connecting to the device jaw. Part No. 2 used for cylindrical shell reinforcement in pin zone. Because of the thin cylindrical shell, it may not be threaded. Therefore, part No. 2 is used to connect to the fixture. Part No. 3 shows section of cylindrical shell. Also in Fig. 1, fixtures can be seen attached to the jaws of the machine and specimen at loading time.

4. Experimental results on the SS304L cylindrical shells

On SS304L cylindrical shells, force-control and displacement-control tests have been performed and displacement and force amplitude have been changed. Also effect of cutout radius and location on softening and ratcheting behavior of SS304L cylindrical shells were studied.

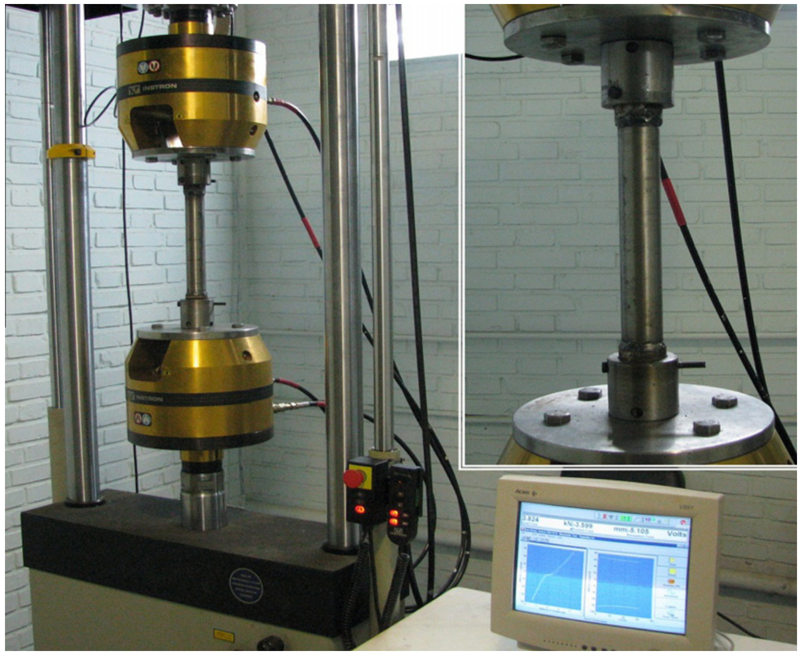

Fig. 1. INSTRON 8802 servo hydraulic machine.

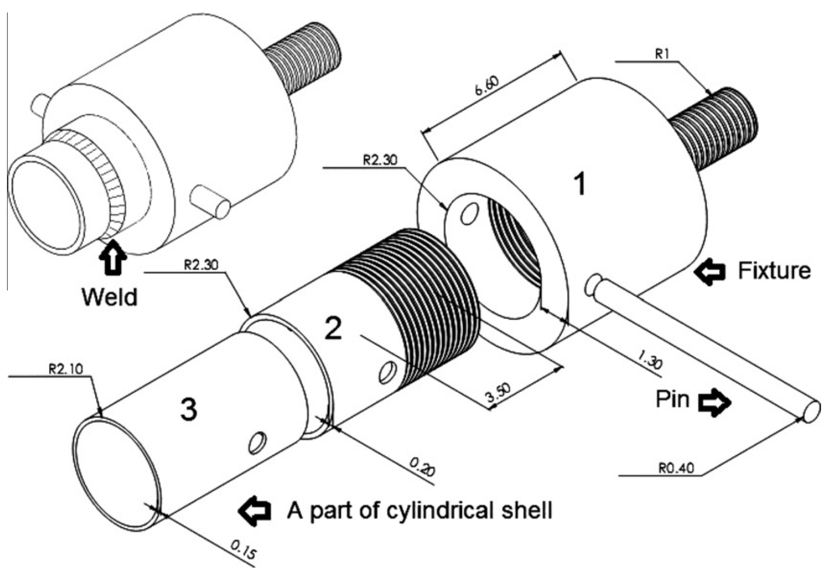

Fig. 2. Schematic of the cylindrical shell connected to the fixture using welding, threading and pin (dimensions are in cm).

4.1. Geometry and mechanical properties of specimens

Tested specimens are made from stainless steel SS304L by geometrical dimensions, shown in Table 1. Mechanical properties of specimens are determined according to ASTME8 standard [38]. Related strain–stress curve is shown in Fig. 3. Loading rate of all tests is 0.1 mm/s for displacement- control loading and 2 kN/s for force-control loading.

Table 1
Geometrical and mechanical properties of SS304L.

External Diameter	D = 42 mm
Thickness	t = 1.5 mm
Length	L = 250,300,340 mm
Modulus elasticity	E = 201 (GPa)
Yield stress	351 σ_y = (MPa)
Ultimate stress	S_u = 815 (MPa)
Poisson's ratio	υ = 0.33

4.2. Buckling effect on softening behavior of cylindrical shell

A cylindrical shell with 300 mm length was placed under displacement-control loading with 10 mm displacement amplitude. Under this loading, shell buckle plastically and hysteresis curves behavior might be seen under the effect of buckling. In Fig. 4, it has been seen that after cylindrical shell buckling, softening behavior in tension zone highly increases and finally specimen results

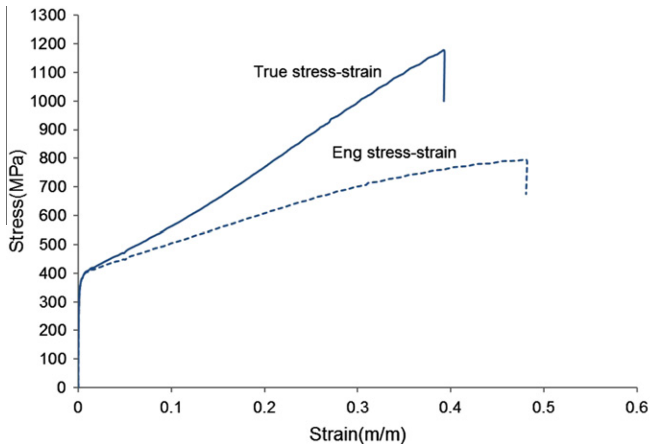

Fig. 3. Strain–stress curve of tension test for SS304L specimen.

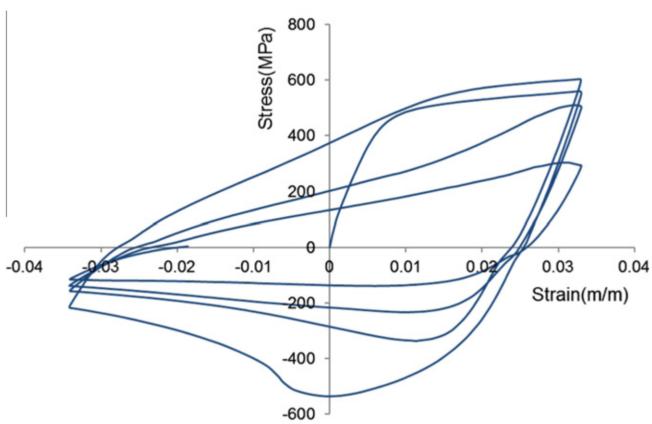

Fig. 4. Hysteresis curves with 300 mm specimen length under displacement-control loading with 10 mm displacement amplitude.

collapse. In Fig. 5, applied stress amplitude in tension and compression zone of hysteresis curves are shown. softening behavior is observed in both zones. Also in consecutive cycles it was observed that endurance loading in compression zone decreases due to occurred buckling. Under buckling effect, softening in tension zone highly increases.

In Fig. 6, cylindrical shell is shown while buckling. Deformations occurred in the middle of specimen and also nearby fixtures.

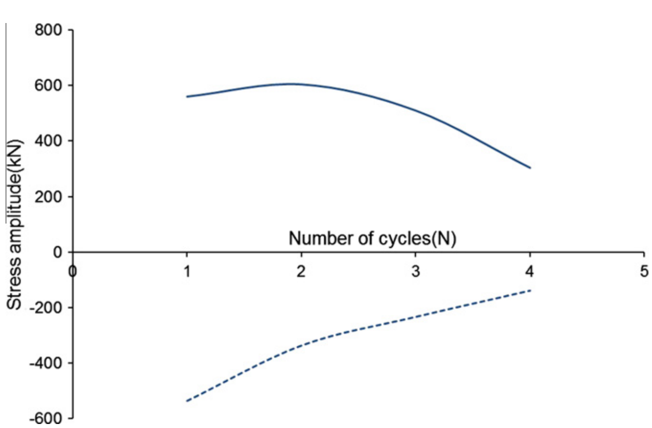

Fig. 5. Stress peaks in cylindrical shells hysteresis curves with 300 mm length under displacement-control loading with 10 mm displacement amplitude.

4.3. History loading effect

4.3.1. Loading sequence effect on softening behavior

Two tests were performed on with 250 mm specimen length under increasing displacement-control loading in displacement amplitude between 0.75 and 4 mm. But there was a difference, at the first test, the specimen was placed under compression load for all of amplitude displacement and then it enters tension zone and in the second test it was performed vice versa. As it is shown in Figs. 7 and 8, hysteresis curves for two tests are displayed.

For both of tests, cylindrical shells were buckled in 3 mm amplitude and softening speed increased afterwards. In Fig. 9, stress peaks in hysteresis curves of both tests are compared.

It was observed that compression load endurance is higher in the test which firstly has been put under tension loading and tension load endurance is higher in the test which firstly has been put under compression loading By comparing of two performed tests in Fig. 9. The buckling behaviors of two specimens were occurred at 3 mm displacement amplitude.

4.3.2. History loading effect on ratcheting behavior of cylindrical shell

Force-control loading was applied on cylindrical shell with length of 250 mm, 30 kN mean force and increasing force amplitude from 10 kN to 45 kN. As it is seen in Fig. 10, due to unsymmetrical force-control loading, ratcheting behavior was created in cylindrical shell. The rate of ratcheting strain became higher by increase of force amplitude Under this loading, force amplitude is decreased to 30 kN after 35 kN. After loading in this amplitude, increase of force amplitude is continued on cylindrical shell. The effect of history loading is obvious on ratcheting behavior in Fig. 11.

Rate of ratcheting strain in 30 kN force amplitude is decreased after 35 kN force amplitude comparing to before loading and it is about zero. Hardworking phenomena is occurred due to history loading with more force and rate of ratcheting strain is decreased during less force amplitude.

4.4. Cutout effect on behavior of cylindrical shells

In order to study cutout effect, and also radius and locations of cutouts on softening and ratcheting behavior of cylindrical shells, displacement and force-control tests were done on specimens.

Cylindrical shells with length of 250 mm without cutout and with circular cutout (radius = 6 mm) in 1/2 and 3/4 of length positions of specimens were tested under cyclic loading to study cutout

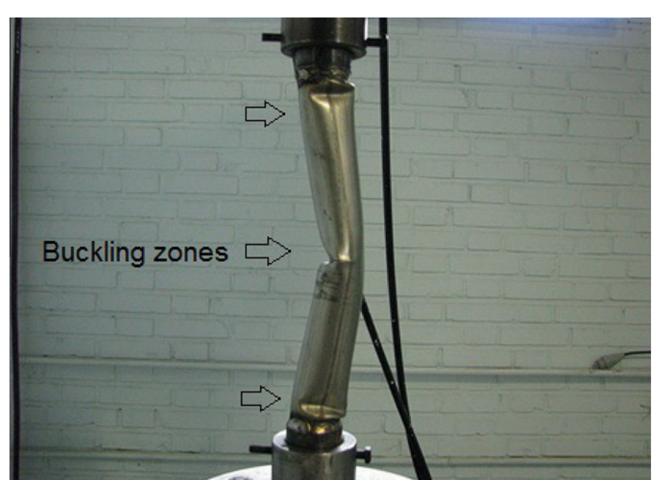

Fig. 6. Buckling of cylindrical shell with 300 mm length under displacement-control loading with 10 mm displacement amplitude.

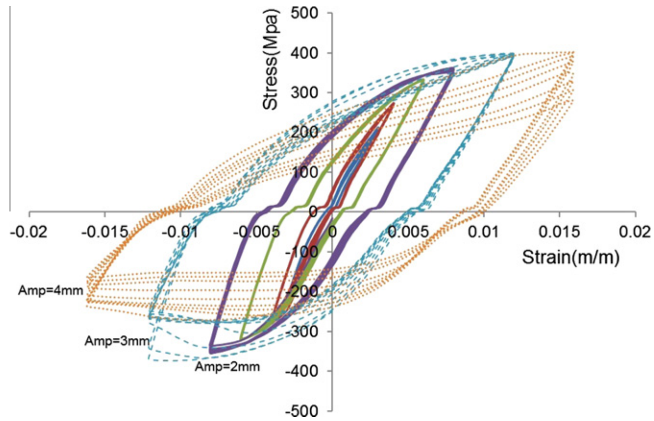

Fig. 7. Hysteresis curves under displacement-control loading with compression – tension sequence.

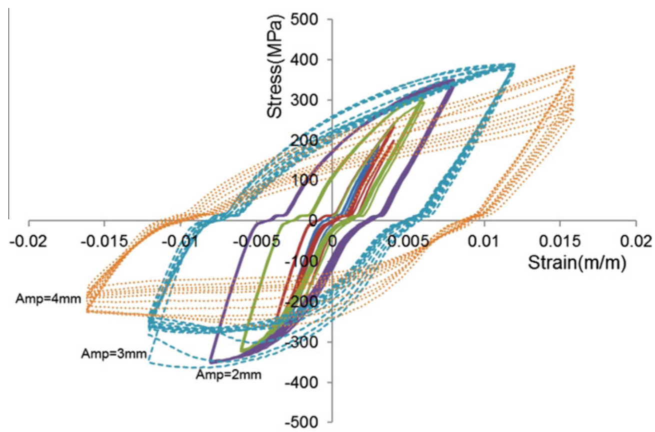

Fig. 8. Hysteresis curves under displacement-control loading with tension – compression sequence.

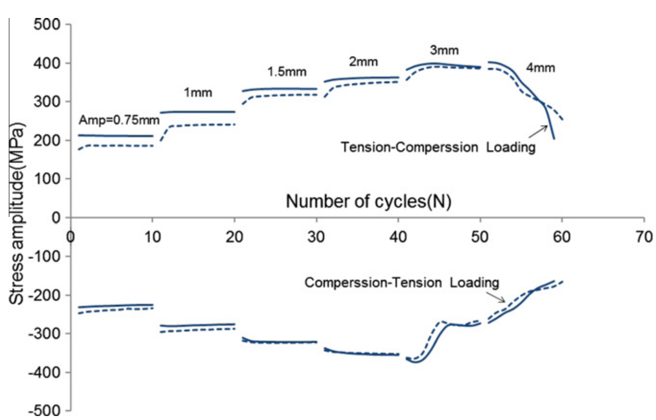

Fig. 9. Stress peaks in hysteresis curves of two displacement-control tests with different loading sequences.

effect and positions of cutout on hysteresis curves behavior. Also cylindrical shell with cutout (radius = 9 mm) in 1/2 of length of specimen was tested to study size of cutout on hysteresis curves behavior.

4.4.1. Cutout effect on softening behavior under displacement-control loading

Displacement control tests were done on specimens with 250 mm length by increasing displacement amplitude from 0.75

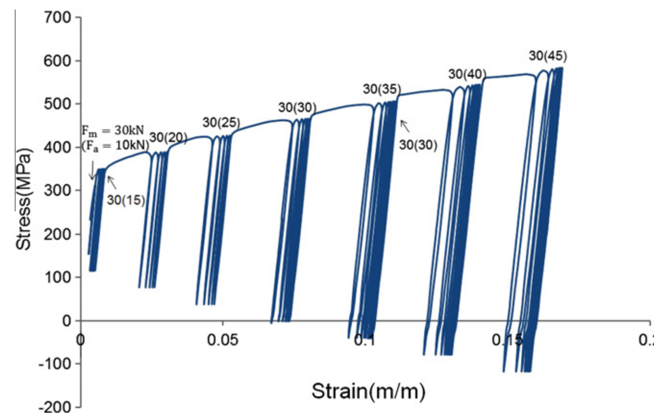

Fig. 10. Ratcheting behavior in cylindrical shell under force-control loading.

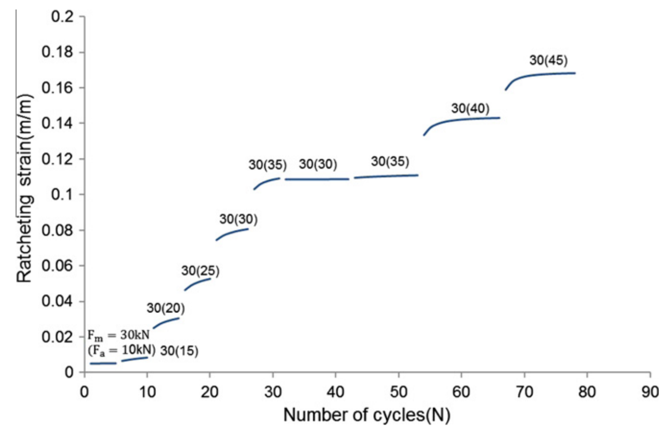

Fig. 11. Effect of loading history on ratcheting behavior of cylindrical shell.

to 4 mm. Circular cutouts (radius = 6 mm) were made on two cylindrical shells in 1/2 and 3/4 of their length positions and a circular cutout (radius = 9 mm) was made on 1/2 of its length for compare of cutout effect, radius and position of cutout on a specimens by a cylindrical shell without cutout.

As it is seen in Fig. 12, stress peaks of hysteresis curves in tension and compression zone is achieved for four different tests. Hardening behavior is seen in cylindrical shell without cutout in tension zone. But in compression zone, softening behavior is seen in first two steps and hardening behavior is seen in next others. Finally, buckling occurred for cylindrical shell in 3 mm displacement amplitude. A cylindrical shell with 6 mm cutout radius at the middle of its length has higher load endurance in both tension and compression zones comparing to the same specimen without cutout because wrinkling occurred nearby of cutout under cyclic loading. In some loading steps that specimen without cutout has hardening behavior; specimen with cutout shows softening behavior due to presence of cutout. Specimen with cutout (radius = 9 mm) in all loading steps shows softening behavior. Also tension and compression load endurance of this specimen is less than the above mentioned two specimens because the radius cutout has increased. At last, specimen with cutout (radius = 6 mm) in 3/4 of its length position shows the same softening behavior compared to the same specimen with same cutout radius at the middle of its length. Compression load endurance of all four specimens in 3 mm displacement amplitude suddenly decrease and show more softening behavior. Also, all four specimens collapse in 4 mm displacement amplitude.

In Fig. 13, some performed tests on specimens with cutout under displacement-control loading are shown. As it is seen, behavior

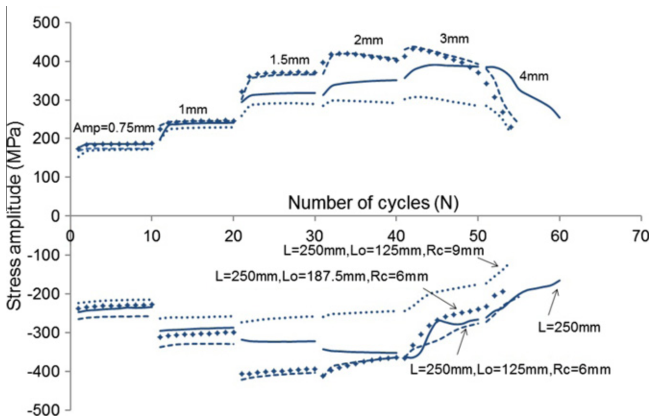

Fig. 12. Cutout and its radius and position effects on cylindrical shells under displacement-control.

of cylindrical shell with 250 mm length are shown nearby cutout place in different loading steps, which is respectively: before loading, loading with 1 mm displacement amplitude in compression zone, loading with 2 mm displacement amplitude in compression zone, loading with 3 mm displacement amplitude in tension zone and finally while specimens collapsed.

4.4.2. Cutout effect on ratcheting behavior under force-control loading

Cutout effect, radius and position of cutout on cylindrical shells under 30 kN mean force and increasing force amplitude (5–60 kN) were tested. In Fig. 14, ratcheting behavior of cylindrical shell without cutout is shown. Also in Fig. 15, graph of ratcheting strain vs. number of loading cycles is shown. It can be observed from the figures that by increasing the force amplitude on cylindrical shell, plastic strain is accumulated rapidly. Ratcheting behavior of specimen continues up to failure point. Also, rate of ratcheting strain increases in higher force amplitude.

In Fig. 16, ratcheting behavior of cylindrical shells with and without cutout is compared. Cutout effect, radius and position effect of cutout on ratcheting behavior of cylindrical shells are studied and compared to specimen without cutout. By comparing ratcheting strain curves, it is observed that specimen with cutout (radius = 6 mm) at the middle of its length shows similar behavior with specimen without cutout. This specimen shows slightly more ratcheting behavior compared to similar specimen without cutout. It is collapsed at 50 kN force amplitude. Specimen with cutout (radius = 6 mm) at 3/4 of its length shows more ratcheting strain compared to two prior specimens. Also the rate of ratcheting strain is higher. Finally specimen with cutout (radius = 9 mm) at the middle of its length shows more ratcheting strain compared to prior specimens. Also the rate of ratcheting strain of this specimen is higher than prior specimens and reaches to collapse point earlier compared to prior specimens.

In Fig. 17, some of preformed tests on cylindrical shells with cutout are shown under force-control loading. Behavior of specimens with 250 mm length is shown nearby cutout location during different steps of loading which is respectably: before loading, while loading, while specimens collapsing.

4.5. Length effect with cutout effect on cylindrical shells under cyclic loading

4.5.1. Length effect with cutout effect under displacement-control loading

As it is seen in Fig. 18, two specimens with 250 mm and 340 mm length were put under displacement control loading with

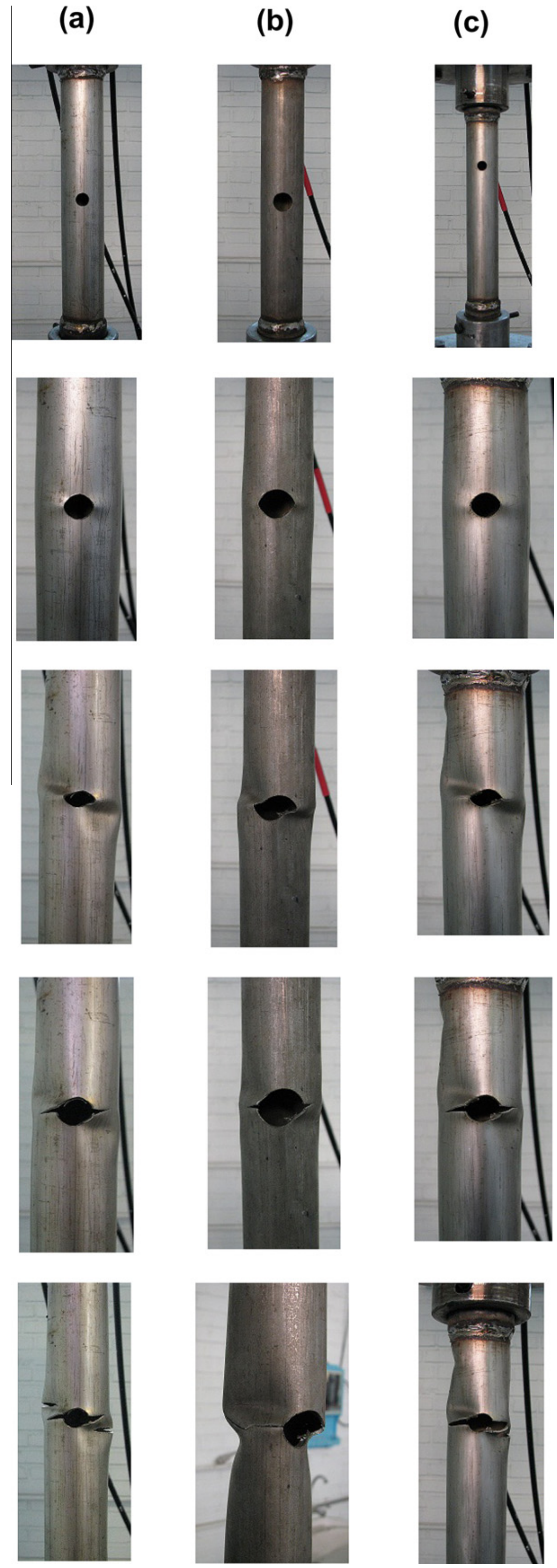

Fig. 13. Behavior of cylindrical shells with 250 mm length nearby cutout under displacement-control loading. (a) With cutout (radius = 6 mm) at the middle of specimen length. (b) With cutout (radius = 9 mm) at the middle of specimen length. (c) With cutout (radius = 6 mm) in 3/4 of specimen length.

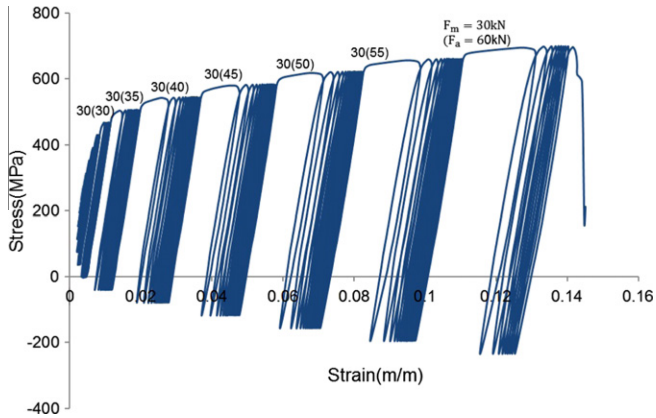

Fig. 14. Ratcheting behavior of cylindrical shell without cutout under force control loading.

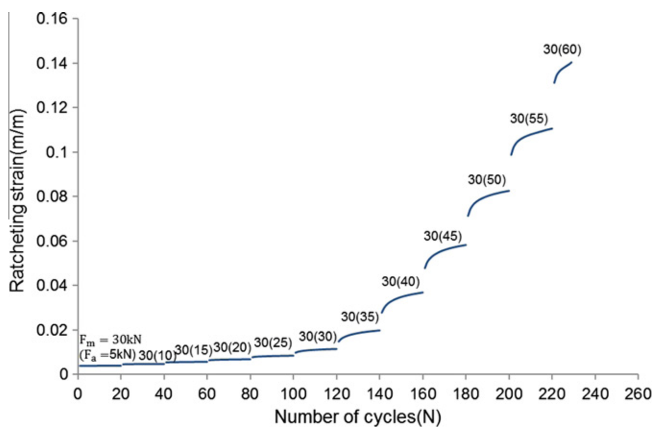

Fig. 15. Ratcheting strain vs. number of loading cycles on specimens without cutout.

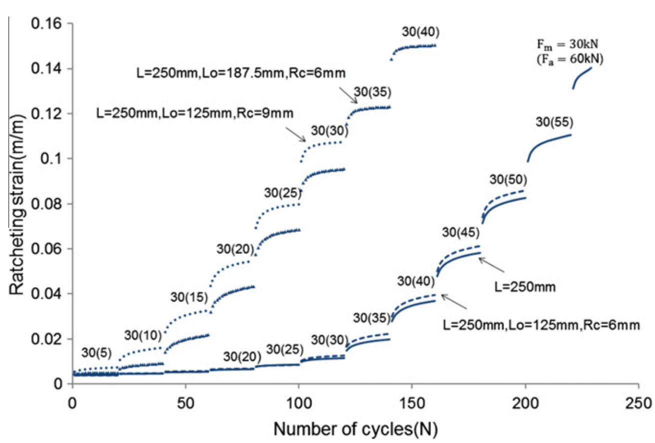

Fig. 16. Comparison of ratcheting behavior on cylindrical shells and the effect of cutout on specimens.

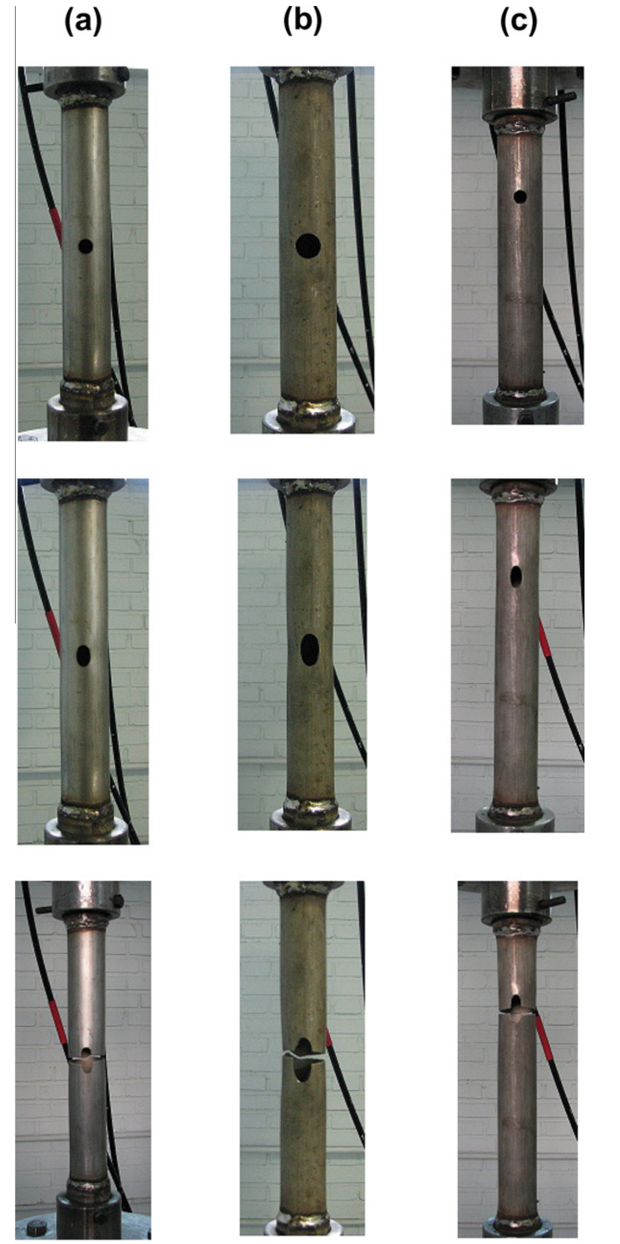

Fig. 17. Behavior of 250 mm cylindrical shells nearby cutout under force-control loading. (a) With cutout (radius = 6 mm) at the middle of specimen length. (b) With cutout (radius = 9 mm) at the middle of specimen length. (c) With cutout (radius = 6 mm) in 3/4 of specimen length.

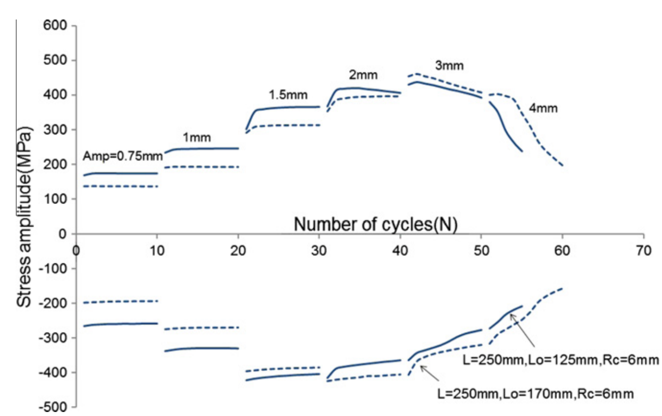

Fig. 18. Length effect with cutout effect on behavior of cylindrical shells under displacement-control loading.

displacement amplitude 0.75–4 mm. Both specimens have cutout (radius = 6 mm) at the middle of specimens length. As it is seen in Fig. 18, tension and compression load endurance of shorter specimen is higher up to 1.5 mm displacement amplitude. Both specimens have softening behavior in compression zone. Also both specimens reach buckling point in 3 mm displacement amplitude at compression zone, then softening behavior of both specimens increase in both zones.

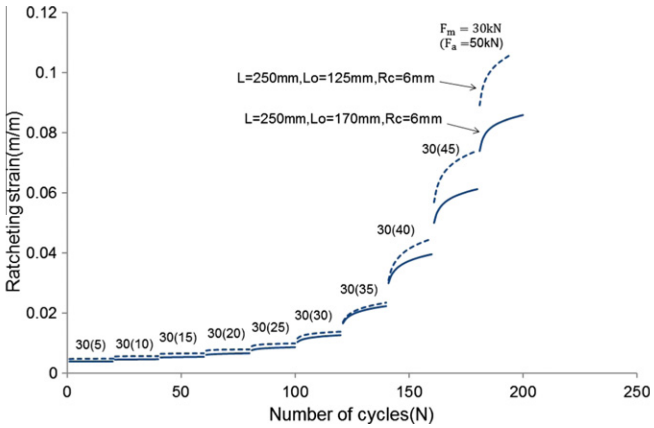

Fig. 19. Length effect with cutout effect on behavior of cylindrical shells under force-control loading.

4.5.2. Length effect with cutout effect under force-control loading

As it is seen in Fig. 19, two specimens with 250 mm and 340 mm lengths were put under 30 kN mean force and increasing force amplitude 5 kN up to 50 kN. Both specimens have cutout (radius = 6 mm) at the middle of their length. Shorter specimen has less ratcheting strain comparing to longer one. Also rate of ratcheting strain of this specimen is less than the other. Both specimens reach collapse point in 80 kN total force. Specimens in force amplitude lower than 35 kN show the same ratcheting strain behavior and by increasing the force amplitude, the ratcheting strain and rate of ratcheting strain of longer specimen is more than shorter specimen.

In Fig. 20, some SS304L cylindrical shells are shown before and after experimental tests.

5. Results

In attention to experimental tests performed on cylindrical shells the below results are extracted:

1. Under force-control loading with non-zero mean force, ratcheting behavior is shown on cylindrical shells and plastic strain accumulation continues up to collapse point of specimens. The rate of ratcheting strain became higher by using of the higher force amplitude.
2. Softening behavior of cylindrical shell under displacement-control loading increases while specimen reaches buckling point.
3. Loading history has effects on ratcheting behavior of cylindrical shell. As, after loading on cylindrical shell is performed to known amount of cycles, while loading on specimen is performed with less force amplitude comparing to primary loading, resulted rate of ratcheting strain is less than preformed loading without primary loading. This happened due to hard-working occurred in cylindrical shell.
4. If sum of stress amplitude and mean stress values are chosen nearby yield stress, then ratcheting behavior is not occurred in cylindrical shell or rate of ratcheting strain approaches zero.
5. While two performed tests on SS304L cylindrical shells in displacement-control loading is compared, it is observed that compression load endurance of specimen which primarily loading was put under tension zone, is higher than the specimen which primarily loading was put under compression zone in the first step of loading. But tension load endurance is always higher in the test which primarily loading has been put under compression zone.
6. SS304L cylindrical shell with cutout (radius = 6 mm) at the middle of specimen length shows more load endurance in both tension and compression zone comparing to the same specimen without cutout under displacement control loading because wrinkling occurred nearby of cutout under cyclic loading. Specimen with cutout (radius = 9 mm) shows softening behavior in all loading steps. Also, tension and compression load endurance of this specimen is less than the above mentioned specimens. At last, specimen with cutout (radius = 6 mm) at 3/4 of its length shows similar behavior compared to the same specimen with same cutout at the middle of its length.
7. While ratcheting strain curves on SS304L cylindrical shells are compared, it is observed that specimen with cutout (radius = 6 mm) at the middle of its length shows similar behavior to the specimen without cutout. This specimen has slightly more ratcheting strain than same specimen without cutout and reaches to collapse point in lower force amplitude. Specimen with same radius cutout at 3/4 of specimen length position shows more ratcheting strain than two other specimens and also slope of its strain ratcheting curve is higher. At last, sample with cutout (radius = 9 mm) at the middle of its length shows more ratcheting strain than other specimens. Rate of ratcheting strain is much higher than the others and reaches collapse point earlier than other specimens.
8. For two specimens with the same cutout size but with different lengths, shorter specimen shows less ratcheting strain than the longer one. Also, rate of ratcheting strain curve is lower. Specimens in lower force amplitude show same ratcheting strain but in higher force amplitude, longer specimen shows more ratcheting strain.

Fig. 20. Some cylindrical shells with different lengths with/without cutout. (a) Before test. (b) After test.

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