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Attempts to improve energy absorption characteristics of circular metal tubes subjected to axial loading

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ABSTRACT

In this paper, experimental investigation of two new structural design solutions with the aim of improving crashworthiness characteristics of cylindrical metal tubes is performed. In the first design method, a rigid steel ring is press-fitted on top of circular aluminum tubes. When this arrangement of dissipating energy is subjected to axial compression, the rigid ring is driven into the cylindrical tube and expands its top area; then, plastic folds start shaping along the rest of the tube length as the compression of the structure continues. In the second design method, wide grooves are cut from the outer surface of steel thick-walled circular tubes. In fact, this method converts thick-walled tubes into several thin-walled tubes of shorter length, being assembled together coaxially. When this energy absorbing device is subjected to axial compression, plastic deformation occurs within the space of each wide groove, and thick portions control and stabilize collapsing of the whole structure. In the present study, several specimens of each developed design methods with various geometric parameters are prepared and compressed quasi-statistically. Also, some ordinary tubes of the same size of these specimens are compressed axially to investigate efficiency of the presented structural solutions in energy absorption applications. Experimental results show the significant efficiency of the presented design methods in improving crashworthiness characteristics and collapse modes of circular tubes under axial loading.

1. Introduction

Energy absorbing devices have been extensively used in all vehicles and moving parts such as road vehicle, railway couches, aircraft, ships, lifts and machinery. The aim is to protect these structures from serious damages while subjected to impact load, or to minimize human injuries while collision is occurred in transportation systems. These energy-absorbing devices can dissipate kinetic energy in a wide variety of ways like friction, fracture, plastic bending, crushing, cyclic plastic deformation and metal cutting [1]. Also, various structures like circular and square tubes, octagonal cross-section tubes, spherical shells, frusta, taper tubes, s-shaped tubes, composite tubes, honeycomb cells, foam-filled and wood-filled tubes may be used as collapsible energy absorbers. Amongst them, metallic cylindrical tubes have attracted much more attention due to their high stiffness and strength combined with the low weight and ease of manufacturing process, which leads to the low cost of the energy dissipating device [2,3]. Therefore, several theoretical and experimental investigations have been performed so for to introduce different methods of plastic collapsing in these structures. Axial crushing of tubes between two flat plates, external and internal inversion of tubes against shaped die and axial splitting and curling of cylindrical tubes against canonical dies are the most common energy dissipating methods, which have been realized and studied by several researchers so far [4–10]. However, investigation on progressive folding process of thin-walled structures under axial load has been the subject of the most of these researches.

As a matter of fact, favorable crashworthiness characteristics for energy dissipation purposes can be achieved from axial collapse of tubes while they crush progressively. However, experimental and theoretical results have shown that depending on various parameters such as tube geometry, material properties of tube, boundary and loading conditions, circular tubes buckle in different modes of deformation, namely concertina, diamond and Euler collapsing modes [11–14]. It is shown that when the tube length is greater than the critical length, the tube deforms in overall Euler buckling mode, which is an inefficient mode of energy absorption and needs to be avoided in crashworthiness applications. Different modes of deformation and load–compression curves of round aluminum tubes of various geometric

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Nomenclature

D_i	inside diameter of tube
D_o	outside diameter of tube
d	depth of grooves
d_i	inside diameter of expanding rigid ring
d_o	outside diameter of expanding rigid ring
E_T	total absorbed energy of the shock absorber
L	crushed length of the shock absorber
L_1	length of expanding ring
L_2	length of aluminum tube
N	number of grooves
$P_{\exp}$	mean expansion load
P_m	mean crushing load
$P_{\max}$	maximum crushing load
t	tube wall thickness
W	depth of wide grooves
λ	length of wide grooves
ρ	material density

parameters were studied experimentally by Andrews et al. [14]. An approximate theory to estimate the mean crushing load of cylindrical tube under axial load was presented firstly by Alexander [15]. Jones and Wierzbicki [16–19] have studied dynamic plastic response and instability of various basic structural members, subjected to large axial impact load. The crushing mechanics of thin-walled structures was investigated experimentally and theoretically by Abramowicz [20] and Wierzbicki [21]. On the other hand, the peak reaction force that happens at the beginning of the crushing is much greater than the subsequent peaks, and this is not desirable for energy dissipation purpose.

Responding the high demand for weigh efficient and crashworthy design of moving structures, several investigations with the aim of introducing design methods to increase the length of progressive crushing of thin-walled structures under axial load have been performed. These investigations also aimed to improve the stabilization of the collapse process and to reduce the peak load magnitude at the initial stage of the collapse process.

Lengseth et al. [22] found that pre-buckling of tubes reduce their initial collapse load. In their case, Lengseth et al. [22] applied a preload to impose a pre-buckle and noticed the increase of the total axial deformation compared to an initial straight tube. El-Hage et al. [23] presented a numerical study on the effect of triggering mechanism by chamfering and placing triangular hole pattern near the loaded end of the tube. El-Hage et al. [23] have found that the folding initiation force could be significantly controlled by triggering mechanisms. The effect of triggering dents on the energy absorption capacity of aluminum tubes under quasi static compression was investigated by Lee et al. [24]. The study showed that introduction of dents reduces the first peak load. Marshall and Nurick [25] studied the effects of cylindrical side dents of different diameter. White and Jones [26,27] studied the static and dynamic axial crushing of top-hat structures. In their studies, White and Jones [26,27] investigated the influence of several design parameters on the collapse behavior of thin-walled top-hat and double-hat section structures experimentally and theoretically. With appropriate selection of design parameters, they found that application of top-hat and double-hat sections can improve crashworthiness characteristics of thin-walled structures. Shakeri et al. [28] have introduced the initial geometric imperfection of plastic buckling modes in the post-buckling analysis as a new factor that can extend the concertina collapsing region. In this study, cutting an initial circumferential edge groove outside the tube and using one- and two-circumferential stiffeners have been suggested as two design methods to activate the axisymmetric plastic buckling mode. These two design methods also reduce maximum crushing force significantly. Introduction of circumferential grooves, which are cut alternatively inside and outside of the tube at predetermined intervals, has been shown as an effective solution by Daneshi and Hosseinipour [29] to force the plastic deformation to occur at these predetermined intervals along the tube. It is observed that this method can control collapse shape of thin-walled structures. Cutting a given tubular structure in several portions and coaxially assembling them by separating non-deformable disc is the other suggested method to encourage the axisymmetric mode in axial crushing of tubes, investigated by Abdul-Latif et al. [30]. The energy absorption characteristics of corrugated tubes are also studied in [31]. In this energy dissipating device, corrugations are introduced in the tube to force the plastic deformation to occur at predetermined intervals along the tube length. The aims are to improve the uniformity of the load–displacement behavior of axially crushed tubes, predict and control the collapse mode in each corrugation in order to optimize the energy absorption capacity of the tube. Investigations into the behavior of tapered sheet metal tubes under axial and oblique dynamic loading have been also reported in Refs. [32,33]. These studies show that tapered tubes can withstand oblique impact loads as effectively as axial loads. In the case of vehicular collisions, the height above the road, which is subjected to impact loads, remains reasonably constant but the direction of the acting force line is subjected to change in a horizontal plane. For such situations, tapered tubes of rectangular cross-section with a constant height but increasing width along its axial direction may prove to be advantageous. Several attempts have also been made to improve the energy absorbing capacity of metal tubes by using filler materials such as foams, wood, honeycomb or metals [34–38]. These researches have shown that filling cylindrical tubes with foams eliminates their non-compact crushing behavior under axial loads and significantly help to prevent global bending. Moreover, in comparison with empty tubes of the same size, foam-filled tubes are less affected by external parameters and are more stable while collapsing. A number of investigations on analysis, design and collapse behavior of thin-walled prismatic members subjected to large deformation also have been carried out by Abramowicz and Wierzbicki [39–41]. Recently, expansion of circular metal tubes by rigid tubes under axial compression has been introduced as an efficient method of dissipating energy without any strong sensitivity to loading uniformity [42].

This study develops two design methods with the aim of improving main energy absorption characteristics of circular metal tubes such as sensitivity to external parameters like loading uniformity and direction, crushing stability, crush force efficiency and collapse modes while subjecting to axial compression. Press fitting an expanding rigid ring on top of circular tubes is proved experimentally to be as the first efficient structural solution. In this design method, the rigid ring has the interference of 1 mm with tube and expands it while driving into it as a result of subjecting to axial compression. Then, further compression of the tube leads to formation of plastic folds along the rest of the tube length, not being expanded by rigid ring. This rigid ring controls loading direction at initial stage of compressing the shock absorber, and then directs the plastic collapsing to occur around axisymmetric line of the structure, leading to considerable better performance of the energy dissipating device. It also eliminates the peak reaction force, happing at the beginning of the axial crushing, and improves significantly crush force efficiency of the shock absorber. As another advantage, experimental studies indicate that this developed method increase significantly transition length between progressive buckling and global bending of circular metal tubes. In the second developed structural solution, introduction of wide external grooves in a long thick-walled circular tube covert it into several thin-walled tubes of shorter length, being assembled together coaxially and become separated by non-grooved areas of the structure. As a matter of fact, while groove-less thick areas of the shock absorber do not contribute in plastic deformation and energy absorption, they play significant role in improving other crashworthiness characteristics such as stability in axial crushing and safety factor. It is shown that this design method encourages formation of concertina folds efficiently. In the present study, several specimens of each developed design methods with various geometric parameters are prepared and compressed quasi-statistically. Through experimental studies of both design methods, developed in this paper, major parameters in design are identified, and typical modes of deformation that may occur during axial compression of tubes are characterized. Also, load–displacement history and deformation mechanism of the studied shock absorbers under axial compression are described. It is shown that, with consideration of design parameters, characterized in this paper, application of suggested structural solutions can improve energy absorption characteristics of circular tubes under axial loads significantly.

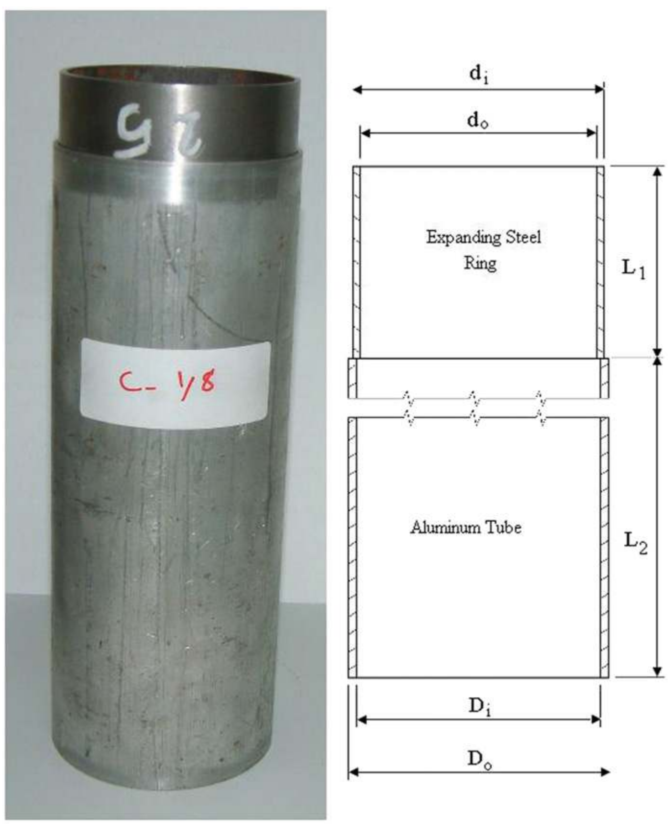

Fig. 1. Shape of a tube with expanding rigid ring press fitted on its top end.

2. Experiments: description and results

2.1. Thin-walled tubes with expanding ring

Aluminum alloy tubes of 75 mm outside diameter and 2.5 mm thickness were machined to the required size and three sets of different lengths. Also, steel tubes of 72 mm outside diameter and 68 mm inside diameter where machined to different required lengths. The outer surface of these prepared steel tubes was heat treated to increase their surface hardness, and their upper edge was rounded by turning machine to the radius of 3 mm. To ease the process of press fitting the rigid steel rings on top of aluminum tubes, circumferential grooves of 2 mm length and 0.5 mm widths were cut from the inner surface of their top areas. As it can be seen from prepared steel rings and aluminum tubes dimensions, there is an interference of 1 mm between them. In all specimens, the rounded edge of the steel expanding tube is press-fitted into the grooved area of the deformable aluminum tube under axial compression up to the groove's length. Fig. 1 shows the typical shape of the prepared specimen for compression test.

The length of expanding rigid ring varies from 1/16 to 1/4 of aluminum tubes length in each set of specimens with the same length. To study the effect of press fitting an expanding rigid ring on energy absorption characteristics and collapse mode of circular tubes under axial compression, in each group of specimens with similar length of aluminum tube, an ordinary once without expending ring was also prepared for compression tests. The geometric parameters of each prepared specimen for compression test are shown in Table 1. Varying length of rigid expanding ring in each set of specimens with equal length can indicate the effect of expanding ring length on collapse mode and energy absorption of the shock absorber, discussed in the present study.

In order to obtain the material data of the aluminum tube and steel ring, quasi-static tension test were performed on a strip, cut from them, and the resulting stress–strain curves were recorded and are shown in Fig. 2. The elastic modulus of aluminum tubes is E=70 Gpa and the density is ρ=2700 kg/m^3. As for steel rings, the elastic modulus is E=210 Gpa and the density is ρ=7800 kg/m^3. It is assumed that the mechanical

Table 1
Specimen's dimension with rigid expanding ring and summery of their test results.

Specimen no.	D_o (mm)	D_i (mm)	d_o (mm)	d_i (mm)	L_1 (mm)	L_2 (mm)	L (mm)	P_{exp} (KN)	P_{max} (KN)	P_m (KN)	E_T (J)
E1	75	70	72	68	–	200	153	–	74.32	45.41	6948.32
E2	75	70	72	68	25	200	162	26.13	68.64	40.68	6590.21
F1	75	70	72	68	–	300	173	–	72.55	41.86	7242.55
F2	75	70	72	68	19	300	241	24.62	67.15	36.71	8847.65
F3	75	70	72	68	38	300	219	24.81	66.25	36.19	7925.36
F4	75	70	72	68	76	300	226	25.52	61.38	32.35	7312.47
G1	75	70	72	68	–	350	–	–	–	–	–
G2	75	70	72	68	22	350	273	26.17	59.78	33.75	9207.84
G3	75	70	72	68	44	350	271	26.36	59.66	33.62	9112.32
G4	75	70	72	68	88	350	267	26.53	57.18	33.68	8993.78

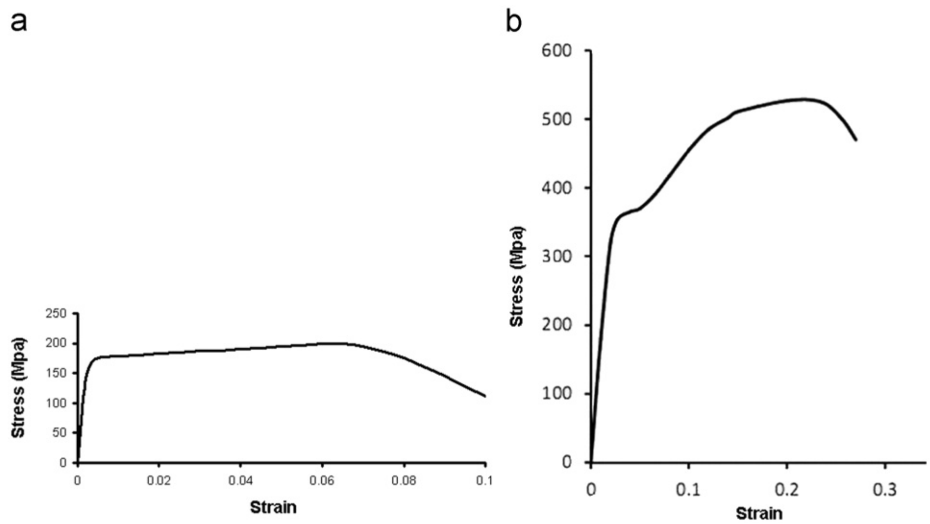

Fig. 2. Stress–strain relationship of (a) aluminum tube material and (b) steel ring material.

Fig. 3. Crushed shape of specimens of 200 mm length with expanding ring after quasi-static compression test.

properties of aluminum alloy tubes are not sensitive to strain rate at room temperature.

All the experimented specimens were compressed in a universal testing machine with a computer controller under quasi-static condition at a nominal crushed speed of 10 mm/min. The latter was used to display the relationship between the holder stroke and the holder load. During the compression tests, specimens were crushed between parallel steel plates of the test machine without any additional fixing. A repeated compression test of each specimen was also performed to ensure the validity of experimental results.

The final crushed shape of specimens in each group of similar length of 200, 300 and 350 mm with varying expanding rings as well as those without expanding ring are shown in Figs. 3–5, respectively, and the corresponding load–displacement curves of some of which are plotted in Fig. 6. Values of energy absorption and mean crushing loads were calculated by measuring the area under the obtained load–displacement curves, and the summary of test results is shown in Table 1.

Comparisons between crushed shapes of ordinary tubes with those an expanding rigid ring press fitted on their top end indicates the reliability end efficiency of the proposed design method, developed in the present study. In fact, application of this design method prevents global bending of specimens with 300 and 350 mm length. In the present study, these experimental results are also used to verify theoretical studies of the proposed shock absorber.

2.2. Thick-walled tubes with wide external grooves

Seamless mild steel tubes of commercial quality with 60 mm outside diameter and 52 mm inside diameter were machined to the required size and length of 144 mm. Then, circumferential wide grooves of different lengths and depths were cut from the outer surface of tubes to prepare specimens for compression tests. Cut surface areas of all specimens were also grinded to improve their surface quality. Fig. 7 shows the typical shape of the prepared specimen for compression test, and Table 2 shows geometric parameters of each prepared specimens. As it is realized from this table, three geometric parameters namely depth, length and number of grooves vary from one specimen to another. Also, to show the extension of axisymmetric collapsing mode in axial crushing of tubes by using the proposed design method, two groove-less tubes of similar L/D and D/t with that of tubes with cut wide grooves were also made for compression tests. The material properties of all grooved specimens are as the same as that of steel expanding ring, described former (see Fig. 2).

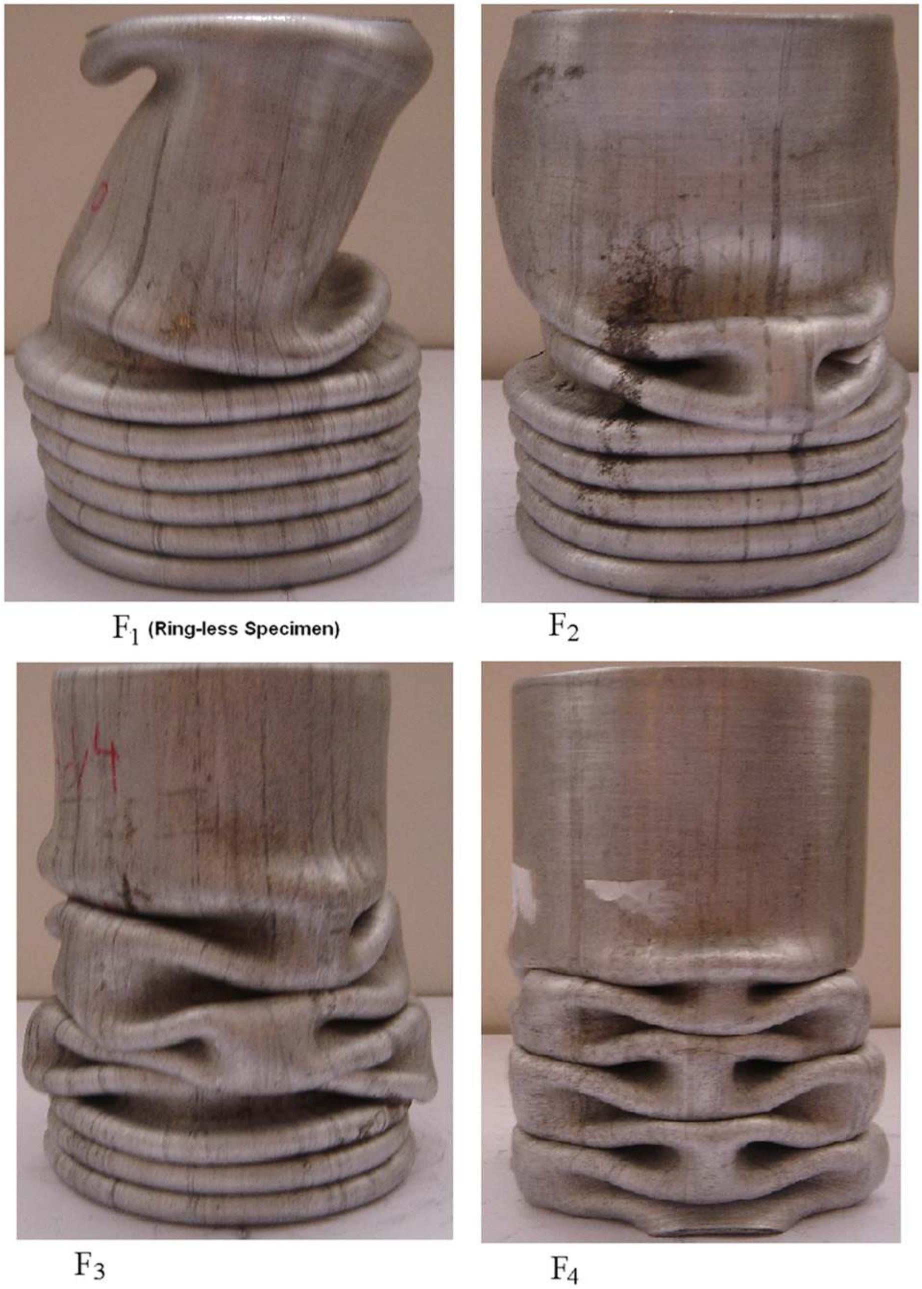

Fig. 4. Crushed shape of specimens of 300 mm length with expanding ring after quasi-static compression test.

In this study, all quasi-static axial compression tests of specimens were performed on a 20 ton ZWICK hydraulic testing machine at a nominal crushed speed of 10 mm/min, and specimens crushed between parallel steel plates of the test machine without any additional fixing. A repeated compression test of each specimen was also performed to ensure the validity of experimental results.

The final shapes of all specimens after compression test are shown in Figs. 8 and 9, and the corresponding load–displacement curves of all specimens are plotted in Fig. 10. Values of energy absorption and mean crushing loads were calculated by measuring the area under the obtained load–displacement curves, and summary of test results is also shown in Table 2.

Comparison between crushed shapes of groove-less tube with that of grooved once show the reliability and efficiency of the proposed design method, developed in the present study, as it extends the limits of axisymmetric collapsing modes of deformation under axial compression significantly. In the present study, these experimental results are also used to verify theoretical studies of the proposed shock absorber.

3. Interpretation of collapse results

3.1. Thin-walled tubes with expanding ring

Experimental and numerical results indicate that press fitting an expanding ring on top of those circular tubes crushing in concertina mode normally do not affect their collapse mode of deformation. As Fig. 3 shows, both specimens E1 and E2 with 200 mm length collapses in concertina mode, and press fitting an expanding ring on top of specimen E1 has not changed its normal collapse mode (see crushed shape of specimen E2 in Fig. 3).

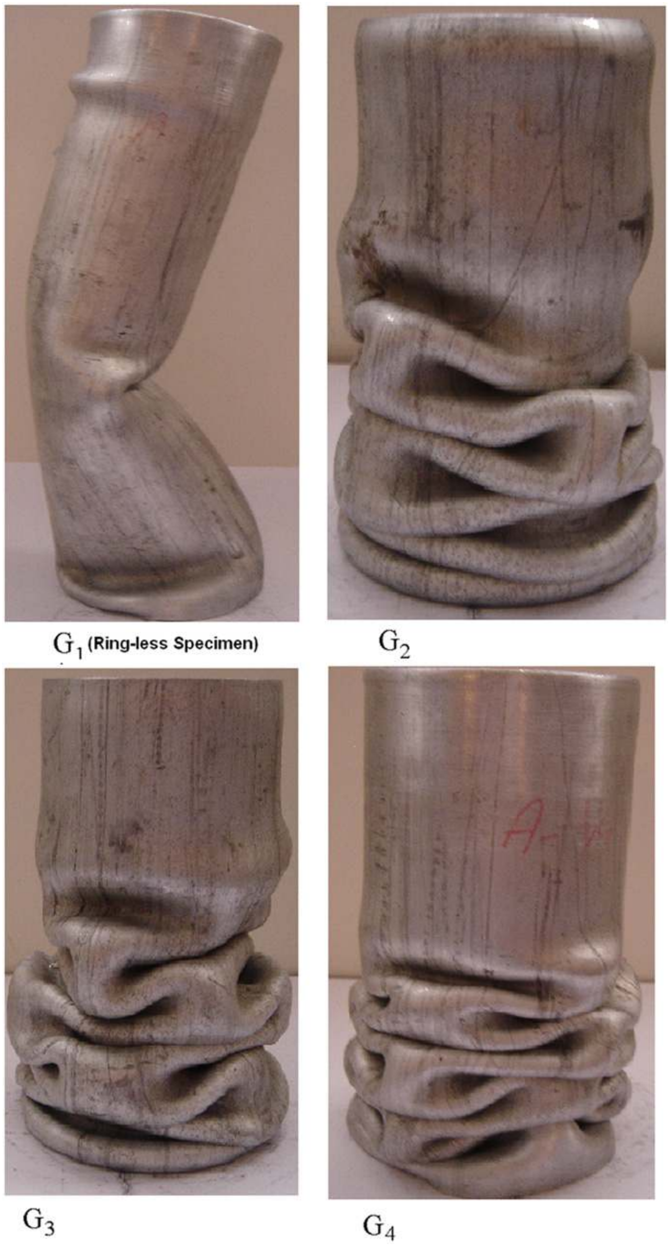

Fig. 5. Crushed shape of specimens of 350 mm length with expanding ring after quasi-static compression test.

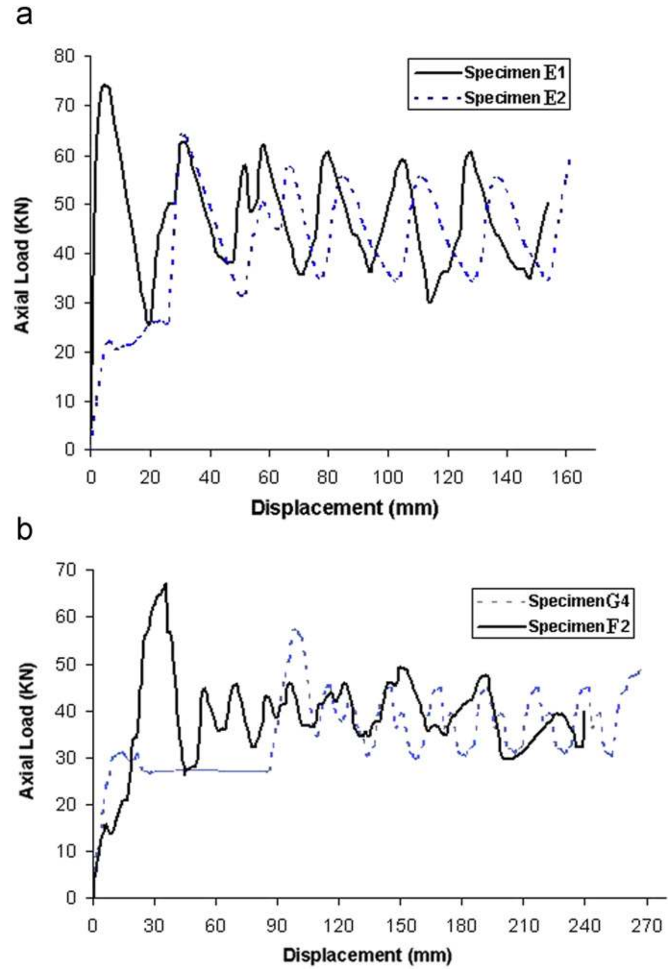

Fig. 6. Load–displacement curves of (a) specimens E1 and E2 and (b) specimens F2 and G4 during axial crushing derived from experimental tests.

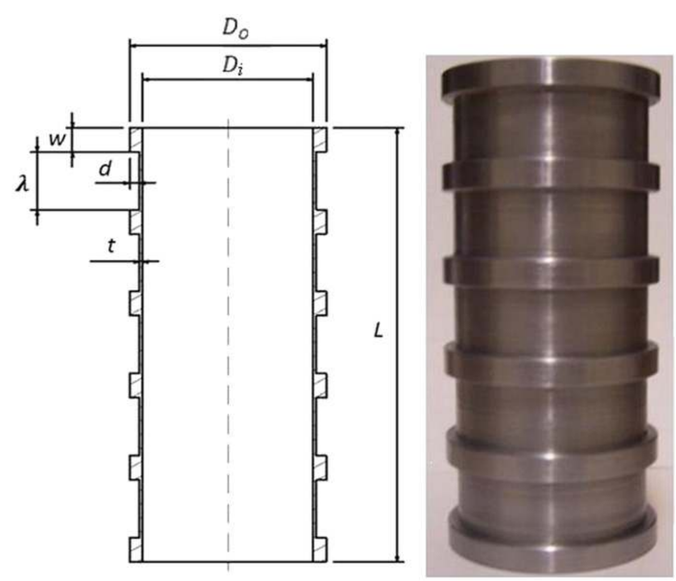

Fig. 7. Shape of a tube with wide external grooves with its detailed design.

However, differences between sequences of shaping concertina folds in specimens E1 and E2 over axial compression is obvious. In specimen E1, concertina folds start shaping from its top end, subjected to axial compression, and the reverse is true for specimen E2. In fact, after the expanding ring is driven into the inner surface of specimen E2 completely during axial compression, concertina folds start shaping from the bottom end of this specimen (see Fig. 11(a)). Moreover, comparison between the relating load–displacement curves of these specimens (see Fig. 6(a)) indicate that press fitting of expanding ring can reduce maximum crushing load of specimen E1, which is caused by the initial elastic resistance of the structure at the initial stage of collapsing in concertina mode, from 74.32 to 68.32 KN in specimen E2 with expanding ring (see also Table 1). Therefore, press fitting of an expanding ring on top of specimen E1 leads to improvement of its crush force efficiency as it can be seen from load–displacement curve of specimen E2. In fact, over the time the expanding ring is driven into the inner surface of specimen E2, a portion of the applying load is transmitted to the bottom end of structure, and shaping of concertina fold is initiated in this area

Table 2
Specimen's dimension with wide external grooves and summery of their test results.

Specimen no.	L (mm)	D_o (mm)	D_i (mm)	t (mm)	d (mm)	λ (mm)	W (mm)	N	P_m (KN)	E_T (KN)
A1[a]	144	54	52	1	–	–	–	–	26.52	1910.45
S1	144	60	52	1	3	16.8	10	5	28.38	1759.56
S2	144	60	52	1	3	13.5	9	6	29.23	1841.49
S3	144	60	52	1	3	19.2	8	5	29.23	2280.00
A2[a]	144	55	52	1.5	–	–	–	–	30.40	2820.17
S4	144	60	52	1.5	2.5	16.8	10	5	44.06	3287.86
S5	144	60	52	1.5	2.5	13.5	9	6	53.03	3441.60
S6	144	60	52	1.5	2.5	19.2	8	5	57.36	3673.36

[a] Groove-less specimen.

Fig. 8. Groove-less specimens after axial crushing.

of the specimen. This phenomenon leads to the reduction of maximum crushing load. As for specimen E1, lack of this time, allowing initiation of shaping concertina folds, forces the structure to experience its elastic resistance against axial load over a very short time prior to formation of concertina fold on top end of this specimen. Theoretical and experimental observations also indicate that specimen E1 takes slightly more energy than specimen E2 after compression tests. This is due to the fact that the required energy for formation of a concertina fold along a portion of specimen E1 length, which should be expanded by rigid ring in specimen E2, is slightly higher than the required expansion energy (see Table 1).

In group of specimens with 300 mm length, quasi-static compressing of specimen F1, lacking any expanding rigid ring, results in a mixture of local folding and moderate global bending. It is observed experimentally and theoretically that press fitting an expanding ring on top of specimen F1 leads to the elimination of the moderate global bending of this specimen over its last collapse stages. This significantly improves the collapsing stability and effective crushing length of the specimen as final collapse shapes of specimens F2, F3 and F4 in Fig. 4 shows. Amongst these specimens, collapse of specimen F2 with the lowest length of expanding ring takes the highest energy since the most numbers of concertina folds (five) are shaped over its compression test. The rest length of this specimen is also crushed by formation of a diamond fold and plastic expansion (see Fig. 4). Although specimen F1 experiences 6 concertina folds over compression test, it takes less energy than specimens F2 and F3. This is due to the fact that the length of this specimen, experiencing global buckling, does not contribute in energy absorption. As for specimen F4 with longest expanding ring length, it collapses in diamond mode of deformation without experiencing any concertina folds during its axial collapse, leading to the lower amount of energy absorption capacity of this specimen in comparison with those of F2 and F3. However, this specimen provides better crashworthiness characteristics comparing with specimen F1 since it provides more crushing stability and effective collapse length. Table 1 also indicates that the lowest value of maximum crush load belongs to specimen F4 due to the formation of diamond folds and effect of expanding rigid ring in this specimen. Collapse results of other specimens with 300 mm length also indicate the efficiency of expanding ring on reduction of maximum crush load. As described above, the observed different collapse modes of specimens with various expanding ring lengths reveals its effect on energy absorption characteristics of specimens.

The significant efficiency of the presented developed design method is obvious in group of specimens with 350 mm length. As it can be seen from Fig. 5, the most unfavorable mode of deformation from the point of energy absorption, global bending, occurs in collapse of specimen G1. Surprisingly, press fitting an expanding ring on top of this specimen encourages significantly progressive buckling of the structure as it can be seen from collapse shapes of specimens G2, G3 and G4 with rigid rings of different lengths in Fig. 5. From this figure, it is obvious that the effect of expanding ring prevent global bending of specimens G2, G3 and G4, leading to considerable better crashworthiness characteristics of their axial crushing in comparison with expanding ring-less specimen G1.

Fig. 9. Grooved specimens after axial crushing.

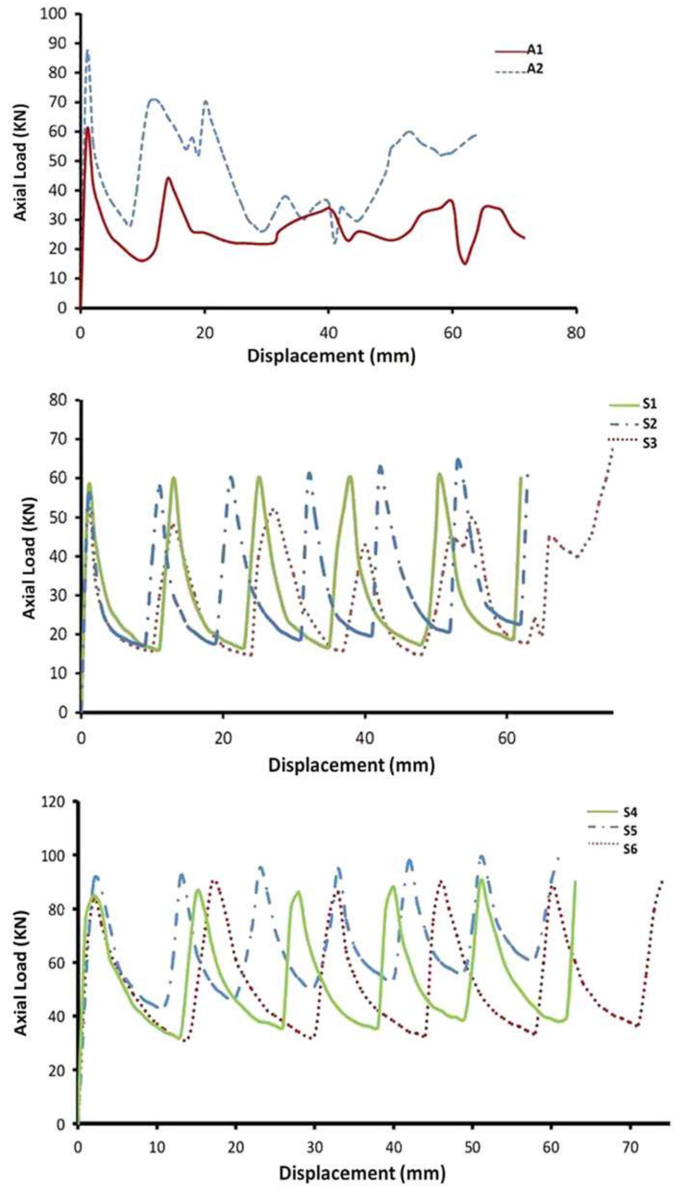

Fig. 10. Load–displacement curves of grooved and groove-less specimens.

In fact, while expanding rigid ring do not affect the effective crushed length of the structure through expanding a portion of its length, it reduces the length of the tube, contributing in progressive buckling under compression. This effect encourages progressive crushing and helps to prevent global bending of the structure. On the other hand, over the time the expanding ring is driven into the inner surface of the tube, it reduces effects of loading non-uniformity, easing the process of axial crushing. Also, after the rigid ring is completely driven into the tube, it prevents deviation of applied load from the tube center line, and directs the plastic collapsing to occur around axisymmetric line of the structure. These mentioned effects of expanding ring on plastic collapse of circular tubes significantly increase their transition length between progressive folding and global bending. As mentioned earlier, expanding ring reduces the elastic resistance of the tube against axial loading, and this effect should not be neglected as contributing reasons in improvement of transition length between progressive folding and global bending.

In some engineering structures, the shock absorber is considered to be a part of the structure, which also should be capable of dissipating kinetic energy to protect other main parts from damages while the structure is subjected to shock loading. For these applications, a shock absorber with extreme deformation is not suitable. Application of press fitting a rigid ring on top end of circular metal tubes prevents their extreme deformation under axial loading. Also, the effect of rigid ring reduces non-uniformity and deviation of the applied loading over crushing process of the tube, and encourages its progressive buckling. Moreover, results of axial collapse in all group of specimen indicate that their effective crushing length is significantly increased by press fitting the rigid steel ring on their top end (see Table 1).

3.2. Thick-walled tubes with wide external grooves

As it can be seen from Fig. 9, except specimen number S3, all experimented specimens buckled completely in concertina mode of deformation. Experimental and numerical results show that with the given geometry of a tube, both length and depth of groove, cut from its outer surface, can affect significantly buckling deformation mode of the shock absorber while subjected to axial compression. These results show that increasing the length of external grooves in specimens with fixed groove depth can decrease the possibility of shaping axisymmetric folds. In specimens with groove depth of 3 mm (S1, S2, S3), increasing the length of groove from 13.5 mm in S2 to 19.2 mm in S3 leads to the

Fig. 11. Different stages of axial collapse of specimen (a) E2, (b) F2 and (c) G4.

change of buckling deformation mode from concertina in specimens S1 and S2 to diamond in S3. However, decreasing the groove depth from 3 mm in S3 to 2.5 mm in S6 changes the diamond buckling mode of deformation in S3 to concertina mode in S6 (these specimens have equal groove length). These observation show that in specimens with large groove length, decreasing the depth of groove, cut from the outer surface of tube, can control buckling mode of deformation. Table 2 also indicates that both values of length and depth of grooves, cut from the outer surface of tube, can affect the mean crush load of the shock absorber; however, the effect of groove depth is considerably more significant. Therefore, mean crush load and buckling mode of deformation in the proposed energy absorber of this study can be controlled by the geometry of tube and both values of groove depth and length, cut from its outer surface.

In the present study, to show the efficiency of this proposed method in extending the limits of axisymmetric mode of deformation, for each sets of grooved specimens with fixed groove depth, a groove-less specimen of the same geometric parameters have been compressed axially. Corresponding results show that (see Figs. 8 and 9) division of tubes by cutting wide grooves from their outer surface can control the axisymmetric collapsing mode of the shock absorber considerably. Even in case of specimen number S3 with non-axisymmetric mode of deformation, the grooved shock absorber provides considerably more favorable crashworthiness characteristics and stability during axial crushing in comparison with groove-less specimen of A1 (see Figs. 8, 9 and 12). Moreover, in contrast with previous design of grooved shock absorbers [29], which reduced the energy absorption comparing with groove-less specimen, the present

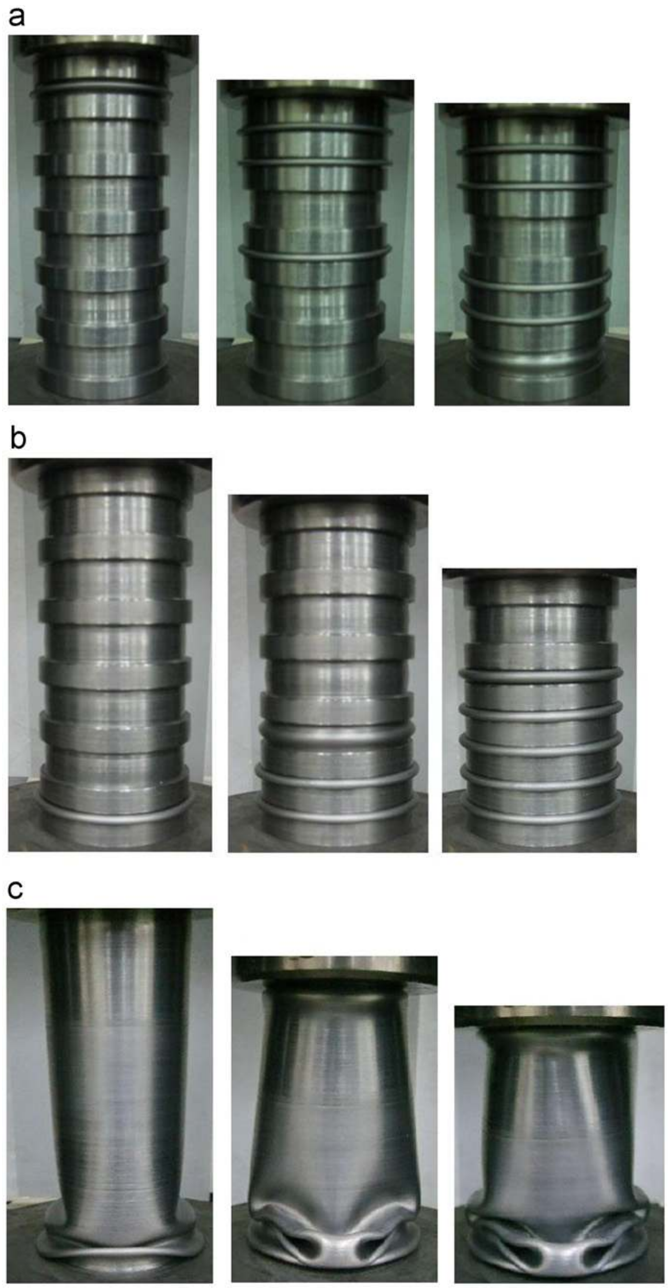

Fig. 12. Different stages of axial collapse of specimen (a) S2, (b) S5 and (c) A1.

design method do not affect this important crashworthiness parameter. In fact, in the present study, the objective to cut wide grooves from the outer surface of tubes is to divide their length to several portions and improve their crashworthiness characteristics. Moreover, division of tube length with wide external grooves can decrease maximum collapsing load of the tube significantly resulting in high crush force efficiency since introduction of wide external grooves affect the initial elastic resistance of the tube during axial compression.

As it can be seen that, although specimens are not chosen in best diameter-thickness to collapse in concertina mode, collapsed shape of grooved specimens show the significant efficiency of the present developed design method in extending the limits of concertina region, having been realized by several experimental tests for groove-less circular tubes. As a matter of fact, this design method provide solution to designers with geometric limitation in design of collapsible shock absorbers to design an energy dissipating device which collapses in concertina mode but not necessarily have of geometric parameters in limited concertina region. As another advantage, this proposed design method help designers to obtain mean crushing loads which may not be achieved by collapsing of a tube with geometric parameters in limited concertina region.

Nevertheless, it can be realized that, specimens with wide external grooves provide less specific energy absorption than groove-less specimens. This is because thick portions in grooved specimens have not any contribution in energy absorption during axial crushing. However, these parts in grooved specimens provide significant advantages which in some special engineering applications outweigh disadvantage of getting the presented energy-absorbing device heavy. They play significant role in improving the stability of the shock absorber while crushing. As it is mentioned former, in some engineering structures, the shock absorber is considered to be as one part of the structure which also should be capable of dissipating kinetic energy to protect other main parts from damages while the structure is subjected to shock loading. For these applications, a shock absorber with extreme deformation is not suitable. Thick portions in the proposed energy dissipating device meet these demands and prevent extreme plastic deformation of the shock absorber, causing unfavorable instability, while crushing. As another advantage, these portions make significant contribution to encourage the shock absorber to collapse in concertina mode, leading to significant increase in safety factor. It should be noted that further theoretical and experimental investigation of the presented shock absorber is required to improve its specific energy absorption by decreasing of both thickness and length of thick portions while maintaining mentioned favorable crashworthiness characteristics.

4. Interpretation of load–displacement curves

4.1. Thin-walled tubes with expanding ring

To understand the collapse progress of the presented shock absorber under axial compression, different stages of axial crushing for specimens E2, F2 and G4 are shown in Fig. 11(a)–(c), respectively. Also, the corresponding force–displacement history of these specimens is shown in Fig. 6. These figures indicate that collapse process of cylindrical tubes with rigid expanding ring can be divided into two different parts of plastic expansion and progressive crushing. Over the process of plastic expansion, occurring at the first stage of the shock absorber collapse, the rigid ring is driven into the inner surface of aluminum tube (see Fig. 11(a)–(c)). During this part of the shock absorber crushing, load increases constantly during its initial stage, and then become more or less constant at the value, required for expanding the aluminum tube up to the value of its interference with rigid ring, till it is driven into inner of aluminum tube completely. Then, with further compression of the shock absorber, the second part of its collapsing process starts. At this stage of deformation, one plastic fold tends to shape from the bottom end of the aluminum tube. Over the formation of this first plastic fold, load increases dramatically and peaks due to the elastic resistance of the structure against axial compression and falls while the fold shapes completely. It is worth noticing that the peak load for formation of the first concertina fold in specimens E2 and F2 is slightly higher than the first diamond fold in specimen G4 (see Fig. 6). Since the process of fold shaping in all specimens with rigid expanding ring is progressive, after formation of the first plastic fold, other folds shape over the rest of tube length, not being expanded. This process leads to moderate increasing and decreasing of load after formation of each plastic fold as shown in Fig. 6.

Observation from different crushing stages of specimens with expanding ring indicates that the external energy is dissipated by their collapse through three different mechanisms, namely plastic expansion of aluminum tube, friction between the surfaces of the aluminum and steel rigid tubes and plastic folding. However, as Table 1 shows the greater amount of energy dissipation relates to plastic folding than plastic expansion. Details on energy absorption mechanism of plastic expansion mode of deformation are presented in [42].

4.2. Thick-walled tubes with wide external grooves

Fig. 12(a) and (b) shows different stages of axisymmetric buckling in specimens S2 and S5 while subjected to quasi-static compression. As it is realized from these figures, at the first stage of buckling, one fold tend to shape within the length of the nearest groove to the bottom end of the specimen, when the shock absorber is compressed quasi-statically. During this stage of deformation, load increases due to the elastic resistance of the divided structure along this groove length, and decline dramatically while a plastic fold shapes completely within this groove space (see Fig. 10). At the next stage of buckling, the second fold tends to shape within the length of another groove, near the former shaped groove with concertina fold. At this stage of deformation, again, load increases as a result of elastic resistance of the divided structure along this groove length, and decline dramatically while a plastic fold shapes completely within this groove space (see Fig. 10). As compression of the shock absorber continues, the same phenomenon tend to occur within the space of other wide grooves, leading to sharp increase and decrease of load, till the buckling process of the shock absorber become complete (see Figs. 10 and 12).

5. Conclusion

In this study, two new design methods to improve energy absorption characteristics of cylindrical metal tubes have been developed and experimentally investigated. Results have shown that the presented developed design methods are efficient in improving crashworthiness characteristics of cylindrical metal tubes such as sensitivity to external parameters like loading uniformity and direction, crushing stability, crush force efficiency and collapse mode while subjecting to axial compression. Through experimental studies of both design methods, developed in this paper, major parameters in design are identified, and typical modes of deformation that may occur during axial compression of tubes are characterized. Experimental results indicate that with consideration of design parameters, characterized in this paper, application of suggested structural solutions can improve energy absorption characteristics of circular tubes under axial loads significantly.

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