Experimental Investigation on the Splitting of Center-Notched Circular Tube

Jafar Rouzegar and Mohammad Karimi

***Abstract*—Energy absorbers are devices that convert the kinetic energy of impact into other forms of energies. Among different types of energy absorbing mechanism, splitting process is one of the most desired ones due to its steady load during the axial stroke. For the implementation of the splitting process, heavy conical dies are needed, which is a drawback of this method. The present research is an attempt for the introduction of a novel method for axial splitting deformation of thin-walled circular tubes. In the present method, some initial slits are created in the middle length of the tubes and consequently, the dependency of the traditional splitting method on the rigid conical dies is eliminated. These notches were created using a milling machine and electrical discharges (sparks) on the perimeter of the circular brazen tube at the middle length. Then, the specimens were compressed axially under quasi-static condition between two rigid plates. The effects of wall thickness, diameter and length of the tubes, and also, number, length, and width of the notches on the energy absorption parameters of the specimens are investigated.**

***Index Terms*—Center-notched, energy absorber, experimental study, splitting.**

I. Introduction

Nowadays, automotive, aerospace and transportation industries, have been developed and new needs for energy absorption devices are necessary for converting the applied kinetic energy into other forms of energies. The aim is to protect these structures from serious damage and minimize human injuries while the collision occurs. Thin-walled metal circular tubes are widely employed in engineering as structural elements, because of their low cost and ease of manufacturing, high strength and stiffness to weight ratios and the wide range of deformation modes [1]. Moreover, it was found that among various cross sections, circular tubes provide the best energy absorption capacity under axial compression [2]. Therefore, considerable studies have been done experimentally, theoretically and numerically by researchers to introduce different mechanisms of energy absorption, such as axial folding [3], lateral flattening [4], inversion [5] and axial splitting [6]. In recent decades, some studies have been carried out on the axial progressive buckling of thin-walled tubes. Abramowicz and Jones [7], [8] observed that the thin-walled tubes exhibited the highest energy absorption efficiency in a progressive buckling mode during a relatively long stroke under quasi-static axial loading. They concluded that geometrical parameters, loading conditions, deformation modes and the type of geometric discontinuity are effective factors on the mechanical behavior of tubes. Reddy and Reid [9] examined the splitting behavior of circular metal tubes. They compressed the specimens axially between a plate and a conical die to generate a splitting mode of deformation. It was observed that this collapse mode has a long stroke although is not as efficient as axial progressive buckling. Also, a steady crush force was observed during the deformation process. In some applications creation of discontinuities on walls of the energy absorbers are mandatory, such as in places of connections, passages of wires, etc. Therefore, some researchers investigated effects of different geometrical discontinuities on axial collapse deformation of thin-walled tubular structures to improve the capability of them. Daneshi and Hosseinipour [10] investigated the effects of geometrical discontinuities in the form of grooves along the tube axis on the initial buckling load and the energy absorption capacity of thin-walled tubes under the axial compression. They found that absorbed energy by the tubes during the axial compression could be controlled by the creation of some grooves in specific locations. Rouzegar and Karimi [11] presented a new finite element model for simulation of deformation mode, fracture mechanism and crack growth in the splitting process of circular brazen tubes. For numerical modeling of splitting mechanism and crack propagation process, the surface-based cohesive technique was employed using the ABAQUS software.

In this paper, the behavior of brazen circular tubes with novel geometrical discontinuities in the form of multiple narrow central notches under quasi-static axial load is investigated, experimentally. The effects of length, number, and width of the initial notches and also, diameter, length and wall thickness of the tubes are studied on the energy absorption parameters of the specimens.

II. Experiments

TABLE I: Material Properties of Brazen Circular Tubes

Material Type	Young's modulus (GPa)	yield stress (MPa)	ultimate tensile strength (MPa)
Brass alloy	44.063	201.74	394.82

The specimens were cut out of commercially available brazen tubes with circular cross-sections. Three dumbbell-shape specimens of the brazen tubes were prepared in order to obtain the material properties using the quasi-static tension test according to standard ASTM E8M [12]. The resultant stress-strain diagram is shown in Fig. 1. Material properties of the brazen tubes are given in Table I.

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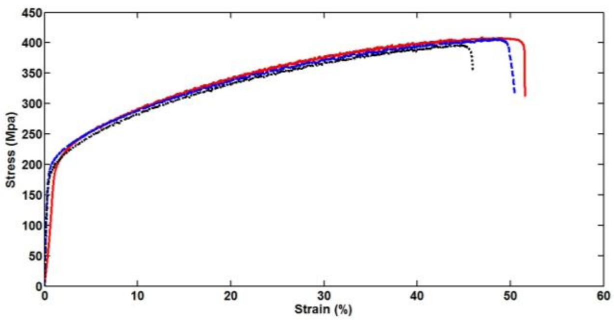

Fig. 1. stress-strain curve of specimens.

Some small holes were drilled at the middle length of the tubes and then the notches were created with a length of *NL*/2 and width of *NW* at both sides of the holes by a electrical discharges (sparks) mechine as shown in Fig. 2 and Fig. 3. The specifications of the specimens are reported in Table II.

TABLE II: GEOMETRICAL CHARCACTERISTICS OF SPECIMENS

Specimens code	*L* (mm)	*t* (mm)	*d* (mm)	*n*	*NL* (mm)	*NW* (mm)	*m* (g)
Cn-01	70	1	35	4	10	1	64.89
Cn-02	70	1	35	6	10	1	64.6
Cn-03	70	1	35	8	10	1	64.57
Cn-04	50	1	35	6	10	1	45.77
Cn-05	100	1	35	6	10	1	92.01
Cn-06	70	1	35	6	14	1	64.09
Cn-07	70	1	35	6	18	1	64.27
Cn-08	70	0.75	35	4	10	1	48.61
Cn-09	100	1.5	50	6	10	1	166.51
Cn-10	100	1	50	4	10	1	128.13
Cn-11	100	1	50	6	10	1	123.9
Cn-12	100	1	50	8	10	1	122.87
Cn-13	70	1	35	6	10	3	62.22
Cn-14	100	1	50	-	-	-	131.9

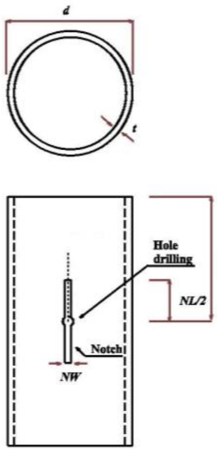

Fig. 2. Geometrical parameters of specimens.

Fig. 3. Specimen Cn-02 before testing.

III. TEST PROCEDURE DESCRIPTION

All the specimens were axially compressed between two rigid plates using a *Zwick* universal testing machine. Speed of crosshead was kept at 5 mm/min, in all tests to insure the quasi-static condition. In each test, the diagram of axial load versus axial displacement was sketched and the energy absorption parameters were calculated.

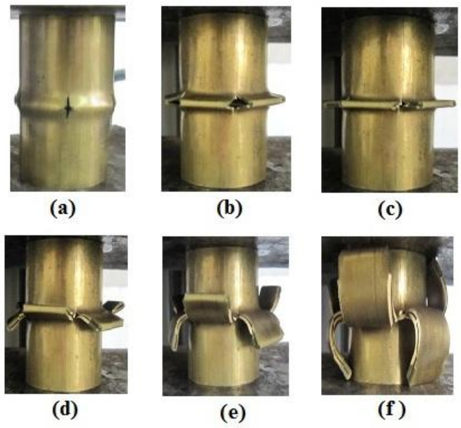

Fig. 4. Specimen Cn-02 during axial splitting process.

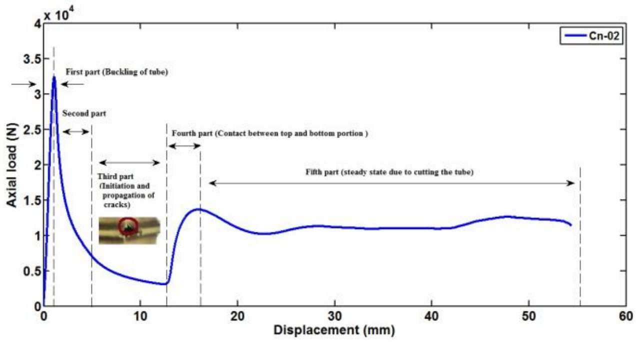

Fig. 5. Different steps of load-displacement diagram of specimen Cn-06.

Fig. 4 shows the different steps of splitting of specimen Cn-02 during the axial splitting and the related load-displacement diagram is illustrated in Fig. 5. As seen, this diagram has different steps. In the first step, the elastic deformation of specimen starts and continues up to buckling of tube wall (as seen in Fig. 4a). After buckling stage, the diagram experiences a falling trend in steps 2 and 3. In step 4, the diagram has a rising trend due to two reasons. The initial notches had not a sharp tip, and initiation of sharp cracks from the slits root needed a quite large amount of load. Also, a contact between upper and lower halves occurs in this step which again increases the amount of load. As the crushing process continues, the folded sidewalls move upward and downward consecutively (Fig. 4d) which result in material cracking in the corner of both the top and bottom portions as shown in Fig. 4.e. During the cutting of the tube, the load remains almost constant (step 5 of Fig. 5). The test is stopped when the folded sidewalls reached to the platen of the test machine as shown in Fig. 4f. For specimen Cn-02, the total axial stroke is about 77% of the initial length.

Experimental results show that the deformation mode of tubes with proposed geometry and specifications is splitting and cutting. As observed in Fig. 5, the main part of the energy is absorbed by the steady load during a long stroke.

Several specimens (as listed in Table II) were prepared to investigate the effect of different geometrical parameters on the energy absorption parameters. Also, an intact specimen (specimen Cn-14) which has a progressive buckling deformation mode was prepared and tested.

IV. Results and Discussion

The main purpose of this research is to introduce a novel splitting process which holds the advantage of the conventional splitting process (the tearing energy related to splitting and crack propagation and having a steady-state deformation with an almost constant force) and eliminates the dependency of the method on the usage of conical rigid dies. After fabricating the specimens and performing the experimental tests, the diagram of the axial load versus the axial displacement of each experiment is sketched. Some useful energy absorption parameters are extracted from the diagrams which are:

- The total absorbed energy (E_t), which is the area under load-displacement diagram,
- The specific absorbed energy (SAE), which is computed by dividing the total absorbed energy by the specimen mass,
- The crush force efficiency (CFE), which is computed by dividing the average load (average value of instantaneous load applied to a specimen) by the maximum crushing load (maximum load that a specimen experiences),
- The critical displacement which defined as the axial displacement in which the critical load occurs.

These parameters are computed and listed in Table III for all specimens.

TABLE III: Experimental Measurements of Brazen Specimens

Specimens code	P_{cr} (kN)	X_{cr} (mm)	P_{ave} (kN)	E_t (J)	SAE (J/kg)	CFE
Cn-01	38.34	2.2	13.03	554.55	8546.06	0.33
Cn-02	32.40	1.09	10.53	579.48	8970.42	0.32
Cn-03	35.10	1.72	12.15	621.35	9622.98	0.34
Cn-04	35.38	1.57	12.09	432.55	9450.59	0.34
Cn-05	33.75	1.67	12.82	947.1	10293.44	0.37
Cn-06	32.62	1.82	10.5	499.79	7798.31	0.32
Cn-07	31.57	1.42	8.76	419.28	6523.86	0.27
Cn-08	24.48	1.24	6.52	259.03	5328.92	0.26
Cn-09	29.38	1.45	12.43	958.51	5756.5	0.42
Cn-10	28.67	1.68	11.34	579.69	4524.24	0.39
Cn-11	26.28	1.39	8.37	602.82	4865.39	0.31
Cn-12	26.51	1.26	10.67	927.3	7547.02	0.4
Cn-13	25.98	1.54	11.62	439.11	7057.42	0.44
Cn-14	18.52	2.73	7.56	554.72	4205.63	0.4

These parameters play an important role in the efficiency of an energy absorber. Increasing the total absorbed energy, the SAE, and the CFE may have desirable effects on performance of an energy absorber. The effects of geometrical specifications of discontinuities such as number, length and width of the notches and also the effects of the wall thickness and the outer diameter of the tubes on the energy absorption parameters of the specimens are investigated.

V. Effects of Number of Initial Notches

Fig. 6 compares the experimental diagrams of the axial load versus the axial displacement of three specimens with the same geometrical and material characteristics and a different number of initial notches (Cn-01, Cn-02 and Cn-03 with n=4, 6 and 8). As seen, by increasing the number of initial slits the total amount of absorbed energy increases. According to Table III, it is clear that by increasing the number of initial notches up to n=6, P_{cr}, P_{ave} and CFE of specimens decrease and after that these parameters experience an ascending trend. The best parameters correspond to the specimens with n=8. In the other word, n=8 is an optimum number of notches which results in the best SAE and CFE.

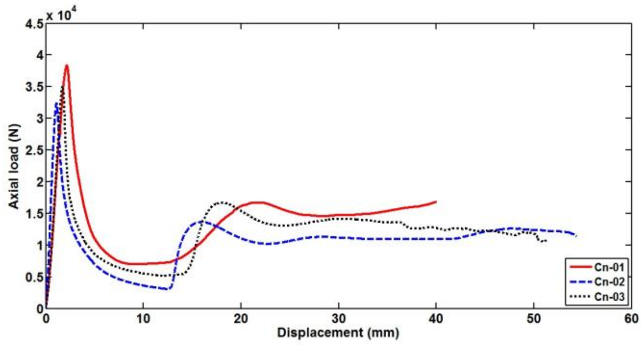

Fig. 6. Comparison between load-displacement diagrams of specimens Cn-01, Cn-02 and Cn-03 with n=4, 6 and 8.

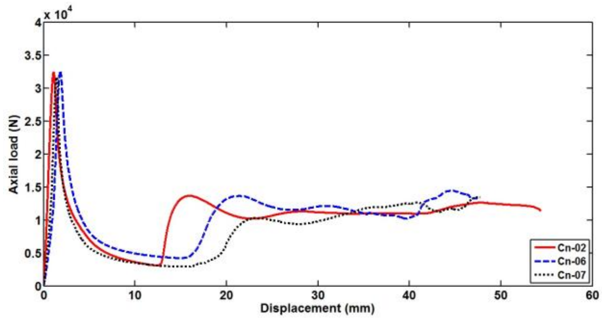

Fig. 7. Comparison between load-displacement diagrams of specimens Cn-02, Cn-06 and Cn-07 with NL=10, 14, and 18 mm.

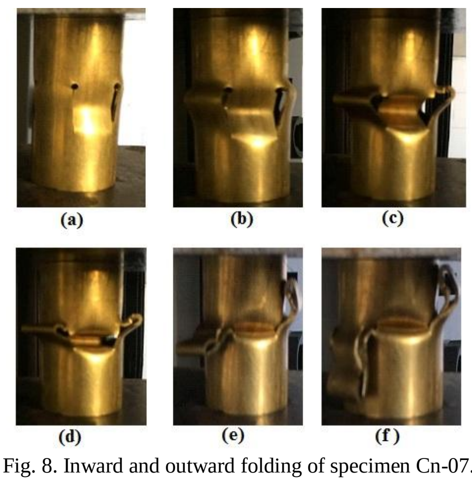

Fig. 8. Inward and outward folding of specimen Cn-07.

VI. Effects of Length of Initial Notches

Three specimens with the same geometrical and material characteristics and different length of initial slits (Cn-02, Cn-06 and Cn-07 with NL=10, 14, and 18 mm) were prepared and tested to investigate the effect of length of initial notches on the energy absorption capacity. The experimental diagram of the axial load versus the axial displacement is sketched in Fig. 7. By increment of initial notches length the contact between upper and lower halves takes place at bigger displacement and consequently, the folded sidewalls become longer and reach to the platens earlier. Thus, the energy absorption parameters decrease by an increase in initial notches length. For sample Cn-07, some sidewalls started to fold inward from the middle of notches as shown in Fig. 8b and by continuing the crushing load, the cutting deformation mode happens (Fig. 8c-f).

VII. Effects of Length of Initial Notches

Fig. 9 illustrates a comparison between the load-displacement diagrams of two specimens with the same geometrical characteristics and different width of initial notches equal to *NW*=1 and 3 mm. According to the figure, the specimen with wider notches deforms about 54% of the total tube length and has a lower amount of absorbed energy and SAE. Also, the specimen with narrower notches has a lower CFE, because it experiences the higher load during the smaller stroke and in comparison to specimen Cn-02, the average load is closer to the critical load.

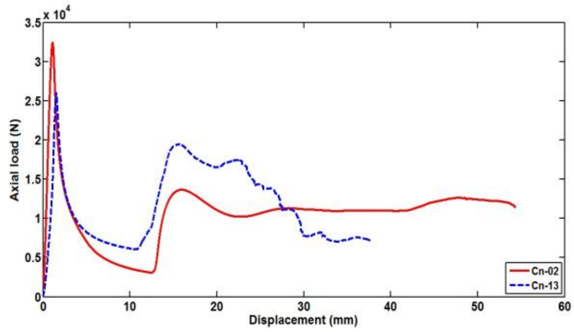

Fig. 9. Comparison between load-displacement diagrams of specimens Cn-02and Cn-13 with *NW*=1 and 3 mm.

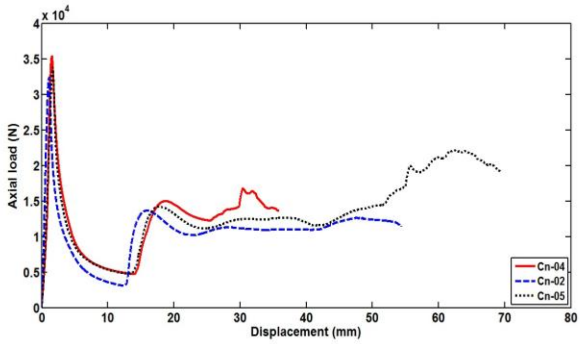

Fig. 10. Comparison between load-displacement diagrams of specimens Cn-04, Cn-02 and Cn-05 with *L*=50, 70 and 100 mm.

VIII. Effects of tube length

Fig. 10 shows the load-displacement diagrams of the notched specimens (Cn-04, Cn-02, and Cn-05) with different tube length (*L*=50, 70 and 100 mm) and the same notches characteristics. According to the experimental results, the increment of tube length increases the area under the load-displacement diagram and consequently, the total absorbed energy. As it is shown TABLE III, the highest value of the SAE and CFE were observed for specimen Cn-05 with maximum tube length (*L*=100 mm).

IX. Effects of Tube Thickness

To investigate the effects of wall thickness on the energy absorption characteristics of notched tubes, two specimens Cn-08 and Cn-01 with different wall thicknesses equal to *t*=0.75 and 1mm are examined. Fig. 11 shows the load-displacement diagrams of these samples. The instantaneous load-displacement curve of thicker specimens was located upper than the curve of specimens with a smaller thickness and as expected the E_t and SAE of the thicker specimen (Cn-01) are 2.14 and 1.6 times bigger than the E_t and SAE of the thinner sample. According to the data listed in TABLE III, by increasing the tube wall thickness, X_{cr}, P_{cr}, P_{ave} and CFE increases. Similar results were observed for the specimens Cn-11 and Cn-09 with *t*=1 and 1.5 mm.

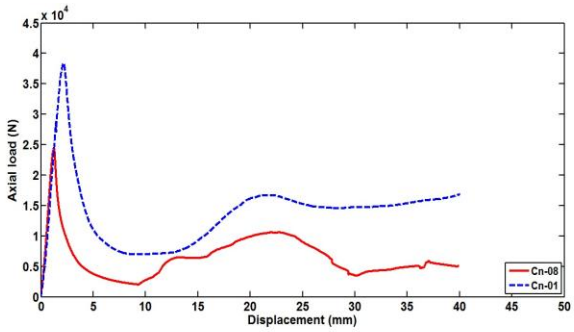

Fig. 11. Comparison between load-displacement diagrams of specimens Cn-08 and Cn-01 with *t*=0.75 and 1mm.

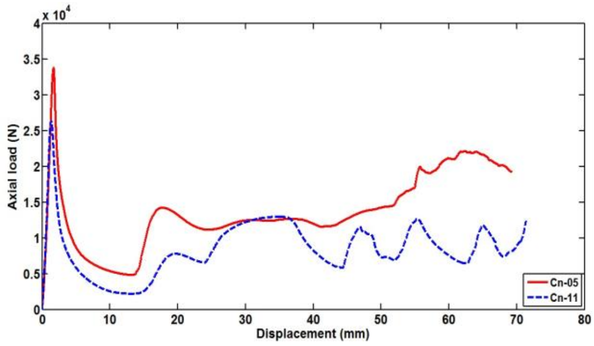

Fig. 12. Comparison between load-displacement diagrams of specimens Cn-05 and Cn-11 with tube outer diameters of *d*=35 and 50 mm.

X. Effects of Tube Diameter

Fig. 12 illustrates the experimental diagram of the axial load versus the axial displacement of two specimens Cn-05 and Cn-11 with the same geometrical and material characteristics and the different tube outer diameters of *d*=35 and 50 mm, respectively. Comparison of curves shows that by increasing the tube diameter, the axial load and the area under the diagram decreases, which results in lower energy absorption capacity. Also, the mass of specimens increases and therefore the SAE decreases. By increasing the tube diameter, the CFE decreases, too which means that the specimen with smaller tube diameter has better performance.

XI. Conclusion

The axial crushing of different circular tubular structures with geometrical discontinuities in the form of multiple axial slits was experimentally studied in current research. a novel axial splitting method was introduced which does not need the heavy rigid dies. The presented method decrease the total mass of the system significantly and also improve the energy absorption parameters in some cases. The effects of various parameters on energy absorption capacity of specimens were investigated.

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