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Experimental Investigation of Energy Absorption Characteristics of Square Thin-Walled Aluminum Tubes under Folding and Splitting Deformation Modes

Motahare Mahmoodnezhad* 

Department of Mechanical Engineering, Shahrood University of Technology, Shahrood, Semnan, Iran;
motahare.mahmoodnezhad@gmail.com.

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Abstract


Thin-walled metal structures have been used extensively in energy absorption systems in various fields such as transport, aerospace, and protection engineering because of their excellent properties, particularly their high strength-to-weight ratios and high energy absorption performance. This paper experimentally evaluates the energy absorption behavior of square thin-walled aluminum tubes subjected to two different deformation behaviors: folding and splitting. The specimens used in all experiments were made of the same type of aluminum material. They had the same geometrical parameters, such as wall thickness, tube length, cross-sectional dimensions, and volume. The dynamic compressive tests were carried out on the specimen samples through the folding deformation method using the drop-hammer machine. The results of the experiment indicated that folding deformation has a better performance in terms of energy absorption capacity with a Specific Absorbed Energy (SAE) value of 15,601.6 J/kg, which is 14.1% higher than that achieved through splitting. In addition, the average crushing force observed during the folding mode tests is about 45% higher compared to that recorded for the splitting deformation mode. On the other hand, the splitting mode yielded a considerably lower maximum force value but had a longer crushing displacement, making it more stable in its force-displacement response. The observations during deformation showed consistent diamond-shaped progressive folding deformation for folding samples, but curling without periodic folds in splitting samples. From the results obtained, it can be deduced that folding is better suited where maximum energy absorption capacity is the key objective.


Keywords: Thin-walled tubes, Energy absorption, Folding deformation, Splitting deformation.

1 | Introduction

Thin-walled tubes and columns have been extensively applied as elements of structures because of their excellent strength and energy absorption properties [1]. Deformation types of thin walled structures used as energy absorbers when subjected to compression, lateral, and flexural forces can include: folding of circular

 Corresponding Author: motahare.mahmoodnezhad@gmail.com

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tubes [2], and of grooved tubes [3], folding of square and rectangular columns [4], internal and external inversions of tubes [5] and [6], respectively; flattening of circular [7], and square tubes [8], and indentation of circular [9] and rectangular tubes [10].

For energy absorber systems used in cases where impacts occur, such designs need a long stroke to work effectively at various impact velocities. Tubular folding, tubular splitting, and curling are more efficient compared to tubular transverse crushing, axial buckling, or inversion and have a good stroke-to-length ratio compared to these other deformation modes [10]. The pioneering works by Alexander [11] on cylindrical tubes in axial loading for the purpose of developing relations for nuclear fuel tank design commenced in this field. Studies on tube inversion and its specifications were conducted by Al-Hassani et al. [12]. Mamalis et al. [13] developed a new theoretical model of steel conical tubes collapsing based on observations in their experiments. Stronge et al. [10] conducted research on the collapse of polygonal thin-walled structures using fixed plastic hinges. Abramowicz and Jones [14] determined the average crushing loads of square tubes under axial static loading conditions.

The effect of a circular groove located along the exterior circumference of a cylindrical tube on the buckling load was experimentally studied by Mamalis et al. [15]. It was concluded that grooves can control the maximum load that causes failure due to buckling in the cylinder. The process of inverting the thin-walled cylinders with varying thickness was examined by Chirwa [16] both experimentally and theoretically. He found that the energy absorption ability of these structures is approximately 50% greater than that of cylinders with a constant thickness. The inversion process of frusta and its various types were investigated by Aljawi and Alghamdi [17], utilizing ABAQUS software. According to them, three kinds of modes of inversion can be considered in the case of frusta: external flattening, internal flattening, and folding. An overview of collapsible energy absorbers was presented by Alghamdi [18]. The deformation behavior of honeycomb structures and their crushing under quasi-static loads in the axial direction were evaluated by Gao et al. [19].

They also studied the crushing of short, thin-walled cylindrical columns with square cross-sections under the impact of a cylindrical projectile. The energy absorption of steel square tubes was investigated both experimentally and numerically by Isaac and Oluwole [20], and it was found that the maximum collapse load decreases by nearly 10% in these tubes if filled with foam. Quasi-static and dynamic energy absorption characteristics of simple and top-hat tubes were studied experimentally by Tarigopula [21], who reported that the energy absorbed in top-hat tubes is higher. The effect of the addition of grooves in the outer wall with different cross-sectional profiles on the crushing and energy absorption characteristics of cylindrical tubes was studied experimentally by Daneshi and Hosseinipour [22]. It was found that the crushing distance and folding efficiency of these tubes are nearly the same, and there is a reduction in the maximum load value in the load-displacement graph for them because of the added grooves.

Recently, many researchers have been studying new structural forms in order to improve the crashworthiness characteristics of thin-walled structures. For instance, Kong et al. [23] studied asymmetrical square tubes with unequal cells and with different wall thicknesses subjected to loads in various directions, indicating that the energy absorption properties of these tubes could be enhanced if the internal and external wall thicknesses were reasonably chosen depending on loading angles. In another study, Ha et al. [24] suggested a new type of fractal multicell square tube using the Sierpinski carpet fractal design, concluding that the specific energy absorption for the 3rd order fractal tube was 100% greater than that for the 0th order tube. Finally, Baroutaji et al. [25] conducted an extensive review of recent advances in thin-walled energy absorbers, covering multicell, functionally graded thickness, and functionally graded foam-filled tubes. Splitting and curling deformations have been extensively studied, too; for example, Huang et al. [26] performed an investigation into the energy-absorbing behavior of axially splitting and curling square mild steel and aluminum tubes, suggesting a quasi-static kinematic model describing all main characteristics of deformation processes. Designs inspired by biological structures and those of hierarchical types have produced considerable advancements in crashworthiness.

For instance, according to Zhang et al. [27], in the analysis of the crashworthiness of hierarchical bio-inspired hybrid multicell tubes under axial crushing, it was observed that the specific energy absorption of the third-order hierarchical tube increased by 49.10% compared to that of a single square tube. Another important trend is the use of TPMS-filled structures; Wan et al. [28] examined TPMS-filled square tubes for quasi-static axial crushing and established that the energy absorption in hybrid TPMS-filled structures may be improved by at least 16.3% compared to other structures. Guo et al. [29] performed experiments regarding splitting and curling failure modes of square sandwiched metal tubes with an aluminum foam core under axial low-velocity impact. Song et al. [34] developed and optimized bio-inspired multicell tubes using square bamboo cross-section patterns, which provided optimum improvement in the specific energy absorption of 133.58% for axial loading cases. Dehghanpour and Alavi [30] conducted experimental and numerical studies of thin-walled tubes subjected to in-plane loading for different shapes and wall thicknesses.

In the present study, the effect of folding and splitting modes on energy absorption and the type of deformation of thin-walled tubes with square geometry and 2 mm wall thicknesses is investigated and compared through an experimental study. All samples have the same volume, height, section area, thickness, and material. The obtained results from experiments are accurate since they were done three times with acceptable consistency between them. These experiments show that the use of various deformation methods may influence the energy absorption capability and shape of deformation of thin-walled structures. Comparison between these two types of deformations showed that the folding mode is better than the splitting mode with respect to energy absorption and average applied force. Considering that the maximum force is considered in impact problems, the splitting method seems to be a proper choice since they have uniform force-displacement relations, and thus, the maximum force and average force will be closer.

This paper aims to investigate the effects of folding and splitting on thin-walled tubes with square cross-section (geometry) and thickness 2 mm, in terms of their capacity for energy absorption as well as deformation form. Thin-walled tubes considered for analysis have the same volume, height, average cross-sectional area, thickness, and material. It should be noted that the results obtained from experiments are reliable since they were repeated three times, and the results achieved in each experiment are similar to one another. Thus, it becomes clear how the use of different deformation modes affects the energy absorption and deformation type in thin-walled structures. Comparison of splitting and folding methods shows that energy absorption and average force are higher in folding. However, due to the fact that in impacts, the maximum force plays a key role, it is recommended to use splitting due to the similarity of the force-displacement curve.

2 | Materials and Methods

2.1 | Test Specimens and Material Selection

As the specimens having a square shape in terms of section geometry, which were able to withstand both the folding and splitting deformations, were not available in the market, they had to be prepared in the workshop by joining metal plates through welding. Welding using argon could have been another factor that may have affected the mechanical properties of the specimen, yet all measures were taken to reduce its effects. Regarding the splitting deformation type, a starting slit of 5 mm was made on the moving end of each specimen in order to allow cracking to occur. As aluminum alloys have lower mass, they were chosen as the material for this study.

2.2 | Tension Test

The mechanical properties of the sheets were determined according to the ASTM E8M-98 standard using an INSTRON 8305 universal testing machine. The results are summarized in *Table 1*. The average yield stress (0.2% offset) was 129.7 MPa, and the average ultimate tensile strength was 135.9 MPa.

Table 1. Mechanical properties of the specimens based on tension test results.

Thickness (mm)	Ultimate Strength (MPa)	Elongation at Break (mm)	Stress at 0.2% Yield (MPa)
2	136.5	6.8	127.4
2	136.9	6.5	127.2

2.3 | Sample Specifications and Coding

All specimens were fabricated from identical material with a 2 mm thickness and shared the same length, average section perimeter, and volume. The detailed dimensions are listed in *Table 2*.

Table 2. Specifications of the samples (dimensions in mm).

Specimen Shape	Length	Rib Width	Thickness
Square prism	160	63	2

To identify the samples, a coding system was used. Three specimens were prepared for each deformation mode. Each code consists of two parts separated by a hyphen: The first part indicates the cross-sectional shape and sample number, and the second part denotes the deformation mode. For example, “Sq 1-F” refers to the first square tube specimen tested in folding mode. *Table 3* summarizes the abbreviations and the number of tested specimens.

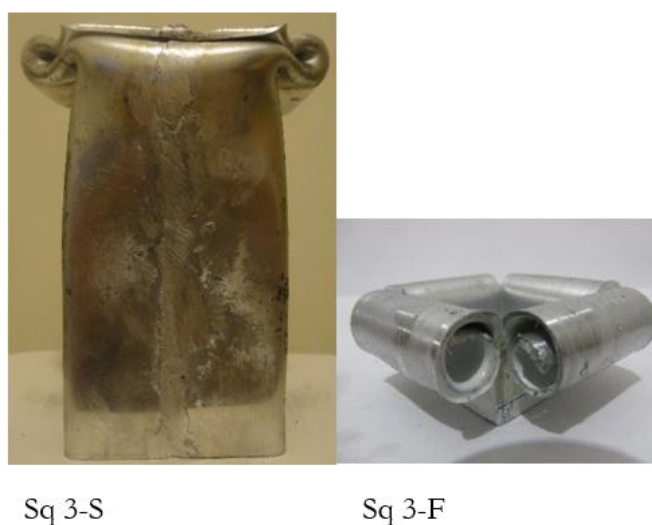


Fig. 1. Some specimens after loading.

Table 3. Abbreviations for samples and their number.

Specimen Shape	Code	Number of Tested Specimens	
		Folding	Splitting
Square prism	Sq	3	3

2.4 | Experimental Setup

Dynamic loading tests on the folding deformation were conducted through the use of the drop hammer test device. This testing device is made up of five major components, namely, the concrete base, anvil, striker, guide rods, and lifting system. Specimens were then loaded axially with vertical orientation, placing one end of the specimens on the anvil (stationary), and the other at the striking end of the striker (movable). An impact speed of 5.97 m/s was chosen since this is high enough to ensure maximum energy absorption .

Tests on the splitting deformation mode were carried out using DMG equipment. In addition to the difference in loading speed, all other specifications remain the same as for the drop hammer apparatus.

Maximum, average forces, crushing length upon completion of the loading process, point of failure, and total absorbed energy (area under load displacement curves) are listed in *Tables 4* and *5*, respectively.

Table 4. Experimental results for all specimens (forces).

Specimen code	Mean force (N)	Maximum force (N)
Sq1-S	11145.3	23240.0
Sq2-S	11145.0	23240.0
Sq3-S	11144.9	23240.0
Sq1-F	20350.2	44057.6
Sq2-F	20350.2	46180.0
Sq3-F	20350.2	36481.1

Table 5. Experimental results for all specimens (energy, crushing length, and collapse start).

Specimen Code	SAE (J/kg)	Crushing Length (mm)	Collapse Starting Point
Sq1-S	13400.0	144.2	Moving end
Sq2-S	13400.0	144.2	Moving end
Sq3-S	13400.0	144.2	Moving end
Sq1-F	15601.6	46	Moving end
Sq2-F	15601.6	46	Moving end
Sq3-F	15601.6	46	Moving end

(Insert Fig. 1 here: specimens Sq 3-S and Sq 3-F after loading)

Fig. 1 shows photographs of selected specimens after testing.

3 | Results and Discussion

The parameters for the study of energy absorption in thin-walled structures are maximum displacement (crushing length), Specific Absorbed Energy (SAE), maximum force, and average force. The average values of these parameters for both splitting and folding modes are presented in *Table 6*.

Table 6. Average values of key results for 2 mm thickness.

Deformation Mode	SAE (J/kg)	Mean Force (N)	Maximum Force (N)	Crushing Length (mm)
Splitting	13400.0	11145.3	23240.0	144.2
Folding	15601.6	20350.2	42239.5	46.0

The results for the two deformation modes are compared in *Tables 7* and *8*. As shown, the differences between the two modes are consistent across most parameters, except for the maximum force of sample 3 (Sq3-F). Nevertheless, the experiments demonstrate reasonable repeatability. The ranking of the samples in terms of energy absorption, maximum force, average force, and crushing length is identical across all tests. Although slight mismatches exist in the load–displacement curves, the overall experimental validity is confirmed.

Table 7. Comparison between folding and splitting modes – Sample 1.

Specimen Shape	Difference (%)			
	SAE	Mean Force	Max Force	Crushing Length
Square prism	14.11	45.23	47.25	68.09

Table 8. Comparison between folding and splitting modes – Sample 2.

Specimen Shape	Difference (%)			
	SAE	Mean Force	Max Force	Crushing Length
Square prism	14.11	45.23	49.67	68.09

Table 9. Comparison between folding and splitting modes – Sample 3.

Specimen Shape	Difference (%)			
	SAE	Mean Force	Max Force	Crushing Length
Square prism	14.11	45.23	36.29	68.09

The Fig. 2 shows the deformed sections in the tested samples. The folding mode follows a diamond-like regular pattern that changes from in-out-in-out. Meanwhile, in the splitting mode, there is no formation of an alternating pattern. Instead, all samples deform into curly form, having either in-in or out-out sections. The splitting crush length, which is 144.2 mm, was found to be much greater compared to folding, which is 46 mm, showing a longer stroke. It was noted that there was some inconsistency with the deformed section, caused by the welding effect.

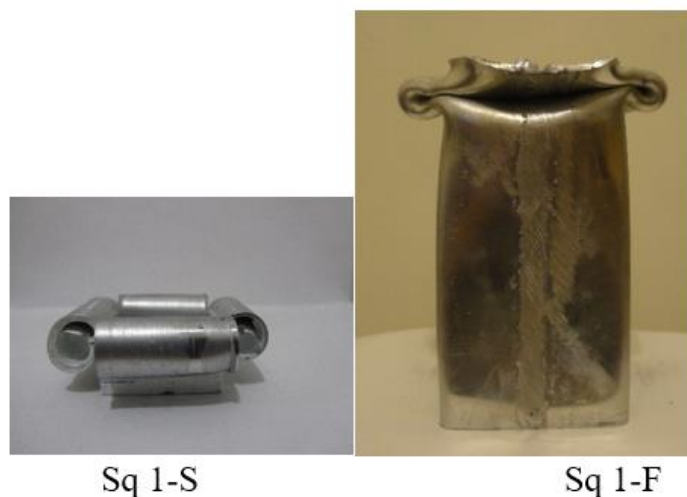


Fig. 2. Comparison of deformed sections of Sq 1, Sq 2, and Sq 3 in splitting and folding modes.

In Fig. 3, it was shown that in terms of the energy absorption capability, the folding mode absorbed more energy (SAE = 15601.6 J/kg) compared to the splitting mode (13400 J/kg). With a similar thickness (2 mm), energy absorption becomes much higher when the number of cross-sectional edges increases. In the axial dynamic test, the increase in energy absorption could result from more folds and plastic hinges formed. Axial quasi-static test results would produce more accurate results with a cleaner cut.

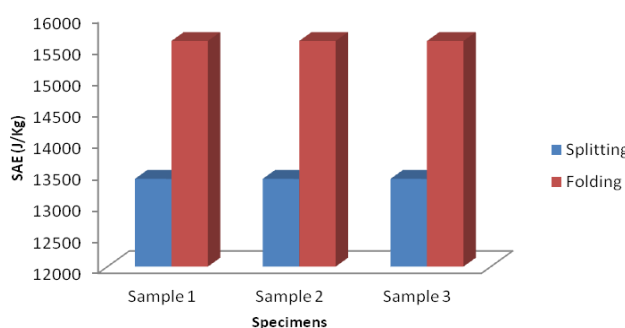


Fig. 3. Comparison of energy absorption capacity of different deformation modes in experiments (2 mm thickness).

The maximum force (first peak in the load–displacement curve) is a critical parameter in impact events. Fig. 4 shows a representative load–displacement curve for the splitting deformation mode. The splitting mode exhibited a considerably lower maximum force (23240 N) compared to the folding mode (42239.5 N). This reduction is advantageous for protecting sensitive components or occupants during an impact.

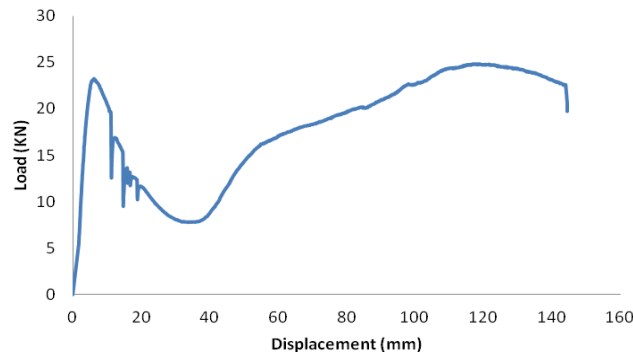


Fig. 4. Load-Displacement curve of splitting deformation mode.

The reduction in the gap between maximum and average forces in energy-absorbing devices is highly desirable. Some of the common practices in this regard include foam filling, creating grooves, or employing variable cross-sections. As is evident from this comparison, the splitting deformation gives rise to a considerably smaller gap between the maximum and average forces compared to the folding deformation. This has been possible because of the reduced total loaded surface area at the impact point and easier deformation due to splitting. The maximum and average forces in both deformations have been shown in Fig. 5 below.

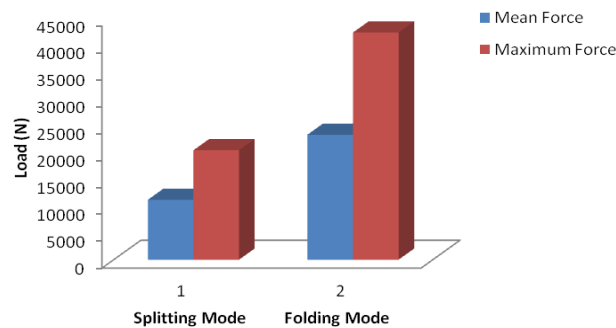


Fig. 5. Comparison of the maximum and the average force of various deformation modes.

5 | Conclusion

In this experiment, a comparison analysis was performed to determine the crashworthiness behavior of square thin-walled aluminum tubes under different deformation modes, such as folding and splitting modes. It is important to mention here that all these samples were designed with similar material properties and geometrical parameters so as to eliminate any effect of other variables in the results.

It was observed that the deformation mode had an important influence on the crushing behavior and energy absorption capacity of these samples. Under the folding deformation mode, a stable folding pattern was observed, which comprised alternate folding inwards and outwards, while in the case of the splitting mode, curling and cracking took place due to longitudinal cracks formed along the pre-cut slit.

Under the folding deformation mode, a high level of energy absorption capacity was achieved, reaching a value of 15,601.6 J/kg, which was approximately 14.1% higher than in the case of the splitting mode. Moreover, the mean crushing force was about 45% higher for the folding mode than for the splitting mode.

Despite its lower energy absorption capacity, the splitting mode exhibited several advantages. The peak crushing force was significantly reduced compared with the folding mode, and the force-displacement response was more uniform, resulting in a smaller difference between maximum and mean crushing forces. Furthermore, the splitting mode provided a crushing stroke more than three times greater than that of the folding mode, making it attractive for applications requiring long-stroke energy dissipation and reduced impact loads.

Overall, the results suggest that folding deformation is the preferred mechanism when maximum energy absorption is required. In contrast, splitting deformation offers a favorable solution for impact protection systems where low peak forces and stable crushing behavior are critical. Future studies may focus on the influence of wall thickness, material grade, triggering mechanisms, and hybrid deformation modes to further enhance the crashworthiness performance of thin-walled energy absorbers.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Data Availability

The datasets generated and/or analyzed during the current study are included in this article.

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