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The Effect of Number of Corrugation on Crashworthiness of Aluminum Corrugated Tube under Lateral Loading

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Abstract

Thin-walled tubes have been developed and are growing in use as new energy absorber structures. The objective of this study is to investigate the energy absorption and crushing characteristics of corrugated tubes with different number of corrugation in a specific length exposed to lateral loading. At the first step, experimental tests were carried out on a corrugated tube with three corrugations (two inner and one outer) and a tube without corrugation. After that, a finite element model was developed by means of ABAQUS software in order to study the effect of corrugation number on crushing properties of thin-walled tubes. The results show that tubes with corrugations have a higher mean crushing force which is directly proportional to the number of corrugations. Moreover, the plateau region in load-displacement curve decreases by increasing the number of corrugations and therefore the tube reaches its densification point earlier. Plastic strain variation pattern along the tubes were investigated as well.

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Keywords: Corrugated tube; crushing analysis; finite element method; specific absorbed energy; mean crushing load

1. Introduction

As a typical class of energy absorbers, thin-walled structures have been widely used in crashworthiness application such as automotive industry to protect passengers from severe injury for their excellent energy absorption capacity and lightweight [1]. Although there are other applications which are reported in [2-28].

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Previously, owing to the high ductility and low cost, steel tubes had drawn researchers' attention [29]. As the increasing importance of lightweight, the use of aluminum structures has become more predominant than before [30]. Afterwards, significant efforts have been made to study the crushing behaviors of the thin-walled structures through analytical and experimental methods. Having high energy absorption capacity and low mass are the principal factors in design of crashworthiness structures. To predict and observe the crushing behavior of thin-walled structures under axial impact loading, there have been numerous researches [31]. Hereby, laterally compressed tubes, eliminating the problems associated with axially loaded tubes (such as sudden initial peak load, low stroke efficiency, and dependency to axial alignment), are extensively used as energy absorbers. Moreover, their efficiency is not affected by loading direction and they present a smooth load-displacement diagram. The effect of different parameters on the energy absorption characteristics of the absorbers have been studied by many researchers [32-48]. Tubes with non-circular cross-sections have also been investigated. Jing and Barton [49] performed numerical and experimental studies on lateral crushing of square tubes. Unfortunately, there is not an extensive literature on crashworthiness of circular corrugated tubes especially under lateral loading. As a periodic configuration, the number of corrugation of circular cylinder plays a pivotal role on its crushing properties. This concept is studied in this research both experimentally and numerically.

2. Experimental tests

In order to investigate the effect of number corrugation on the lateral loading response, experimental tests were performed which then followed by finite element simulations. All the specimens were cut from one continuous tube made up of Aluminum alloy A6060. Two different specimens were provided, Figure 1.

(a) (b)

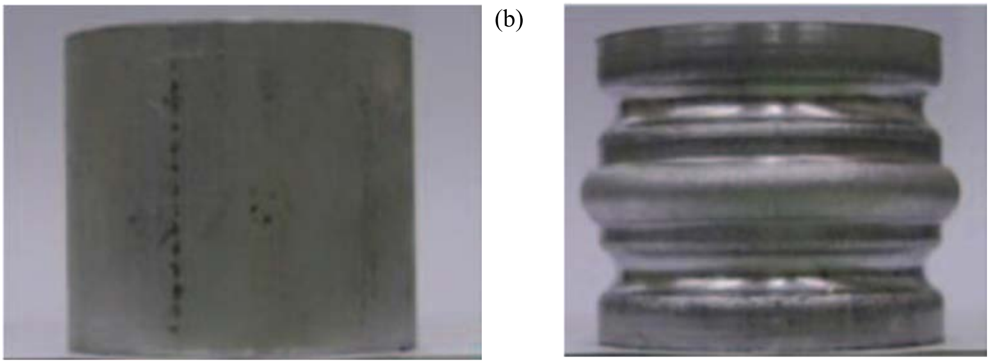

Figure 1 the created tubes without and with corrugations; (a): S, (b): CIO3

The S-type is a tube without corrugation and CIO3, which bears two inner and one outer corrugations with amplitude of 4 mm. Corrugations were created through stamping method. Special machinery was designed to produce different types of corrugations in which the dies were installed and rotated in parallel axes.

The specimens have the same wall thickness of 2.5 mm and the diameter of 79.5 mm. The initial length of the samples is 70 mm. The specimens exposed to quasi-static lateral compression. Instron digital testing machine with a full scale load of 500 kN was employed and all the tubes were compressed at the rate of 5 mm/min. Then, load-displacement diagrams were recorded by data acquisition system [45].

3. Finite element modeling

Three dimensional finite element model of the tubes were developed by means of ABAQUS software package. The tubes were modelled using four-node linear S4R shell elements. In addition to S and CIO3 types, three other tubes were created with different number of corrugations, Figure 2.

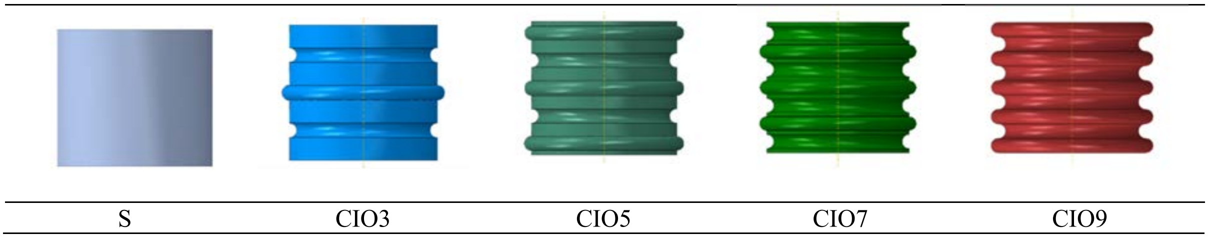

Figure 2 generated tubes in finite element model

The mechanical response of sample's material was obtained through tensile testing of the extruded wall material, parallel to the direction of the tube axis. Representative engineering stress-strain curve was used to compute true stress-strain diagram and then imported to the FE model. General contact algorithm was defined by considering self-contact of tube's wall. After studying mesh sensitivity, each tubes were meshed with an element size of 1 mm. Stationary and movable plates were modelled as rigid parts via analytical rigid feature. The movable plate was constrained to move only in the compression direction while the stationary plate was constrained in all of its degree of freedom, Figure 3.

Explicit/Solver was implemented for compression analysis. The loading rate was obtained according to the fundamental natural frequency of tube. Moreover, the movable plate was moved in the smoothest possible manner by means of smooth-step built in ABAQUS.

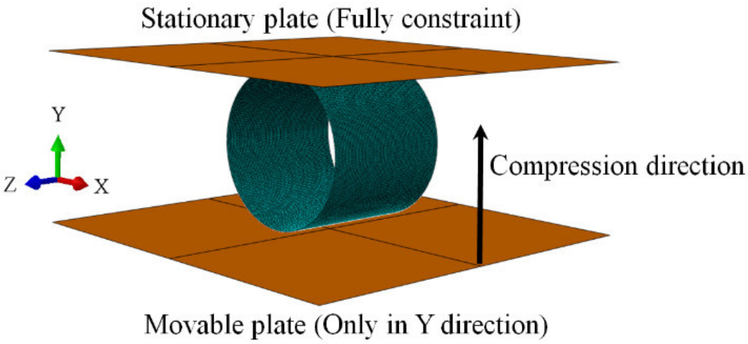

Figure 3 Finite element model of compression test

4. Results and discussion

4.1. Finite element model validation

In this sub-section, the lateral crushing response of FE model was compared with experimental results in order to validate the numerical model. Load-displacement curves of the tubes, which were obtained by quasi-static analysis, were implemented to determine crushing parameters (mean crushing load, and total energy absorption). In order to obtain the mean crushing load in the FE model, load-displacement response of movable plate was attained in each case. Then, the area under load-displacement curve was calculated and by dividing the value to the associated densification point, the mean crushing load was computed. The crushing parameters are listed in Table 1 and compared with experimental results. It is clear in that the obtained values by FE model are in a good agreement with the experimental results and the maximum differences are about 13%.

Table 1 crashworthiness parameters of the S and CIO3 tubes obtained by FE model and experimental tests

Type	Mean Crushing Load (N)			Total Absorbed Energy (J)		
	Exponential	FEM	Difference (%)	Exponential	FEM	Difference (%)
S	809.15	914.17	13	61.79	69.2	12
CIO3	3256.91	3680.3	13	202.77	227.71	12.2

At the next step, crushing mechanisms of different corrugated tubes were compared with experimental tests. The crushing mechanism is directly associated with the number and the geometry of the specimen. It did find out that there are two distinct types of failures: two-hinge failure and four-hinge failure [45]. The energy absorption characteristics is directly contributed with the failure mechanism. Figure 4 depicted crushing mechanism of each case during lateral compression. It is clear that four-mechanism failure happens only for tubes with corrugation [45].

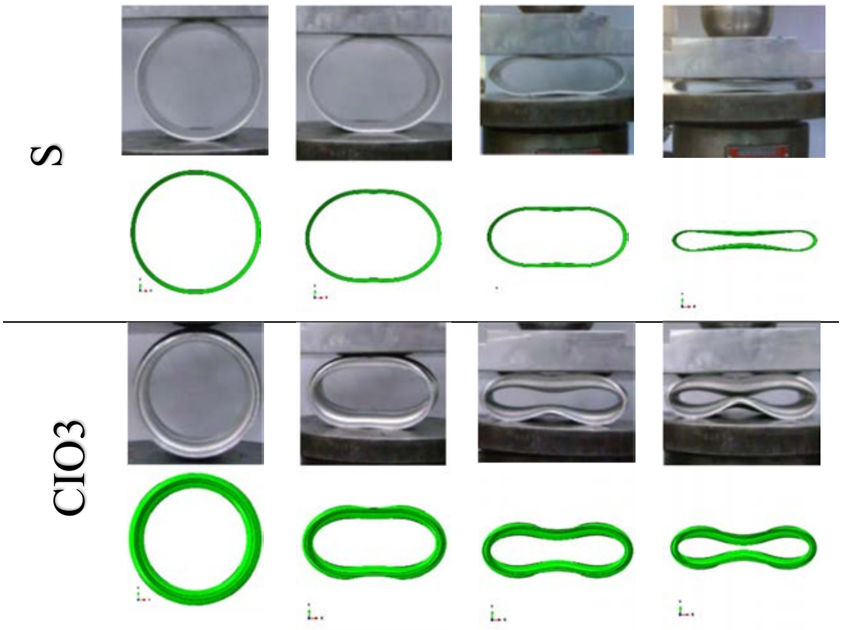

Figure 4 Deformation history of S and CIO3 tubes under lateral loading

4.2 Effect of number of corrugation

It is clear that crushing energy is absorbed by progressive plastic energy dissipation. Therefore, the magnitude and distribution pattern of plastic strains gives a better understanding of efficiency of tubes in crushing energy absorption. With regard to this point, two critical regions, which plastic hinges are formed, are considered and plastic strain contours are derived at the same level of compression and for each case.

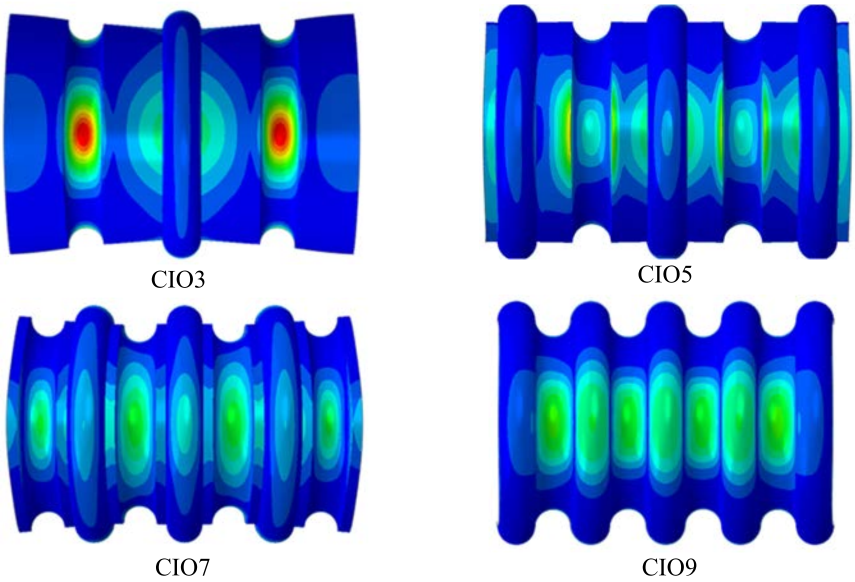

Figure 5 Plastic strain contours in horizontal view

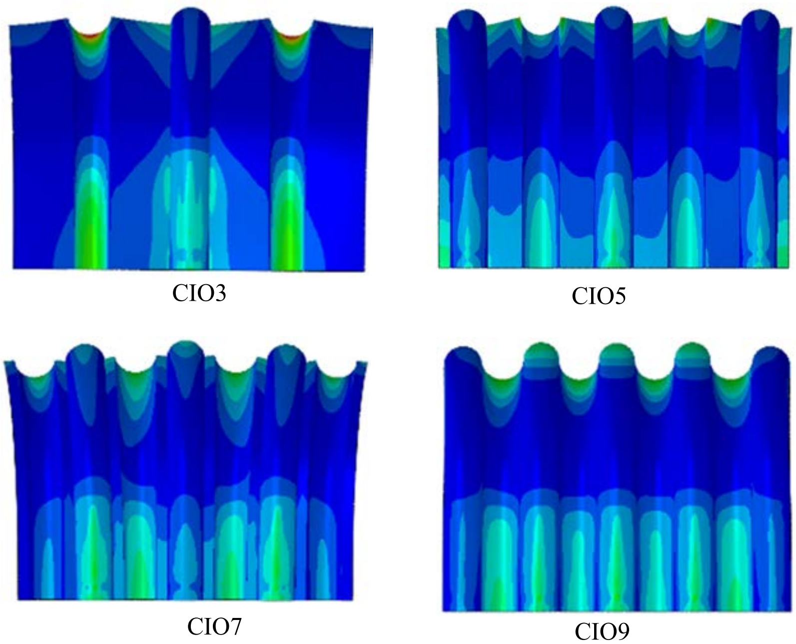

Figure 6 Plastic strain contours in vertical view

It can be seen that by increasing the number of corrugation, the plastic bond in the crushing regions is extended and the tube undergoes significant cumulative plastic deformation during lateral compression. For example, it is seen that CIO3 experiences local plastic deformations exactly at the location of corrugations although the other regions are not deforming beyond the elastic regime. On the other hand, CIO9 undergoes a uniform plastic deformation because of the fully corrugated shape of the tube, which leads to have a higher capacity in crushing energy absorption.

Figure 7 shows the load-displacement diagrams of tubes. It is clear that by increasing the number of corrugation the area under diagram increases as well. Moreover, the more number of corrugation, the earlier densification of tube.

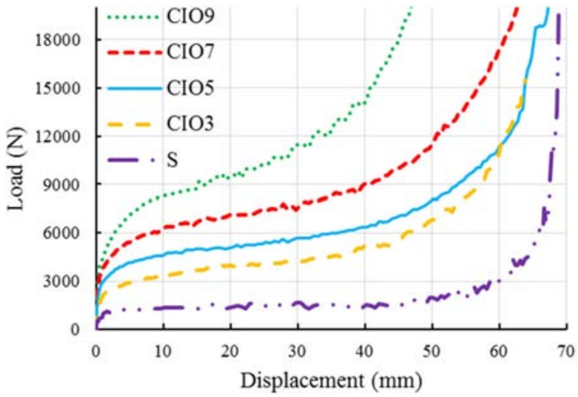

Figure 7 load-displacement diagrams of the tubes

Table 2 shows the crushing parameters of the tubes which are then plotted in Figure 8.

Table 2 crashworthiness characteristics of the corrugated tubes

Tube type	Total absorbed energy (J)	Mean crushing load (N)	Specific absorbed energy (kJ/kg)
CIO3	227.1	3680.3	1588.11
CIO5	321.6	5847.2	1997.5
CIO7	404.8	7784.6	2339.8
CIO9	494.7	10755	2688.58

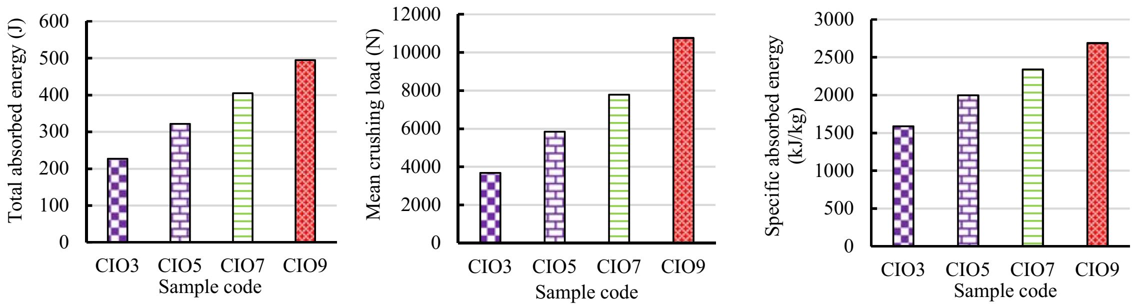

Figure 8 Crushing parameters of the corrugated tubes

It is seen that mean crushing load enhanced by increasing the number of corrugation. The variation of specific absorbed energy (SAE) reveals that CIO9 has 69% higher value than CIO3. Moreover, the relative enhancement of SAE value, compared with CIO3, is 25.7% and 47.3% for CIO5 and CIO7, respectively.

5. Conclusion

In this work, energy absorption and crushing characteristics of corrugated tubes with different number of corrugation in a specific length, under lateral loading, was studied. Quasi-static compression tests were conducted on a corrugated tube with three corrugations and a tube without corrugation. At the next step, a 3D finite element model was developed to investigate the effect of number of corrugation on crushing response of tubes. After validating the FE model, three corrugated tubes were created. Comparing the obtained results through numerical simulations revealed that the fully corrugated tube provides significantly higher energy absorption capacity although it was observed that the more number of corrugation considered, the earlier densification response attained. Moreover, plastic strain distribution on the critical regions in which plastic hinge forms was depicted. It was illustrated that by increasing the number of corrugation, the plastic deformation in critical zones forms more uniform and therefore presents more crushing energy absorption through dissipated plastic energy.

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