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# Axial splitting of conical frusta: Experimental and numerical study and crashworthiness optimization

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ABSTRACT

This paper investigates the axial splitting process of thin-walled conical aluminum frusta, experimentally and numerically. The specimens were prepared using the spinning method and some edge slits were created at the specified locations. The specimens were axially compressed between a rigid plate on top and a rigid conical die at the bottom using *Zwick* universal testing machine. Some key parameters of energy absorbers such as specific absorbed energy (*SAE*), non-dimensional load-carrying capacity (*NLC*) and undulation of load-carrying capacity (*ULC*) were extracted from the load-displacement diagrams. Effects of different parameters such as specimen wall semi-apical angle, die semi-apical angle, number, and length of initial slits were studied on the energy absorption capability of specimens. The numerical analyses were performed by finite element method using Abaqus/Implicit software package. The surface-based cohesive behavior technique which works only with implicit solver was employed for cracks propagation. The numerical simulations were compared with experiments and good agreements were found between numerical and experimental results. To find the optimum energy absorber parameters, the design of experiments (DOE) method was employed. Using the existing data and applying the Taguchi technique, the optimal specimens with best *SAE*, *ULC*, and *NLC* were found. To check the efficiency of the DOE approach, these specimens were fabricated and tested and it was observed that the tested specimens had the best *SAE*, *ULC*, and *NLC* among all specimens. So, the excellent performance of DOE technique in present application was proved.

## 1. Introduction

Energy absorbers are systems that can partially convert the kinetic energy of impacts into other forms of energies. Thin-walled structures such as cylindrical tubes and conical shells are common energy absorbers that the researchers have paid considerable attention to their collapse behavior in the last decades. Among different energy absorption methods, axial splitting is an efficient mechanism of energy dissipation due to its relatively constant force over a long stroke [1]. Stronge et al. [2] examined the splitting of square tubes compressed axially on a die and they found that the energy is dissipated by fracture and plastic deformation of metal tubes. Lu et al. [3] experimentally studied tearing energy of square aluminum and mild steel tubes under splitting process. They also determined the bending energy considering rigid-perfectly-plastic material behavior. Huang et al. [4] investigated the energy absorption capacity of square metal tubes in axial splitting. Pyramid shaped dies with various semi-angles were used and the square tubes were pushed slowly against them. Also, they studied splitting behavior of circular metal tubes by compressing the specimens on to conical dies with various semi-angles [5]. The effects of different parameters such as tube dimensions, semi-angle of the die and friction coefficient were investigated on the results. Bheemineni et al. [6] studied the tearing behavior of circular metal tubes under axial compression. The numerical simulations were carried out using ANSYS/LS-DYNA software. Yuen et al. [7] studied splitting process of circular tubes under blast load. Effect of length of cut on mean cutting load, cutting force efficiency and peak cutting load was investigated. Niknejad et al. [8] presented some theoretical relations for prediction of axial force of circular metal tubes during the splitting process. They investigated the effects of wall thickness and inner radius of the tubes, number, and length of initial slits, and die semi-angle on the results, experimentally. Tanaskovic et al. [9] combined shrinking and splitting processes to increase energy absorption characteristics of circular tubes. The efficiency of presented energy absorber was approximately 60% higher than absorbers with only shrinking. Li et al. [10] performed experimental and numerical studies on new energy absorber which combines expanding and splitting processes to enhance the energy absorption capability of circular metal tubes. A finite element model for

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the axial splitting of circular tubes was presented by Rouzegar and Karimi [11]. They performed some experimental tests to validate the numerical results. The effects of number and length of initial slits, diameters and thickness of tubes, and semi-angle of dies on energy absorption capacity of specimens were investigated. Assaee et al. [12] investigated the splitting behavior of E-glass/vinylester and E-glass/polyester composite columns, experimentally. The specimens were axially compressed on conical dies under quasi-static condition. The effects of initial slits, cross sections type, side lengths, number of composite layers, resin type, fiber fabric type and angle of conical dies on the results were investigated.

Thin-walled frusta are the energy absorbing systems that can be used in many applications like aerospace and armaments. Gupta [13] investigated the collapse behavior of varying thickness aluminum frusta, experimentally and computationally. The numerical simulations were performed using a non-linear finite element package considering a rigid visco-plastic model for material behavior. Mamalis et al. [14] determined load-displacement behavior and deformation modes of thin-walled PVC frusta and square tubes under axial crushing. Based on the folding mechanism, a theoretical model was developed for predicting the mean loads. Gupta and Abbas [15] presented a theoretical model for the axial crushing of thin-walled frusta. They compared the presented model with several experiments and good agreement was found between two results. El-Sobky et al. [16] studied the energy absorption capacity of circular frusta under dynamic axial load and the results were compared with quasi-static tests. The experimental observations showed that the effects of end constraints and heat treatment on the energy absorption capacity were similar to those observed under quasi-static testing. Alkateb et al. [17] performed an experimental study on energy absorption characteristics of composite elliptical cones under quasi-static axial crushing load. The failure mode of elliptical tubular specimens was compared with elliptical conical specimens and considerable improvements in energy absorption parameters were observed in the case of elliptical conical shells. Gupta et al. [18] tested conical metal frusta with different thickness and semi-angles under axial compression loading. Also, numerical simulations were carried out for all samples using ANSYS software. Several experimental and numerical analyses on frusta under impact loading were carried out by Mohamed Sheriff et al. [19] in order to optimize the energy absorption parameters of specimens. Ahmad and Thambiratnam [20] examined foam-filled conical metal tubes under axial impact loading by non-linear FE techniques. The dynamic response of the specimens was studied and the energy absorption response was quantified with respect to variations in the parameter of foam density, wall thickness, semi-apical angle, impact mass and velocity. They also investigated the axial crushing of foam-filled conical tubes and the effects of some important parameters such as wall thickness, semi-angle, and density of foam filler were investigated where the results show the advantages of using the foam-filled conical tube as energy absorber [21]. Ghamarian et al. [22] investigated the crash behavior of empty and foam-filled conical tubes by nonlinear dynamic finite element (FE) method. Good agreement was found between the predicted numerical crushing force and experimental results. Niknejad and Tavassolimanesh [23] studied the inversion process of capped-end frusta under axial loading applied by a solid cylindrical punch. They predicted a theoretical model for plastic deformation and inversion of frusta wall and compared the analytical solution with experimental results. Kathiresan et al. [24] studied crashworthiness of conical composite shells under the quasi-static axial compression. The experimental load-displacement characteristics of GFRP composite conical shells were compared with the numerical results obtained through ABAQUS finite element package. Baroutaji et al. [25] investigated the energy absorption capability of a sandwich tube composed of a circular tube and aluminum foam core under lateral loading, numerically and experimentally. The effect of various geometrical parameters on the behavior of sandwich tubes was studied using the design of experiment method and the multi-objective optimization of specimens was performed using a desirability approach. Wu et al. [26] studied the effects of number of cells and topological configurations of multi-cell structures on their crashworthiness characteristics, numerically and experimentally. Several energy absorption parameters were investigated for various multi-cells structures and the results show that the five-cell tube has the best behavior as an energy absorber. The Genetic Algorithm was adopted for multi-objective optimization of the five-cell tube in order to find the energy absorber with maximum specific energy absorption and minimum peak crushing force. Zheng et al. [27] investigated the crushing behavior of laterally variable thickness (LVT) multi-cell tubes under axial loading. The presented theoretical relations and also finite element simulations were verified with experimental results of five-cell and nine-cell specimens. Theoretical, numerical and experimental studies of axially and laterally functionally graded thickness square structures under axial loading were performed by Sun et al. [28]. The results of analytical solutions and numerical simulations were in good agreements with experiments. The results indicated that in comparison to uniform thickness samples, the functionally graded thickness square tubes have better energy absorption characteristics. Sun et al. [29] presented a comparison between crashworthiness of square and criss-cross tubes using numerical and experimental analyses. The results showed that a criss-cross tube can absorb energy about 150% higher than a square column with the same weight. Using the genetic algorithm, the optimal criss-cross tubes with maximum specific energy absorption and minimum peak crashing force were found.

In this paper, for the first time, the splitting process of circular aluminum frusta under axial compression loading is investigated, experimentally and numerically. The FE simulations are performed by ABAQUS package and the obtained numerical results are verified by experiments. The effects of different parameters such as specimen semi-apical angle, conical die semi-apical angle and number, and length of initial slits are investigated on energy absorption characteristic of specimens. Also, using the design of experiments (DOE) method the optimal energy absorbers are predicted. The presented energy absorbers can be used in many applications such as automobile, railway, naval and aerospace industries [29]. Fig. 1 shows a typical application of the energy absorber mounted between wagon frame and buffer [9]. For each particular application, the characterization of the energy absorber should be designed specifically.

## 2. Experiment investigations

The thin-walled aluminum conical specimens with a height of 100 mm, a bottom diameter of 120 mm, the thickness of 2 mm and semi-apical angles varied from 10° to 20° were prepared using the spinning method. Some axial slits were created at the bottom of the tube using a thin saw. Fig. 2 shows a specimen with initial slits before the test. The specimens were axially compressed between a rigid platen on top and a rigid conical die at the bottom using *Zwick* universal

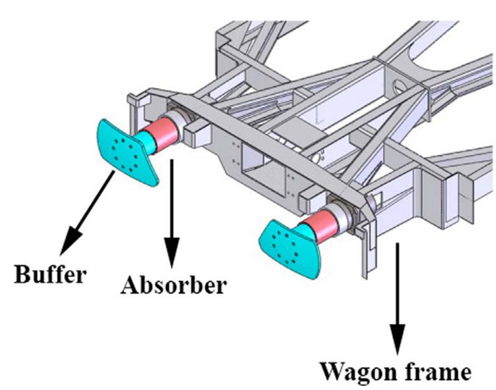


**Fig. 1.** A typical energy absorber mounted between wagon frame and buffer [9].