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Investigation of mechanical behavior of energy absorbers in expansion and folding modes under axial quasi-static loading in both experimental and numerical methods

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ABSTRACT

In this paper, a new form of energy absorbing structures has been introduced which energy absorbing is occurred during a combined process. The structure consists of a thin-walled aluminum matrix and a thin-walled steel punch. Energy is absorbed as the matrix gets expanded followed by simultaneous matrix and punch folding. In order to demonstrate the effectiveness of absorbent introduced, many samples of each type were fabricated and tested. In one case, it was found that, the new structure tends to absorb up to 32% more energy than sum of the energy absorbed by its individual parts. Also, the energy absorption properties and the parametric study were simulated using finite element code LS-Dyna. The results showed that among different section geometries, structures with rectangular section have the lowest energy absorption and the highest crush force efficiency; by increasing the number of sides of the cross section the absorbed energy increased and crush force efficiency is decreased. In addition, increasing the thickness of the punch leads to increased energy absorption. Also, it was found that, selecting an appropriate thickness for the punch, one can predict overall shape of load-displacement curve and maximum force location for the combined structure.

1. Introduction

Thin-walled energy absorbers are structures used to reduce injuries resulting from road accidents. Absorbing accident-generated energy in the form of plastic deformations, these structures prevent the energy from being transmitted to the vehicle's structure and passengers [1]. Numerous research works have studied thin-walled structures of various geometries and forms, introducing high-efficiency thin-walled structures and optimum collapse parameters. Effective parameters on energy absorption include specific energy absorption (SEA; the ratio of absorbed energy to mass of the structure), maximum force (Fm; peak force on force-displacement curve), collapse efficiency (Δ; ratio of collapse length to initial length of absorber), average force (Fa; average force over force-displacement curve), and finally, crush force efficiency (CFE; the ratio of Fa to Fm). A brief description of prior research on energy absorbers is presented in the following.

Alexander [2] carried out theoretical investigations on thin-walled cylindrical tubes assuming a rigid-plastic behavior for them; this model was based on plastic work due to tensile and flexural deformations of a thin-walled cylinder. Abramowicz and Jones [3,4] extended Alexander's theory and determined average force for symmetric folding mode in a cylindrical shell. Hanssen et al. [5] investigated static and dynamic crushing of square aluminum extrusions filled with aluminum foam. They examined 144 samples. Then, energy absorption behavior and interactions between filler foam and square shell were studied. Based on experimental observations, empirical relationships were derived for force and energy absorption in these structures. Zarei and Kroger [6] tried to optimize foam-filled aluminum tubes for crush box application, based on column geometry optimization to maximize energy absorption capacity with minimal structural weight.

Yang et al. [7] investigated energy absorption of expanding tubes using a conical–cylindrical die, both experimentally and numerically. Yan et al. [8] performed a theoretical research where they determined energy absorption of circular tubes in expanding mode numerically and experimentally. Comparing the results of analytical (and numerical) studies against experimental data, analytical results were found to be accurate. Huang et al. [9] analytically investigated axial splitting and curling of circular metal tubes, with the results validated by conducting series of experiments.

Alavi Nia and Haddad [10] comparatively analyzed energy absorption and deformation of thin-walled tubes of various section geometries including circular, square, rectangular, hexagonal, triangular,

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Fig. 1. Materials, capped-end steel cones and cylindrical aluminum tubes.

pyramidal, and conical, both experimentally and numerically. They found the highest specific energy absorption for tubes with circular cross-section. By comparing the polygonal tubes, it was concluded that, energy absorption capacity decreases as the number of corners increases, so that triangular shells were of the lowest energy absorption. Yin et al. [11] optimized energy absorption of tubes filled with honeycomb. They considered triangular, square, pentagonal, hexagonal and circular sections filled with honeycomb cells.

In Refs. [12] and [13], collapse properties of conical absorbers with different cross-section geometries were studied under quasi-static loading. Analysis of collapse behavior of combined-geometry metallic shells with different dimensions and thicknesses under axial impact was done by Gupta et al. [14] who examined capped-end frusta absorbers with hemispherical caps.

El-Sobky et al. [15] investigated collapse mode and energy absorption characteristics of constrained frusta under axial impact loading. They compared their results with those obtained under axial quasi-static loading. Akisanya and Fleck [16] studied plastic collapse of thin-walled frusta and egg-box material under shear and normal quasi-static loadings, both experimentally and numerically. Ghamarian et al. [17] investigated, experimentally and numerically, crashworthiness of empty and foam-filled end-capped conical tubes under axial quasi-static loading and showed better performance of foam-filled end-capped conical tubes.

Kathiresan et al. [18] analyzed, experimentally and numerically, the performance of fiber metal laminated thin conical frusta under axial compression. In another study in 2014 [19], they studied crashworthiness of glass fiber/epoxy laminated thin-walled composite conical frusta under axial compression at different semi-apical angles (15° to 27°). In 2016, Kathiresan and Manisekar [20] investigated crush behaviors and energy absorption characteristics of aluminum and E-glass/epoxy over-wrapped aluminum conical frusta under axial low velocity impact loading.

In some studies, foam was used to improve energy absorption characteristics, such as Ref. [21] wherein dynamic energy absorption characteristics of foam-filled conical tubes under oblique impact loading was studied by Ahmad et al.

The energy absorption characteristics of tapered circular tubes with graded thickness were investigated by Zhang et al. [22]. In ref. [23] single and double wall structures for crashworthiness have been investigated to introduce a novel system with better energy absorption and crushing characteristics under both axial and oblique loading. Crashworthiness performance of conical tubes with various thickness distributions is investigated in [24]; the influences of tube shrinking and thickness distribution on response of the tubes are analyzed. Ref. [25] has examined the crush response and energy absorption of empty and foam-filled conical tubes clamped at both ends under axial and oblique loadings.

Energy absorbers have been under research and development for years, but an optimal absorber with controllable collapse parameters is still needed. Therefore, in this study, a new type of combined energy absorber is introduced that absorbs energy in a dual process. Energy absorption in this type of absorbers occurs with expansion of matrix followed by folding of matrix and mandrel at the same time. In order to discover and investigate features of the new absorber, experimentations and numerical simulations using a finite-element software, namely LS-Dyna, were conducted.

2. Materials and properties

According to Fig. 1, the materials used in the present research included capped-end cones (produced by deep drawing process) and aluminum extruded tubes. The aluminum tubes were annealed to have their ductility enhanced. Undertaking quantometery tests, composition of the steel cone and aluminum pipes materials were determined and shown in Tables 1, 2, respectively. According to the tables, the cones and tubes were made from steel alloy 430 [26] and aluminum alloy 6101 [27], respectively. Height, larger diameter, smaller diameter, and thickness of sample capped-end cones were 70, 60, 36 and 0.2 mm, respectively. Average diameter and shell thickness of the aluminum tubes were 44 and 1.12 mm, respectively. According to Refs. [26,27], steel and aluminum densities were 7800 and 2690 kg/m^3, respectively.

By wire cutting, dumbbell-shaped tension test specimens were separated from the cones and tubes, according to ASTM E8/E8M-09 [28]. Fig. 2 shows dumbbell specimens cut from the conical and cylindrical tubes and how to get the samples in Santam apparatus is also shown.

Table 1
Steel alloy 430, A: composition of steel alloy430 in weight percentages, as defined in Ref. [26], B: quantometery test results.

Element	C	Mn	Si	P	S	Cr	Ni	Fe
A	0.12 Max	1 Max	1 Max	0.04 Max	0.03 Max	16 To 18	0.5 Max	Rem
B	0.06	0.33	0.44	0.02	0.01	16.5	0.11	√

Table 2
Aluminum alloy 6101, A: composition of aluminum alloy in weight percentages, as defined in Ref. [27], B: quantometery test results.

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	B	Others (each)	Others (total)	Al
A	0.3 To 0.7	0.5 Max	0.1 Max	0.03 Max	0.35 To 0.8	0.03 Max	0.1 Max	0.06 Max	0.03 Max	0.1 Max	Rem
B	0.42	0.1	0.02	Trace	0.51	Trace	0.01	< 0.001	√	√	√