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A new bi-tubular conical–circular structure for improving crushing behavior under axial and oblique impacts

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ABSTRACT

In this study single and double wall structures for crashworthiness are investigated to introduce a novel system with better energy absorption and crushing characteristics under both axial and oblique loading. The new developed double wall structure is constructed from inner conical and outer circular tubes, incorporated with and without foam filler. Foam filled bi-tubular structure subject to direct axial and oblique impact loadings are simulated using nonlinear finite element analysis software package LS-DYNA. Numerical simulations obtained via non-linear explicit dynamic FEM are firstly validated using theoretical and experimental solutions. Next, effectiveness of the new developed bi-tubular structure has been shown by comparing with similar common thin-walled structures. Different types of structures namely bi-tubular empty and foam filled new design, empty and filled frusta as well as empty and foam filled circular tubes were considered in order to make a more insightful of capabilities of the proposed structure. A parametric study including the effect of geometrical and material properties of the structure on the crashworthiness has been carried out. Results show the possibility of amending the peak crushing load along with keeping other energy absorption characteristics unchanged or even improved. Also an improvement in absorbed energy under oblique loading by using the new developed structure is observed.

1. Introduction

The use of thin-walled structures as energy absorbent has been recently proven to be an efficient and applicable solution as they offer high values of absorbed energy in spite of their light weight in the automotive, high speed railway and aerospace industries.These crush boxes are made in different geometries, along which circular [1–3], squared [4–6] and conical tubes [7–8] with a variety of materials such as aluminum, steel, compositesas well as use of foam-filler [8–9] has gained a notable interest. To make an inference of energy absorption capacity and measure the effectiveness of these structures, energy absorption per unit mass called specific energy absorption (SEA) and mean crush forceas well as maximum induced load during crushing called peak crushing force (PCF) has been utilized by researchers. Alexander [1] firstly introduced axial crushing of thin walled circular tubes as a mechanism for energy absorption. Furthermore he was able to derive a theoretical solution by assuming perfect plastic material behavior. Ever since numerous attempts have been made by researchers to improve his solution [10–12]. Singace et al. [13] indicated that frusta have a more stable structure compared to cylinders. They also observed that constraining the end of frusta leads to more energy absorption [13]. Improving energy absorption capacity and reducing crushing force and weight of structures is the main object considered by researchers in studying of energy absorbers. Numerous researches have been conducted theoretically, experimentally and numerically in thin-walled structures as energy absorbers. In this regard, Seitzberger et al. [14] studied steel tube with aluminum foam fillers. Hanssen et al. [15] confirmed that by using aluminum foam fillers considerable weight savings are achievable. Foam filling would affect the buckling shape causing tubes to go under more plastic deformation. Hanssen et al. [16] also observed a shift in deformation pattern from diamond to concertina mode for a critical value of foam density. Hanefi et al. [17] tested reinforced compound metal/composite wall and derived an analytical model for it based on Alexander's theory. Xue et al. [18] analyzed flat-topped conical cells made of textile composite and found them in good agreement with both theoretical and experimental solution. Kim [19] proposed new multi-cell profiles base on the idea of adding more square elements would cause in more energy absorption and also investigated effect of different types of triggering. By performing optimization they alsowere able to increase the SEA up to 200% [19]. Zhang et al. [20] introduced patterns to conventional surface of squared tube cross section which led to a new octagonal collapse mode as well as an enhancement of the absorbed energy. Ahmad et al. [21] performed a parametric study on foam-filled

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Nomenclature

A_f	cross section area of the foam
CFE	Crush force efficiency
D_f	frusta's diameter
D_t	circular tube's diameter
d_m	mean diameter
E	Young's modulus
EA	energy absorption
F_x	resultant impact force
F_{mean}	mean load
$F_{initialpeak}$	initial peak force
F^d_{avg}	average dynamic crush force
F^s_{avg}	average static crush force
h_f	frusta'slength
h_t	circular tube's length
k, C	material parameters
k_D	dimensionless constant
N	Poisson's ratio
P	density
SEA	specific energy absorption
t	wall thickness
V	velocity
Vp	plastic coefficient contraction
Y	yield stress
α	semi-epical angle
δ	maximum deflection of the crushed structure
$\hat{\varepsilon}$	equivalent strain
$\dot{\varepsilon}$	plastic strain rate
ε_p	plastic strain
$\alpha_2, \gamma, \varepsilon_D$ and β	material parameters for foam
σ_f	plateau stress
σ_y	yield stress
σ_p	plateau stress of the foam
σ^e	effective Von Mises stress
σ_m	mean stress
σ_t	true stress
ρ_{f0}	density of the foam base material

conical tubes and concluded that foam-filled conical tubes collapse in a stable manner while having more lobes in comparison to empty tubes. Hosseini et al. [22] developed a mathematical model by considering the change in thickness of the frusta and tubes during collapse progressing as well as assuming different values for compressive and tensile strength of the materials and found the results more justifiable with experiments. Ghasemnejad et al. [23] investigated the effect of delamination crack growth of hybrid composite tubes and concluded the ones with higher fracture toughness will absorb more energy in crushing process. As an innovative way to absorb energy, Morris et al. [24,25] loaded circular tube segments transversally. This allows the possibility to reduce the occupied space without compromising the crashworthiness characteristics. Further investigation by Baroutaji et al. [26] showed that exposing these tubes to external constraints will lead to more deformed volume as well as specific energy absorption. Li et al. [27] made a comparison between functionally graded thickness (FGT) tubes and straight and tapered tubes with constant thickness found them in advantage to previous models under oblique loading. Lu et al. [28] introduce double functionally graded tubes by filling FGT tube with functionally graded foams (FGF) and found them to improve energy absorption characteristics without raising the initial peak load.

Recently a great notice has been focused on using multiwall and multicell structures as they have offered a significant step up on absorbed energy [29–31]. Tang et al. [32] investigated multi-cell cylindrical and square columns and inferred that cylindrical columns offer better energy absorption properties. Jusuf et al. [33] performed a comparison between single-walled and double-walled square tubes and improved the double-walled tubes energy absorption efficiency by introducing internal ribs to them. Fang et al. [34] investigated rectangular multi-cell tubes under axial and oblique loading. They concluded that tubes with fewer cells perform better under oblique loading with large angle. Qiu et al. [35] studied multi-cell hexagonal tubes and found that number of corners plays a significant part in improving energy absorption. Borvik et al. [36] investigated empty and foam filled circular tubes under oblique loading for load angles of $\beta = 0, 5, 15, 30$ and found that dramatic reduction in energy absorption occur even for small impact angles. Fang et al. [37] investigated multi-cell square tubes under oblique loading and found that despite their good response under axial loading, global bending occurs for impact angle of 20°. Reyes et al. [38] investigated the crushing behavior of aluminum squared section extrusions under oblique loading both experimentally and numerically, and concluded that energy absorption drops drastically in a small impact angle of 5° and will continue to drop by increasing the impact angle.

While there have been several studies on multi-cell tubes, few studies have investigated the use of bi-tubular structures on crashworthiness parameters. In those studies multi-wall structure with identical thin walls mainly investigated for direct axial loadings [29–31]. So, there exist wide extents of research to optimize the energy absorber structures for different practical applications especially including oblique loadings.

Based on this fact, this paper focuses on combining the existing structures for crashworthiness to introduce a novel system with better energy absorption characteristics under both axial and oblique loading. A double walled structure including a frustum inside of a circular tube, incorporated with and without foam filler.

Empty and foam filled bi-tubular structure subject to direct and oblique axial impacts are simulated using explicit dynamic finite element analysis software LS-DYNA. The numerical simulations were validated using experimental and theoretical solutions presented in appropriate publications.

In order to make a more insightful of capabilities of the proposed structure, a comparison between it and previously existed models has been done. In this regard, different types of structures namely bi-tubular foam Filled (BTF), bi-tubular (BTE), empty and filled frusta (SFE, SFF) and empty and filled circular tubes (ACE, ACF) were considered under oblique impact. In addition a parametric study of new design including effects of geometrical parameters on the structural crashworthiness has been carried out. Obtained results clearly show that the crash ability of the new developed double wall structure is better than the other structures as it achieve a more absorbed energy while the peak crushing force decreases significantly. It is also observed that the empty bi-tubularcircular-conical structure improves the crushing performance considerably in oblique impacts.

2. Description of the new developed bi-tubular structure

The study consists of a new innovative model proposed to offer better energy absorption and comparisons to simpler existing models. Improving crushing behaviors in axial impacts as well as oblique ones has been the motivation to combine circular and conical tubes. This double walled model includes a single frustuminside of a