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Attempts to improve energy absorption characteristics of circular metal tubes subjected to axial loading

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ABSTRACT

In this paper, experimental investigation of two new structural design solutions with the aim of improving crashworthiness characteristics of cylindrical metal tubes is performed. In the first design method, a rigid steel ring is press-fitted on top of circular aluminum tubes. When this arrangement of dissipating energy is subjected to axial compression, the rigid ring is driven into the cylindrical tube and expands its top area; then, plastic folds start shaping along the rest of the tube length as the compression of the structure continues. In the second design method, wide grooves are cut from the outer surface of steel thick-walled circular tubes. In fact, this method converts thick-walled tubes into several thin-walled tubes of shorter length, being assembled together coaxially. When this energy absorbing device is subjected to axial compression, plastic deformation occurs within the space of each wide groove, and thick portions control and stabilize collapsing of the whole structure. In the present study, several specimens of each developed design methods with various geometric parameters are prepared and compressed quasi-statistically. Also, some ordinary tubes of the same size of these specimens are compressed axially to investigate efficiency of the presented structural solutions in energy absorption applications. Experimental results show the significant efficiency of the presented design methods in improving crashworthiness characteristics and collapse modes of circular tubes under axial loading.

1. Introduction

Energy absorbing devices have been extensively used in all vehicles and moving parts such as road vehicle, railway couches, aircraft, ships, lifts and machinery. The aim is to protect these structures from serious damages while subjected to impact load, or to minimize human injuries while collision is occurred in transportation systems. These energy-absorbing devices can dissipate kinetic energy in a wide variety of ways like friction, fracture, plastic bending, crushing, cyclic plastic deformation and metal cutting [1]. Also, various structures like circular and square tubes, octagonal cross-section tubes, spherical shells, frusta, taper tubes, s-shaped tubes, composite tubes, honeycomb cells, foam-filled and wood-filled tubes may be used as collapsible energy absorbers. Amongst them, metallic cylindrical tubes have attracted much more attention due to their high stiffness and strength combined with the low weight and ease of manufacturing process, which leads to the low cost of the energy dissipating device [2,3]. Therefore, several theoretical and experimental investigations have been performed so for to introduce different methods of plastic collapsing in these structures. Axial crushing of tubes between two flat plates, external and internal inversion of tubes against shaped die and axial splitting and curling of cylindrical tubes against canonical dies are the most common energy dissipating methods, which have been realized and studied by several researchers so far [4–10]. However, investigation on progressive folding process of thin-walled structures under axial load has been the subject of the most of these researches.

As a matter of fact, favorable crashworthiness characteristics for energy dissipation purposes can be achieved from axial collapse of tubes while they crush progressively. However, experimental and theoretical results have shown that depending on various parameters such as tube geometry, material properties of tube, boundary and loading conditions, circular tubes buckle in different modes of deformation, namely concertina, diamond and Euler collapsing modes [11–14]. It is shown that when the tube length is greater than the critical length, the tube deforms in overall Euler buckling mode, which is an inefficient mode of energy absorption and needs to be avoided in crashworthiness applications. Different modes of deformation and load–compression curves of round aluminum tubes of various geometric

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Nomenclature

D_i	inside diameter of tube
D_o	outside diameter of tube
d	depth of grooves
d_i	inside diameter of expanding rigid ring
d_o	outside diameter of expanding rigid ring
E_T	total absorbed energy of the shock absorber
L	crushed length of the shock absorber
L_1	length of expanding ring
L_2	length of aluminum tube
N	number of grooves
$P_{\exp}$	mean expansion load
P_m	mean crushing load
$P_{\max}$	maximum crushing load
t	tube wall thickness
W	depth of wide grooves
λ	length of wide grooves
ρ	material density

parameters were studied experimentally by Andrews et al. [14]. An approximate theory to estimate the mean crushing load of cylindrical tube under axial load was presented firstly by Alexander [15]. Jones and Wierzbicki [16–19] have studied dynamic plastic response and instability of various basic structural members, subjected to large axial impact load. The crushing mechanics of thin-walled structures was investigated experimentally and theoretically by Abramowicz [20] and Wierzbicki [21]. On the other hand, the peak reaction force that happens at the beginning of the crushing is much greater than the subsequent peaks, and this is not desirable for energy dissipation purpose.

Responding the high demand for weigh efficient and crashworthy design of moving structures, several investigations with the aim of introducing design methods to increase the length of progressive crushing of thin-walled structures under axial load have been performed. These investigations also aimed to improve the stabilization of the collapse process and to reduce the peak load magnitude at the initial stage of the collapse process.

Lengseth et al. [22] found that pre-buckling of tubes reduce their initial collapse load. In their case, Lengseth et al. [22] applied a preload to impose a pre-buckle and noticed the increase of the total axial deformation compared to an initial straight tube. El-Hage et al. [23] presented a numerical study on the effect of triggering mechanism by chamfering and placing triangular hole pattern near the loaded end of the tube. El-Hage et al. [23] have found that the folding initiation force could be significantly controlled by triggering mechanisms. The effect of triggering dents on the energy absorption capacity of aluminum tubes under quasi static compression was investigated by Lee et al. [24]. The study showed that introduction of dents reduces the first peak load. Marshall and Nurick [25] studied the effects of cylindrical side dents of different diameter. White and Jones [26,27] studied the static and dynamic axial crushing of top-hat structures. In their studies, White and Jones [26,27] investigated the influence of several design parameters on the collapse behavior of thin-walled top-hat and double-hat section structures experimentally and theoretically. With appropriate selection of design parameters, they found that application of top-hat and double-hat sections can improve crashworthiness characteristics of thin-walled structures. Shakeri et al. [28] have introduced the initial geometric imperfection of plastic buckling modes in the post-buckling analysis as a new factor that can extend the concertina collapsing region. In this study, cutting an initial circumferential edge groove outside the tube and using one- and two-circumferential stiffeners have been suggested as two design methods to activate the axisymmetric plastic buckling mode. These two design methods also reduce maximum crushing force significantly. Introduction of circumferential grooves, which are cut alternatively inside and outside of the tube at predetermined intervals, has been shown as an effective solution by Daneshi and Hosseinipour [29] to force the plastic deformation to occur at these predetermined intervals along the tube. It is observed that this method can control collapse shape of thin-walled structures. Cutting a given tubular structure in several portions and coaxially assembling them by separating non-deformable disc is the other suggested method to encourage the axisymmetric mode in axial crushing of tubes, investigated by Abdul-Latif et al. [30]. The energy absorption characteristics of corrugated tubes are also studied in [31]. In this energy dissipating device, corrugations are introduced in the tube to force the plastic deformation to occur at predetermined intervals along the tube length. The aims are to improve the uniformity of the load–displacement behavior of axially crushed tubes, predict and control the collapse mode in each corrugation in order to optimize the energy absorption capacity of the tube. Investigations into the behavior of tapered sheet metal tubes under axial and oblique dynamic loading have been also reported in Refs. [32,33]. These studies show that tapered tubes can withstand oblique impact loads as effectively as axial loads. In the case of vehicular collisions, the height above the road, which is subjected to impact loads, remains reasonably constant but the direction of the acting force line is subjected to change in a horizontal plane. For such situations, tapered tubes of rectangular cross-section with a constant height but increasing width along its axial direction may prove to be advantageous. Several attempts have also been made to improve the energy absorbing capacity of metal tubes by using filler materials such as foams, wood, honeycomb or metals [34–38]. These researches have shown that filling cylindrical tubes with foams eliminates their non-compact crushing behavior under axial loads and significantly help to prevent global bending. Moreover, in comparison with empty tubes of the same size, foam-filled tubes are less affected by external parameters and are more stable while collapsing. A number of investigations on analysis, design and collapse behavior of thin-walled prismatic members subjected to large deformation also have been carried out by Abramowicz and Wierzbicki [39–41]. Recently, expansion of circular metal tubes by rigid tubes under axial compression has been introduced as an efficient method of dissipating energy without any strong sensitivity to loading uniformity [42].

This study develops two design methods with the aim of improving main energy absorption characteristics of circular metal tubes such as sensitivity to external parameters like loading uniformity and direction, crushing stability, crush force efficiency and collapse modes while subjecting to axial compression. Press fitting an expanding rigid ring on top of circular tubes is proved experimentally to be as the first efficient structural solution. In this design method, the rigid ring has the interference of 1 mm with tube and expands it while driving into it as a result of subjecting to axial compression. Then, further compression of the tube leads to formation of plastic folds along the rest of the tube length, not being expanded by rigid ring. This rigid ring controls loading direction at initial stage of compressing the shock absorber, and then directs the plastic collapsing to occur around axisymmetric line of the structure, leading to considerable better