Thin-Walled Structures 124 (2018) 468–488

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Axial crash performance of press-formed open and end-capped cylindrical tubes – A comparative analysis

A. Praveen Kumar[a], M. Nalla Mohamed[a,*], A. Jusuf[b], T. Dirgantara[b], L. Gunawan[b]

[a] Department of Mechanical Engineering, SSN College of Engineering, Chennai, Tamil Nadu, India
[b] Light-Weight Structures Research Group, Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung, Indonesia

ARTICLE INFO

Keywords:
Deceleration pulse
Deep-drawing simulation
End-capped tubes
Forming effects
Initial peak force

ABSTRACT

Thin-walled cylindrical tubes are usually employed as impact energy absorbing members in automotive vehicles due to their high energy absorption capacity through progressive plastic deformation. Despite their superior impact performance, high initial peak force is the crucial problem which has potential to cause serious injury to the occupants. Hence in this study, end-capped cylindrical tubes with reduced initial peak force are proposed as energy absorbing members when subjected to axial static and impact loading conditions. The proposed tubes were fabricated by a multi-stage deep drawing process, that induces forming effects such as thickness variation, and residual stress/strain. Subsequently, numerical simulations were carried out using HyperForm 14.0® and LS-DYNA R-971® with particular attention for the transfer of forming history from deep-drawing simulations to the subsequent crash models. The axial crash performance of the end-capped tubes was also compared with open cylindrical tubes and it was found that the initial peak force of the end-capped tube is significantly reduced by 15–30% than the open cylindrical tube without compromising the energy absorption capacity. The results revealed that end-capped tubes can stabilize the deformation behavior and could be used as a good alternative to the conventional energy absorbing structures in aerospace and automotive applications respectively.

1. Introduction

Recent advances in automotive technology have propelled high speed transportation which increases the probability of collisions and threats to life [1]. Due to the strict safety protocols, development of occupant protection systems is one of the major issues in vehicle design to safeguard occupants from serious injuries. To improve the occupant's safety, a vehicle needs a protective body accompanied with some additional deformable components embedded in the vehicle bumper which can absorb the impact energy during the crash events [2]. In this context, thin-walled tubular structures have proved to be fairly effective and have been widely employed as impact energy absorbers which irreversibly dissipate kinetic energy into permanent plastic deformation [3,4]. Energy absorption capacity, initial peak force, mean crush force and specific energy absorption of the tubes are some of the important crashworthy parameters to be considered while designing the energy absorbers. The pioneer research study by Alexander [5] on thin-walled tubes revealed that material property, configuration of the cross-section, wall thickness, boundary condition, and other factors could affect the deformation response and energy absorption capacity. Lighter and more deformable structural elements have been the most important means for improving crashworthiness. Ductile material like aluminium is one of the most preferred choices due to its excellent energy absorption capacity and considerable light weight [6]. When aluminium alloys are used in the structure of a vehicle, weight reduction to the extent of 25–35% can be achieved when compared to the conventional steel structures [7].

Amongst these factors, the cross-section of a thin-walled tube is the most crucial one on energy absorption capacity during the collision. Extensive research [8–12] have been carried out on the deformation behavior and energy absorption capacity of thin-walled tubes with various sections (cylindrical, conical, square, prismatic, hexagonal, double hat, and frusta). Out of these sections, cylindrical and square shaped tubes have attracted the attention of researchers in the recent decades due to their light weight, high energy absorption capacity and ease of fabrication [13,14]. Despite their superior impact performance, high initial peak force is the major problem which has potential to cause heavy damage to the occupants and the vehicle. A series of experimental, numerical, and theoretical studies have been performed on the axial crushing of simple cylindrical and square tubes with various

* Corresponding author.
E-mail addresses: apraveenkumar@ssn.edu.in (A.P. Kumar), nallamohamedm@ssn.edu.in, nallamohamed@gmail.com (M.N. Mohamed), annisajusuf@ftmd.itb.ac.id (A. Jusuf), tdirgantara@ftmd.itb.ac.id (T. Dirgantara), gun@ftmd.itb.ac.id (L. Gunawan).

https://doi.org/10.1016/j.tws.2017.12.037
Received 17 October 2017; Received in revised form 19 December 2017; Accepted 27 December 2017
0263-8231/

arrangements/configurations such as filling with foam material, adding external or internal stiffeners, using functional graded or variable thickness, and composite hybrid tubes to reduce the initial peak force [15–17]. In this regard, Sun et al. investigated the influence of the number of cells on the crash performance of uniform thickness multi-cell tubes [18] and laterally variable thickness multi-cell tubes [19] subjected to static and impact loading. The results obtained from experiments and numerical simulation revealed that five-cell square tube has reduced the initial peak force in both the cases. Jie song et al. [20] explored the crushing and energy absorption mechanics for Functionally Graded Thickness (FGT) square tubes theoretically,experimentally and numerically. The comparative results demonstrated that FGT tubes could effectively reduce the initial peak force compared to the conventional uniform thickness square tubes. Qiang Liu et al. [21] attempted to improve crashworthiness characteristics of CFRP square tube filled with honeycomb made of aluminium. The outcomes showed that the filled aluminium honeycomb effectively enhanced the stability of progressive deformation during crushing, thereby leading to both hinges symmetrically occurring along the vertical side.

On the other hand, several investigations have been conducted on a simple tube geometry by applying imperfection techniques (triggering methods) such as holes, grooves, corrugation, patterns, and buckling initiator with the aim of reducing the initial peak forces during vehicular collisions [22–24]. For instance, Nalla Mohamed et al. [25] have investigated the effect of grooves on the deformation behavior of thin-walled long tubes subjected to axial compression. The results showed favorable characteristics with the grooved tubes exhibiting lower initial peak forces, more uniform and stable deformation modes with decreased energy absorption capacity. Arameh Eyvazian et al. [26] analyzed the effect of corrugations on the deformation behavior of aluminium cylindrical tubes under axial loading. The results presented in this work confirmed that tubes with corrugations have a uniform load-–displacement curve without an initial peak force, but with reduced energy absorption. Javad Marzbanrad et al. [27] have studied the effect of triggers (rectangular holes) on the deformation behavior of cylindrical tubes. Their studies showed that the triggering is the cause of a significant decrease in the initial peak force level of about 10–15% during collisions.

Overall, the aforementioned techniques can reduce the initial peak force and obtain uniform cum stable deformation responses of cylindrical and square tubes but still, it has a drawback of reduced energy absorption capacity. Therefore, the necessity for further structure optimization has prompted the researchers to experiment with new geometries, configurations and material combinations. The level of deceleration pulse with delayed transfer of impact crush force is also important, while designing an efficient energy absorbing device. The level of the deceleration pulse can be controlled by extending the time period required to dissipate kinetic energy arising as a result of the collision of energy absorber [28]. On this subject, very few studies have investigated the use of end-capped tubular structures to achieve a superior energy absorption performance with a delayed transfer of low-level impact forces. Ali Ghamarian and Mohamed Tahaye Abadi [29] examined the deformation mechanisms and energy absorption capacity during the static crushing of an end-capped cylindrical aluminium tube. Their experimental and numerical investigation results reported that the initial peak force of the end-capped tube is smaller than the non-capped tubes. Hamidreza Zarei et al. [30] performed numerical and experimental quasi-static crush tests on the conical capped tubes manufactured using the spinning process. They studied the influence of geometrical parameters of the tubes on their deformation behavior and highlighted the benefits of using end-capped tubes for impact energy absorption related applications.

Among the various sheet metal forming processes such as deep drawing, extrusion, spinning, and tube hydro forming, deep drawing process is one of the most popular and flexible methods for fabricating the end-capped tubes for crashworthiness applications. Deep drawing is a large deformation process for shaping circular sheets into tube shaped structures without excessive thinning. The deformation behavior of the cylindrical tube was found to be affected by the manufacturing processes, i.e. sheet metal forming or extrusion. Hence, it is essential to consider these manufacturing effects in the crash simulation model to improve the accuracy of the simulation results. Exclusion of these effects in crash model simulations could lead to inaccurate results. Many crash simulation analyses performed earlier [29,30] for estimating the crashworthiness of tubes without considering the forming effects, provided erroneous results in the deformation history and the amount of energy absorbed. Ryou et al. [31] found that neglecting the forming history of a stamped aluminium alloy s-shaped component in a crash simulation led to a peak acceleration prediction that was 20% lower than that of the crash model which accounted for forming effects. With the enhanced insight into the deep drawing process, a four stage deep drawing simulation was performed to form end-capped cylindrical tubes using HyperForm-14.0® and LS-DYNA R-971® to generate various forming histories such as thickness variations, residual stress, and plastic strain.

Hence, the objective of the current study is to investigate the influence of various forming parameters on the axial deformation behavior and crash performance of the open and end-capped cylindrical tubes through static and dynamic numerical simulations. The numerical results obtained were compared with the experimental results in terms of the initial peak force, mean crush force, energy absorption capacity and specific energy absorption. The significant practical outcomes related to the press-formed endcapped tubes highlight the benefits of using end-capped tubes in the automotive industry to design a convenient crash protection system for absorbing impact energy during the vehicular collisions.

2. Material characterization

In this study, the cylindrical tube specimens were fabricated from an aluminium alloy AA6061-O rolled sheets. The aluminium alloy 6061-O was selected due to its common usage in automotive parts and aircraft structures, such as wings and fuselages for crash energy management [32]. A chemical analysis test was conducted as per the ASTM-E1251 standard for confirming the presence of various elements in as-received aluminium sheets. The chemical composition of the tested sample is presented in Table 1.

The anisotropic properties of the selected material were determined using uni-axial tensile test. Dogbone-shaped specimens were prepared based on the ASTM E8M-04 standard from the aluminium sheet in 0°, 45° and 90° with respect to the rolling direction as shown in Fig. 1(a). The experiments were performed in Instron Universal Testing Machine (UTM) under displacement control with a crosshead velocity of 5 mm/min. The tested specimen before and after the test is shown in Fig. 1(b).

Table 2 summarizes the mechanical properties of the aluminium sheet material obtained from the tensile test based on ASTM E-8 standard and anisotropic characteristics acquired as per the ASTM E-517 standard, where E is the Young's modulus, $\mu$is the Poisson's ratio, ρ is the density, σ_y is the yield stress, n is the strain hardening exponent, K is the strength coefficient and R_0, R_{45}, and R_{90} denote the experimental anisotropy coefficients obtained from uniaxial tensile tests at 0°, 45° and 90° with respect to the rolling direction respectively. The data obtained was used for defining the true stress-plastic strain curve during forming and crash simulation in LS-DYNA R-971®.

Table 1
Chemical composition of AA6061-O alloy.

Elements	Si	Fe	Cu	Mg	Zn	Mn	Cr	Ti	Al
Weight (in %)	0.54	0.62	0.15	0.41	0.12	0.065	0.032	0.009	98.05