Engineering Structures 167 (2018) 459–470

Contents lists available at ScienceDirect

Engineering Structures

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

Structural response and performance of hexagonal thin-walled grooved tubes under dynamic impact loading conditions

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ARTICLE INFO

Keywords:
Crashworthiness
Hexagonal grooved tube
Mean crushing force
Finite element
Energy absorption capacity

ABSTRACT

This paper numerically investigates the structural response and crashworthiness performance of a hexagonal thin-walled grooved tube subjected to axial and oblique impact loading conditions. First, an analytical formulation that estimates the mean crushing force and total energy absorption are obtained for both hexagonal and circular tubes subjected to high dynamic impact loading conditions. The solutions of the analytical model are used to verify and compare the approximate solutions of the finite element model. The inclusion of grooves to the conventional hexagonal thin-walled tubes shows the great potential for improving the crashworthiness performance such as the energy absorption capacity, crushing force efficiency and specific energy absorption. In further, parametric studies are performed, deformation modes of different models are obtained and their crushing force-displacement characteristics are described. The improved crashworthiness performance of the hexagonal thin-walled grooved tubes make them good candidate used as energy absorbers.

1. Introduction

The crashworthiness of vehicles in recent years has been a subject of great importance. Increase in fatalities and death of passengers during the incident of vehicular crash have made recent researchers focus on how to improve the crashworthiness performance of energy absorbing thin-walled tubes. These tubes have great potential of converting the high kinetic energy generated during the events of a crash into plastic deformation energy. The efficiency of these crushed tubes to absorb energy is measured by one of the crashworthiness parameters known as the crush force efficiency (CFE). A number of researchers have developed various energy absorbing thin-walled tubes with the aim of increasing the energy absorption capacity [1–5] and consequently increasing the CFE. The energy absorption can be obtained either by experimental testing [6] or by numerical methods [7,8], which is a virtual testing of the experiment. In recent years, crashworthiness application has witnessed unprecedented progress by adopting new techniques in the analysis and optimization of single and multi-cell thin-walled structures. The crashworthiness performance of multi-cell thin-walled structures has been investigated by Wu et al. [9]. Theoretical formulations, finite element simulations and experimental tests were carried out for multi-cell thin-walled tubes to evaluate their crashworthiness characteristics [10]. Researchers have performed some crushing analysis of thin-walled tubes with functionally graded thickness [11]. Also, new variable thicknesses of some typical energy absorbing thin-walled structures have been investigated by Sun et al. [12].

A number of researchers have reported ways to increase the energy absorption capacity by giving attention to the type of material and the geometry of the thin-walled tube [13,14]. Metallic [15,16] or composite [17] materials are commonly used for crash tubes and different geometries have been adopted to investigate their crushing behavior. Moreover, the different geometries of these crushed tubes have been reinforced with foam [18], concrete [19], rings [20] and trigger mechanism [21]. Also, surface designs such as patterns [22], grooves [23] and corrugations [24,25] have been introduced on thin-walled tubes to increase their energy absorption and lower the peak crushing force. Ma and You [26] performed numerical simulations of a square tube with a prefolded origami pattern. In their findings, the patterned tubes gave higher absorption energy and lower peak force than those of the conventional square tubes of identical weights and without patterns. Daneshi and Hosseinipour [27] performed experiments to investigate the energy absorption and mean crushing load of circular thin-walled grooved tubes subjected to axial loading condition. The authors reported that the grooved tubes showed favourable energy absorption characteristics in terms of load uniformity than the tubes without grooves. Also, Singace and El-Sobky [28] investigated the behavior of corrugated tubes when crushed under axial condition. Their results showed improved energy absorption capacity of the corrugated tubes than the non-corrugated ones. Tapered [7,29] and tailored rolled [30,31] structures have also been adopted for crashworthiness application.

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https://doi.org/10.1016/j.engstruct.2018.04.053
Received 3 December 2017; Received in revised form 13 March 2018; Accepted 16 April 2018

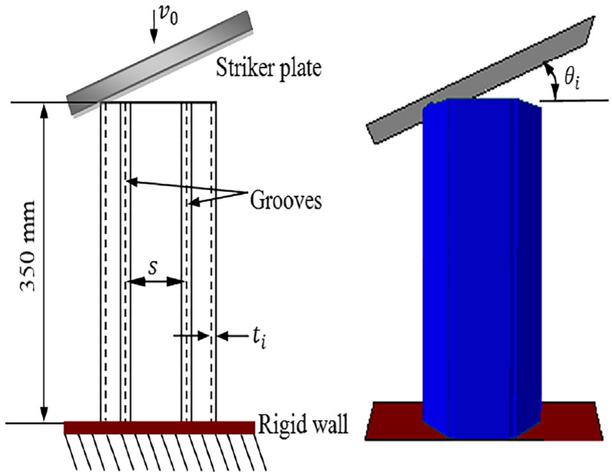

Fig. 1. Schematic of modelled hexagonal thin-walled grooved tube set-up.

Crushed tubes and vehicular crashes are either axially or obliquely impacted and in some cases, both impacts could occur simultaneously. A good number of authors have investigated the quasi-static axial crushing of thin-walled tubes [32,33] and also the dynamic axial impact of these tubes [34,35]. Some authors have also studied the crushing behavior of these energy absorbing tubes under oblique impact loading condition [36,37]; while other authors investigated a combination of axial and oblique impacts loading [38–40]. Investigation showed that during oblique loading condition, the tube is susceptible to bending and the consequence is that it decreases the crashworthiness performance [41]. To reduce this bending vulnerability during oblique impact and to raise the crush force efficiency for improved crashworthiness performance, hexagonal tubes with a grooved surface are studied. Hexagonal foam filled tube with triggered mechanism was investigated by [42]. The authors' findings showed that the energy absorption of this tube competes favorably with the triggered circular thin-walled tube in both loading and perimeter conditions. Moreover, design imperfection can also contribute to the bending tendency of thin-walled tubes.

However, altogether, little is still known of the great potentials of the hexagonal thin-walled grooved tube in terms of its crashworthiness performance over their circular tube counterpart. This study numerically investigates the crashworthiness performance of the axial and oblique impact of hexagonal thin-walled grooved tubes. It further compares the results obtained from the hexagonal thin-walled grooved tubes and those from hexagonal tubes without grooves and circular thin-walled tubes of the same parametric and loading conditions. Crashworthiness parameters such as the energy absorption, mean crushing force (MCF), peak force, specific energy absorption (SEA) and crush force efficiency (CFE) are presented.

2. Structure, materials and method

2.1. Structural description

The hexagonal thin-walled tube used for this study is a surface–like structure with thickness t_i, side $s = 37.5$ mm, perimeter $P = 225$ mm and length $L_0 = 350$ mm. The thickness which is one of the main variables in this study is significantly smaller than the other two dimensions. Grooves of radius $r = 3$ mm are modelled to run axially from the impacting end to the wall end of each side of the tube as shown in Fig. 1. The tube has a high plastic behavior which makes it an excellent material used for energy absorbing purpose. High dynamic impact velocity predisposes the tube to bending. However, the introduction of grooves to the hexagonal thin-walled tube reduces the bending tendency and allows all wall materials in the tube to fully participate in the energy absorption during the plastic deformation process. The thin-walled grooved tube can be manufactured using the roll grooving technique. First, a hexagonal tube is positioned such that an upper roll runs along the crushing in or flow in direction of each side of the tube. During this rolling process, the material at each side of the tube is made to displace inward, hence, creating the groove by cold forming operation. This operation ensures that no part of the thin-walled grooved material is removed and therefore, retaining the same original mass before it was grooved. However, after the complete deformation process, the crushed mass of the grooved tube is slightly lower than the original mass of the grooved tube.

2.2. Problem description

The model consists of a striker plate of mass $m = 350$ kg moving with a velocity $v_0 = 15.56$ m/s and impacting a thin-walled tube fixed to a rigid wall. The impact velocity is in accordance with the speed requirement of the National Highway Traffic Safety Administration (NHTSA) New Car Assessment Program (NCAP) [43]. The mass of the striker plate used for this study is 31.82% of 1100 kg mass of a compact car. The rationale for selecting this value is to ensure that inertial effect is negligible, therefore, making the mass of the tube to be far much lower than the mass of the striker plate. It was shown by [20] that a reduction in the value of the striker mass with increase in velocity increases the inertial effect. The effect of inertial causes deformation to develop over the entire length of the tube, therefore, allowing the tube to absorb more energy during its initial deformation. First, for the idealized tubes, the circular tube is designated as A-CIR while the hexagonal tube is designated as A-HEX. Table 1 shows the different tube profiles, dimensions and impact conditions adopted for the finite element simulations. For the purpose of comparison and verification, the same tube dimensions and impact conditions used in the finite element simulations are also used for obtaining the analytical results. In the finite element simulations, three different thin-walled tube profiles namely, hex-grooved, hexagonal and circular are considered and their crashworthiness performances are compared. The hex-grooved profile is a hexagonal thin-walled tube with grooves which is identified as HGT. The hexagonal profile is a hexagonal thin-walled tube without groove, it is identified as HTT. Lastly, the circular profile is a circular thin-walled tube without groove and is identified as CTT. In Table 1, five different tube thicknesses ranging from 1.6 mm to 2.5 mm were adopted for the simulation. For all the tube configurations, the perimeter of the cross-section (225 mm) and the length (350 mm) of the tube profiles were made constant. Various impacting angles ranging from 0° to 30° at intervals of 10° were used. The 0° impacting angle indicates the axial impact loading condition while the 10°, 20° and 30° impacting angles indicate the oblique impact loading condition.

Table 1
Designation, dimensions and angle of impacts used for study.

Tube profile	Tube length (mm)	Tube perimeter (mm)	Model identification	Impacting angle (degree)				Tube thickness (mm)				
				θ_0	θ_1	θ_2	θ_3	t_1	t_2	t_3	t_4	t_5
Hex-grooved	350	225	HGT	0	10	20	30	1.6	1.8	2.0	2.2	2.5
Hexagonal	350	225	HTT	0	10	20	30	1.6	1.8	2.0	2.2	2.5
Circular	350	225	CTT	0	10	20	30	1.6	1.8	2.0	2.2	2.5