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Technical note

Quasi-static axial crushing behaviour and energy absorption of novel metal rope crochet-sintered mesh tubes

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ABSTRACT

This paper presents a novel reinforcement structure for composite tubes, i.e. crochet-sintered mesh tube (CSMT), for energy absorption applications. The CSMTs are fabricated by crocheting, followed by swelling and vacuum solid-phase sintering of super-fine soft 304 stainless steel wire rope twisted with 49 steel wires. This study focuses on their quasi-static crushing response and energy absorption, and investigates the influence of tube diameter and length on these characteristics. Unlike the dense structure of thin-walled metal tubes used at present, the CSMTs have a special porous structure characterised by inter-crocheting and multiple inter-locking rope skeletons and metallurgical bonds. The crushing deformation exhibits progressive folding with collapse of the mesh pores and densification, without fracture under large plastic deformation, and with rope skeleton stretching, bending, twisting and warping. The diameter and length of the CSMTs have a significant effect on the crushing mode and stability. With the same length, the larger the diameter, the better is the stability; the larger the ESR (effective stroke ratio), the higher are the SEA (specific energy absorption) and CFE (crushing force efficiency). With the same diameter, the greater the length, the weaker is the stability; the smaller the ESR, the lower are the SEA and CFE. The CSMT3 with 40 mm length and 35 mm diameter shows the best deformation stability, an ESR of 0.59, and an SEA of 1114.7 J/kg. The CSMT5 with 65 mm length and 35 mm diameter presents the lowest ESR (0.44) and SEA (592.3 J/kg). The CFE values of all the CSMTs are very high and lie in the range of 0.7–1.0. There is no significant initial impact effect. The CSMTs' lightweight, porous, and continuous wire structure, their long and stable plastic platform, and their collapsing deformation and high crushing force efficiency make them suitable for applications related to energy absorption components. The CSMTs may be used as a new reinforcement structure in composite tubes, and play an important role in the development of the novel structure of thin-walled metal tubes for energy absorbing components.

1. Introduction

Energy absorption materials and structures, such as aluminium foams [1,2] and honeycombs [3,4], porous metal fibre/wire materials [5–7], natural fibre materials [8,9], hollow metal spheres [10], thin-walled metal tubes [11,12], and composite tubes [13], are widely used to dissipate energy during the collision of vehicles such as automobiles, trains, helicopters and ships. The important issues related to the practical application of energy absorption materials are crashworthiness, energy absorbing and transforming mainly by plastic deformation, viscous dissipation, and friction or fracture during large deformation of materials and structures. While thin-walled metal tubes are the most traditional lightweight energy absorption components, they are also the most effective anti-collision structures because of their smart and simple structure, superior rigidity, stable deformation, high energy absorption efficiency, good workability and low cost. They have attracted considerable attention for several years because of their practical applications for impact resistant and energy absorbing materials.

The thin-walled metal tubes are produced mainly from aluminium alloys, mild steel and a few stainless steels. They have been investigated from different perspectives, such as single tubes, multi-celled thin-walled prismatic tubes, and composite structures.

Numerous studies on the energy absorption of a single tube have analysed the effect of various cross-sections of thin-walled tubes on crashworthiness. Apart from the circular and square tubes, the odd-sided straight tubes such as triangular and pentagonal tubes, the even-

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sided straight tubes such as hexagonal and octagonal tubes, the 12-sided and 16-sided star tubes, and taper tubes have also attracted the attention of researchers [14–17]. All these tubes show their distinctive features during axial progressive crushing, and their cross-sectional shape greatly affects their energy absorption capacities. The circular tubes show better specific energy absorption and mean crushing force. Polygon tubes with fewer sides show low energy absorption capacity. Compared with cylindrical tubes, tapered pipes have better energy absorption efficiency and stable load-displacement curve. Erdin et al. [18], Li et al. [19], Zhang et al. [20] and Fang et al. [21] experimentally and numerically investigated the crushing energy absorption of transversely and longitudinally graded tubes. The gradient parameters and direction play critical roles in determining the initial peak force and specific energy absorption (SEA). Gradient tubes can effectively integrate a low initial crushing peak and a high SEA. The initial crushing peak is a very large initial force much higher than the average compressive force. A high initial peak force is a drawback of metal tubes used in anti-collision absorption applications. To optimise the buffering and energy absorption capacities of tubular structures, the initial peak force must be reduced. Several methods of introducing initial geometric imperfections in tubes to reduce the initial peak force have been studied. Some of the methods used are making a rectangular groove along the internal and external surfaces of the tubes (Wei et al. [22] and Rezvani et al. [23–26]), drilling holes on the tube wall in the axial direction (Taştan et al. [27]), fabricating thin-walled structures with origami patterns (Song et al. [28]), and fabricating cylinder tubes stiffened with annular rings and initiators (Rezvani et al. [29]). For example, Rezvani and his team [23–26] conducted several studies on the crashworthiness of the thin-walled grooved conical tube and its bitubal and polyurethane foam-filled structure through a systematic combined response surface method, finite element analysis, and multi-criteria decision-making technique [24]. The results revealed that the thickness of the tube, groove depth, distance between the grooves, taper angle and foam density affect the energy absorption. Compared to the conical simple tube, the efficiency of crush force of the conical segmented tube increased by 23.8%; the initial peak load and mass decreased by 54% and 17.54%, respectively [25]. The bitubal grooved tubes as per new innovation can help achieve a structure with improved crashworthiness in a collision [26]. The positive effects of such initial geometric imperfections are, they can decrease the weight of the tubular structure, initiate a specific axial collapse mode, stabilise the collapse process, and reduce the peak load [22,30,31]. However, the negative effects of those are, they can reduce the stiffness and load-bearing capacity of the tubular structures and particularly weaken the radial stiffness and lateral or oblique impact resistance significantly.

Several studies have also been conducted on the energy absorption of multi-cell thin-walled prismatic tubes. Triangular, square, hexagonal and octagonal tubes were equally divided into two, three, four, nine, or sixteen sections with thick aluminium sheets. It was found that the energy absorption capacity of the multi-cell sections was greater than that of simple sections. The SEA values for the hexagonal and octagonal geometries were approximately 120% and 118% greater, respectively, than the SEA values for the simple triangular geometry. The energy absorption efficiencies of the square tubes that were divided into four, twelve and sixteen sections were approximately 50–100% greater than those of the foam-filled thin-walled single tubes [32–34]. Tapered tubes [35], "8"-shaped tubes [36], and internally nested multi-cell tubes [37] have been investigated using experimental and numerical methods to improve their energy absorption performance.

The energy absorption properties of composite structures have also been studied. Composites of metal tubes and carbon fibre reinforced polymer (CFRP) [38–40], glass/epoxy composites [41,42] and combinations of metal tubes [43–45] have more stable crushing process, smaller load fluctuation, and better energy absorption capacity than single metal tube because of the interaction between the two materials in the tubes. Metal tubes filled up with lightweight materials such as aluminium foam [46–48], aluminium honeycomb [36] and hollow metal spheres [49] have good energy absorption ability. Much of the research in the literature shows that a greater number of folds are formed during the crushing process because of the interaction between the porous fillers and the thin-walled metal tubes. In recent years, composite tubes of natural fibres, such as hemp, kenaf, jute, ramie and silk, have been attracting a growing interest, because natural fibres have some special advantages such as renewability, biodegradability and low cost [8,9,50–54].

In addition, Gracianoa et al. [55] and Martíneza et al. [56] proposed a unique energy absorption structure, i.e. expanded metal tube, which absorbs energy by combining the collapsing of pores with plastic deformation of the skeleton.

Literature survey clearly shows that numerous studies have been conducted to thoroughly and comprehensively study the energy absorption characteristics of thin-walled metal tubes using experimental, numerical and analytical approaches [57]. Using composite structure is an effective method of improving the energy absorption of the tubes. There has been a great need for developing new filler materials or using existing materials in innovative ways to fill tubes that are lightweight, do not crash under large plastic crushing deformation, and show good energy absorption in impact or crash scenarios. Such a filler material, when composited with a thin-walled metal tube, would result in a composite structure having enhanced energy absorption similar to that of aluminium foam-filled tubes, and its initial crushing peak would not be high. This would result in a rigid structure that effectively integrates the ideal properties of being lightweight, having good energy absorption, and showing a low initial peak. The concept of porous metal fibre/wire materials is borrowed from natural and carbon fibres composited with thin-walled metal tubes to improve anti-collision property and energy absorption capacity. Wire as a raw material offers several benefits such as high strength, good toughness, minimal defects and low cost. Further, wire-based products are well developed for various classical textile manufacturing processes. Porous metal fibre/wire materials such as porous sintered fibre/wire materials [5,58], entangled fibre/wire materials [6] and wire-woven cellular metals [7,59,60] have good energy absorption properties and large plastic deformation capacity. Kang et al. [7] demonstrated strucwire® crash elements integrated in the buffer bar of a car. The crash elements were designed to protect passengers and drivers from crash impact through the high energy absorption ability of the wire-woven metal during compressive deformation.

In this paper, novel crochet-sintered mesh tubes (CSMTs) are presented. Literature survey shows that the research on crashworthiness of thin-walled tubes has undergone changes in the area of focus from single tubes to multi-celled tubes, and then to composite tubes. Most of the studies have investigated circular tubes and their composite structures, and then studied tubes with other section shapes. In addition, Nia et al. [15] has investigated the deformations and energy absorption capacities of thin-walled tubes with circular, square, rectangular, hexagonal, triangular, pyramidal, and conical section shapes through experiments and numerical simulation under quasi-static axial loading. The results show that the section geometry has a significant effect on energy absorption, and that the circular tube has the highest energy absorption capacity and the largest average force among the above sections. Hence, the CSMT with circular shape has been chosen as the research object in this study. The CSMTs are fabricated by crocheting and subsequent swelling, and vacuum solid-phase sintering of superfine soft 304 stainless steel wire rope. The axial crushing and energy absorption of the CSMTs under compressive loading are investigated. The effects of tube diameter and length on crushing mode and energy absorption are investigated. This work is valuable for providing a new method of preparing composite metal-fibre tubes having improved crashworthiness and energy absorption capacity. It is expected that the results of this research will contribute to further investigation of crashworthiness and energy absorption of laminated composite