Thin–Walled Structures 110 (2017) 97–105

Contents lists available at ScienceDirect

Thin–Walled Structures

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

Full length article

Low velocity impact of empty and foam filled circumferentially grooved thick-walled circular tubes

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ARTICLE INFO

Keywords:
Energy absorption
Collapse mode
Thick-walled tubes
Circumferential grooves
Low velocity impact
Foam filled

ABSTRACT

In this work, the energy absorption and collapse mode of circumferentially grooved thick-walled tubes are scrutinized analytically and experimentally under dynamic loading condition. Circumferential grooves are machined around thick-walled tubes and thin-walled portions are acquired within the groove spaces. Low velocity impact tests of the specimens are conducted using the drop hammer rig. An analytical formulation based on the energy dissipation through the plastic hinges is presented and the effect of strain rate is incorporated into the equations by implementing the Cowper-Symonds constitutive equation. In the case of foam filled tubes, the interaction at the interface of foam and tube is taken into account. Comparison of the analytical results with experimental ones shows reasonable accuracy for the analytical model. According to the experiments, circumferentially grooved tubes show favorable energy absorption behaviour and concertina mode of deformation is dominant under dynamic loading condition. Foam filled tubes show an approximately 26% increase in the energy absorption compared to empty tubes which is much lower than in the case of quasi-static loading condition. This shows that foam filling in dynamic loading, though effective from the energy absorption perspective, is not as effective as in the case of quasi-static loading.

1. Introduction

Within the few past decades and together with the evolution of many various engineering fields and applications, the need to improve the reliability and safety of the structures resulted in a great deal of research being conducted on the energy absorbing elements. These energy absorbers should be capable of deforming to the maximum extent in a stable manner to absorb the highest amount of energy. Thus, prevention from the Euler buckling which is considered not to be stable and efficient from the view point of energy absorption is favorable. Therefore, the investigation of energy absorbers initiated by Alexander's theoretical model for the axial compression of thin-walled circular tubes in 1960 [1] was gradually directed to the classification of modes of deformation, transition from one mode to another and the methods to control the mode of deformation in a way to achieve a stable and efficient energy absorber. Andrews et al. [2] performed numerous experiments on the quasi-static axial collapse of cylindrical tubes and categorized the modes of deformation with respect to wall thickness to diameter and tube length to diameter ratios. Abramowicz and Jones [3–5] carried out several experiments on circular and square tubes under static and dynamic loading conditions. They also presented a modification of Alexander's theoretical model. Some experiments were conducted on different geometries such as cylindrical, pyramidal, square, rectangular, triangular, hexagonal and frusta by Alavi Nia et al. [6] the results of which showed that circular tubes have the most energy absorption capacity and average force among all sections. Abramowicz and Jones studied transition from initial global bending to progressive buckling of square and circular tubes loaded statically and dynamically [7]. Fyllingen et al. investigated the same topic for aluminum square tubes [8]. In 1986, in an attempt to control the mode of deformation, Mamalis et al. [9,10] investigated thin-walled grooved tubes quasi-statically and observed diamond mode of deformation. They cut grooves just on the outer surface of the tubes; however, Hosseinipour et al. [11,12] cut grooves alternately on inner and outer surfaces of the tubes and investigated the collapse modes. It was concluded that grooved tubes show favorable energy absorption characteristics. Another type of grooved tubes, thick-walled circular tubes with wide circumferential grooves, was investigated experimentally, numerically and analytically by Mokhtarnezhad et al. [13]. They concluded that cutting wide circumferential grooves is an efficient and reliable method to improve crashworthiness characteristics. Two new design methods were suggested by Salehghaffari et al. to improve

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http://dx.doi.org/10.1016/j.tws.2016.09.002
Received 27 February 2016; Received in revised form 25 August 2016; Accepted 2 September 2016
0263-8231/

Nomenclature

L	length of the tube
D_o	outside diameter
D_i	inside diameter
t	wall thickness in grooved parts
λ	length of the grooves
l	half length of the grooves
w	length of the shoulders (thick parts)
d	depth of grooves
$\overline{D}$	mean diameter
$\overline{R}$	mean radius
R_i	inner radius
θ	bending angle
ε	strain
σ_0	flow stress of the tube material
σ_P	plateau stress of the foam
M_0	plastic bending moment per unit length
W_{str}	stretching energy between hinges
$W_{1,2,3}$	energy absorbed in hinges
V_0	impact velocity
δ_e	effective crushing distance
Z	number of grooves
N	number of shoulders

crashworthiness characteristics of cylindrical metal tubes under quasi-static loading condition [14]. They press fitted a rigid steel ring on top of circular aluminum tubes as the first design method. As the second design method, wide grooves were cut from the outer surface of steel thick-walled circular tubes. They concluded that their presented design methods are efficient in improving crashworthiness characteristics and collapse modes of circular tubes under axial loading. In another work, Salehghaffari et al. numerically investigated the quasi-static axial collapse response of cylindrical tubes which are externally stiffened by multiple identical rings [15]. Single- and multi-objective optimization was performed and optimum designs for different response characteristics were found. They concluded that progressive collapse or buckling is dependent on the ratio of stiffener spacing to stiffener height as well as the ratio of wall thickness to stiffener thickness. According to their optimization results, the effectiveness of externally stiffened tubes as energy absorbers is proved.

Besides cutting grooves, foam filling is proved to be efficient in increasing the energy absorption and in improving the stability of the tubes and numerous investigations have been made into their effect. Reid et al. [16] examined static and dynamic axial crushing of thin-walled square and rectangular foam filled tubes. Progressive folding of foam filled prismatic columns was investigated by Abramowicz and Wierzbicki [17]. Seitzberger et al. [18] studied the crushing of axially compressed steel tubes of square and circular cross sections filled with aluminum foam. The effect of low density filler material, such as aluminum honeycomb or foam, on the axial crushing resistance of a square box column under quasi-static loading condition was investigated by Santosa et al. [19]. So as to study the effects of different tube and filler arrangements on the crushing behaviour of axially compressed tubular crush elements, Seitzberger et al. performed quasi-static experiments on monotubal and bitubal, empty and filled steel profiles with different materials, dimensions and cross-sectional shapes [20]. Mantena et al. analyzed the impact and dynamic response of high-density structural foams used as filler inside circular steel tube [21]. Hanssen et al. carried out an experimental programme consisting of 96 tests to study the axial deformation behaviour of triggered, circular AA6060 aluminum extrusions filled with aluminum foam under both quasi-static and dynamic loading conditions [22]. Thin-walled cylindrical shells filled with hollow foam were analytically modeled by Ye et al. [23]. The energy absorption in a foam-filled thin-walled aluminum tube was investigated based on experimentally determined strengthening coefficient by Kavi et al. [24]. Ref. [18] reported a 40–60% increase in the energy absorption due to foam filling. Aktay et al. [25] investigated polystyrene foam filled thin-walled aluminum tubes experimentally and numerically under quasi-static loading condition and reported 21% increase in the energy absorption due to foam filling. Ref. [19] reported 80% and Ref. [20] reported 30–60% increase in the energy absorption as a result of foam filling.

Therefore, forming grooves and foam filling proved to be suitable solutions for improving crashworthiness characteristics. Investigating the effect of both had not been performed and; thus, the authors in their previous works examined the energy absorption of empty and foam filled grooved tubes experimentally and analytically under quasi-static loading condition [26,27]. Generally, concertina mode of deformation or twisted concertina for some specimens was observed and the energy absorption was increased approximately twice that of the empty tubes in the case of foam filling. It is worth noting that a type of foam with low density and very low strength (3 kPa) was used and approximately 90% increase in the energy absorption was an interesting finding as well.

To the authors' knowledge neither thick-walled tubes with circumferential grooves, nor foam filled ones had been studied dynamically except for only 2 empty specimens by [28]. Therefore, the authors decided to further extend their previous works and designed a set of experiments using the Taguchi method so as not to pick up the geometrical parameters of the specimens randomly. The present work is aimed at extending the previous works to the dynamic loading condition for both empty and foam filled thick-walled tubes with circumferential grooves. The analytical model is modified to take the

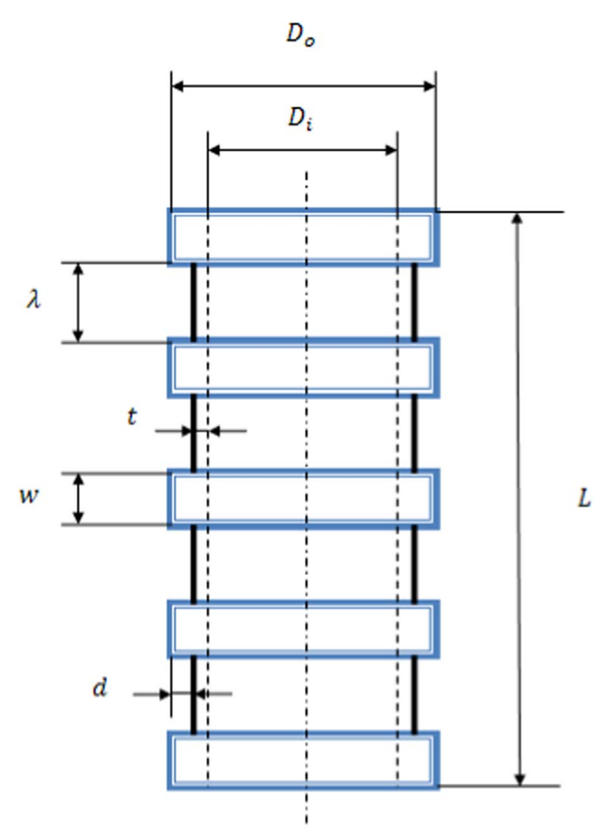

Fig. 1. Schematic of the specimens.