Thin-Walled Structures 98 (2016) 337–350

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Quasi-static, impact and energy absorption of internally nested tubes subjected to lateral loading

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ARTICLE INFO

Article history:
Received 22 May 2015
Received in revised form
14 September 2015
Accepted 2 October 2015
Available online 20 October 2015

Keywords:
Nested tubes
Energy absorbing systems
Lateral collapse
ANSYS-LSDYNA
Quasi-static loading
Dynamic loading

ABSTRACT

This paper presents the responses of nested tube systems under quasi-static and dynamic lateral loading. Nested systems in the form of short internally stacked tubes were proposed as energy absorbing structures for applications that have limited crush zones. Three configurations of nested tube systems were experimentally analysed in this paper. The crush behaviour and energy absorbing responses of these systems under various loading conditions were presented and discussed. It was found that the quasi-static and dynamic responses of the nested systems were comparable under an experimental velocity of $v=4.5$ m/sec. This is due to insignificant strain rate and inertia effects of the nested systems under the applied velocity.

The performance indicators, which describe the effectiveness of energy absorbing systems, were calculated to compare the various nested systems and the best system was identified.

Furthermore, the effects of geometrical and loading parameters on the responses of the best nested tube system were explored via performing parametric analysis.

The parametric study was performed using validated finite element models. The outcome of this parametric study was full detailed design guidelines for such nested tube energy absorbing structures.

1. Introduction

The function of energy absorbing structures is to minimise injuries to human beings and to protect vital structures from impact damage or any other dynamic loads. The design and development of these systems require study and understanding of materials engineering, structural mechanics, impact mechanics, and the theory of plasticity. The behaviour and response of energy absorption structures under dynamic loadings such as the impact loading, is considered to be a very important field for design and research engineers who are involved in the automobile, aircraft, spacecraft, and nuclear industries. Thin-walled tubes of different geometry and materials are commonly used to absorb kinetic energy through plastic material deformation. Over the last four decades, a significant amount of research has been conducted on the energy dissipated by thin-walled tubes. The main findings were outlined and presented in a review article by Olabi et al. [1], Alghamdi [2], and Abramowicz [3]. General information and discussion about energy absorption structures and materials can be found in books by Lu and Yu [4] and Jones [5].

Many applications employ thin walled tubes as energy absorption devices such as thin walled tubes at the front of passenger trains and vehicles, aircraft sub floor structures, and thin-walled tubes at the base of lift shafts.

Thin-walled tubes can absorb kinetic energy as a result of many types of deformation, leading to various energy absorption responses. The principle ways of destroying tubes include lateral compression [6–17], lateral indentation [18–27], axial crushing [28–37], tube inversion [38,39], and tube splitting [40–45].

The axially loaded tubes have been widely used as energy absorbing devices and have received considerable amount of attention due to the fact that these structures have high energy absorbing capacities and stroke length per unit mass. In spite of these superb features, the axially crushed structures still experience certain drawbacks, such as very large fluctuations of the collapse load about a mean load, and the unstable deformation mode termed as global bending deformation mode which restrict their use in all energy absorption applications.

The energy absorbing capacity of laterally flattened tubes was found to be greater than that of lateral indentation, but not as much as for axial crushing.

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http://dx.doi.org/10.1016/j.tws.2015.10.001
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Laterally loaded tubes have a distinct advantage over tubes compressed axially due to fact that the bending collapse mode generated from lateral loading result in a smooth force-deflection response. Also, the laterally loaded tubes do not undergo any kind of unstable deformation mode even under the off-axis loading. However, the deformation mode of these structures is plastic bending at plastic hinges. This deformation mode results in plastic strains localisation around the plastic hinges and makes the dissipation of energy through the lateral collapse inefficient.

Therefore, to overcome the aforementioned drawback and to enhance the energy absorbing capacity of single empty tubes, foam-filled components [46–48] and nested tube systems have [49–53] been proposed.

Much of the research on the laterally crushed energy absorbers has focused on those which are empty or foam filled components. However, the nested tube systems, which consist of more than one component, have received less attention.

In the present study, nested tube systems using internally stacked groups of circular and oblong tubes have been proposed as energy absorbers. These systems are of particular importance for applications that are restricted in terms of space and with a limited crush zone. Three different configurations were analysed, all of which had deformable tubes arranged so that they deformed synchronously upon loading, in order to achieve the desirable force-deflection response. The quasi-static and dynamic responses of these systems were investigated. A series of experiments were carried out by using Instron instrument for the quasi-static loading and Zwick Roell machine for the dynamic loading. The effect of geometrical and loading parameters on the energy absorption behaviour and deformation modes of these systems was examined numerically by using finite element analysis.

2. Experimental work

2.1. Material properties and specimens

Mild steel tubes were used for manufacturing the samples. The tubes were drawn over a mandrel (DOM), cold finished and manufactured according to the DIN standards, DIN 2393 ST 37.2. The chemical composition of the steel used in this work is displayed in Table 1. Tensile tests were carried out in order to determine the mechanical properties of the tubes as shown in Fig. 1. Dog bone samples (tensile samples) were prepared by flattening the tube and cutting the specimens. Fig. 1 displays the true stress–strain curves of the tensile sample. Upon examination of this figure, it can be seen that the stress–strain curve displays unusual behaviour in which strain softening occurred almost immediately after yielding with no evidence of strain hardening. This phenomenon is due to sample necking which takes place immediately after yielding. This behaviour is termed tension instability and the cold rolling process might be the reason for this. In addition, the method of preparing tensile samples might also have an effect on the stress–strain behaviour of the tensile sample.

Table 2 shows the mechanical properties of the mild steel material derived from the true stress–strain curve. The yield stress is validated according to DIN standards, which state that the yield stress of this material is within the range of 450–525 MPa [51,52].

Table 3 summarizes the geometry profiles and the dimensions of all nested tube systems used in this work.

Table 1
Chemical composition of steel tubes (obtained from supplier).

	C % (max)	*Si % (max)*	*Mn % (max)*	*P % (max)*	*S %*
DIN 2393 ST 37.2	0.17	0.35	0.7	0.05	0.05

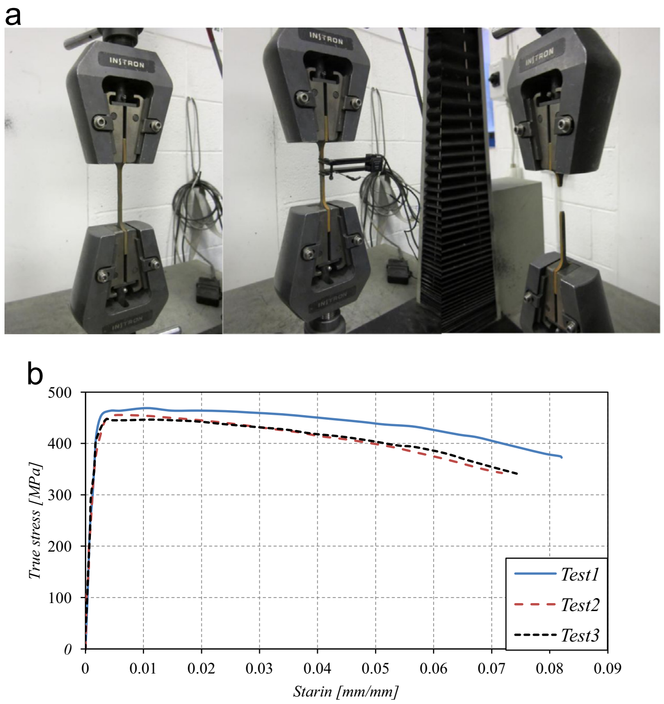

Fig. 1. (a)The tensile test set-up. (b)True stress–strain curves obtained from three tensile tests.

Table 2
Material properties of empty and nested tubes.

	Density (kg/m3)	*Young's modulus (GPa)*	*Poisson's ratio*	*Yield strength Rp0.2 (MPa)*
DIN 2393-ST 37.2	7861	200	0.3	470

2.2. Experimental set-up

For the quasi-static loading, The Instron Model 4204 testing machine was used to perform the quasi-static experiments on the respective specimens. The loading frame comprises of two vertical lead screws, a moving crosshead and an upper and a lower bearing plate. The maximum capacity of this loading frame is 50 kN. The loading force is measured by a loading cell which is attached to the moving crosshead of the loading frame. This load cell is comprised of multi strain gauges. The gauges are connected as a Wheatstone bridge, so any unbalance in this bridge is recorded as voltage. This voltage is then used to indicate the amount of force applied to the samples. A CPU is used as control unit to control movement of the crosshead. This control unit also provides the data acquisition and data readout from the loading frame. Instron 4204 series software is integrated to display the results. Many parameters such as displacement, load, strain and energy can be obtained. A prescribed velocity of 10 mm/min was applied to the moving crosshead of the instrument to ensure that there were no dynamic effects. Many researchers [47,48] used velocities between 0.5 and 15 mm/min in the quasi-static lateral compression tests. The quasi-static test set-up for the nested tube sample is shown schematically in Fig. 2.

The Impact testing of the various samples was conducted using the Zwick Roell 5HV series (Fig. 3). The load-time response, during the impact event, was captured by using a Kistler 9091 series piezoelectric force transducer which has a maximum load capacity of 250 kN. The transducer was mounted on the moving carriage