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Quasi-static response and multi-objective crashworthiness optimization of oblong tube under lateral loading

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ABSTRACT

This paper addresses the energy absorption responses and crashworthiness optimization of thin-walled oblong tubes under quasi-static lateral loading. The oblong tubes were experimentally compressed using three various forms of indenters named as the flat plate, cylindrical and a point load indenter. The oblong tubes were subjected to inclined and vertical constraints to increase the energy absorption capacity of these structures. The variation in responses due to these indenters and external constraints were demonstrated. Various indicators which describe the effectiveness of energy absorbing systems were used as a marker to compare the various systems. It was found that unconstrained oblong tube (FIU) exhibited an almost ideal response when a flat plate indenter was used. The design information for such oblong tubes as energy absorbers can be generated through performing parametric study. To this end, the response surface methodology (RSM) for the design of experiments (DOE) was employed along with finite element modeling (FEM) to explore the effects of geometrical parameters on the responses of oblong tubes and to construct models for the specific energy absorption capacity (SEA) and collapse load (*F*) as functions of geometrical parameters. The FE model of the oblong tube was constructed and experimentally calibrated. In addition, based on the developed models of the SEA and *F*, multi-objective optimization design (MOD) of the oblong tube system is carried out by adopting a desirability approach to achieve maximum SEA capacity and minimum *F*. It is found that the optimal design of FIU can be achieved if the tube diameter and tube width are set at their minimum limits and the maximum tube thickness is chosen.

1. Introduction

Tubular systems which consist of one or more circular or square sectioned tubes are commonly used to absorb kinetic energy through plastic deformation.

These structural elements can absorb kinetic energy from many types of deformation leading to various energy absorption responses. The principle deformation mechanisms of tube include lateral compression, lateral indentation, axial crushing, tube splitting, and tube inversion. A significant amount of research has been conducted on the energy dissipated by tubular systems over the last three decades. The main findings were outlined and presented in a research article by Olabi et al. [1] and Alghamdi [2].

The lateral compression of circular tube were analyzed by DeRuntz and Hodge [3], flat plate indenter was used to compress the tubes. The authors used rigid perfectly plastic material model to predict the force–deflection response of the tube. They found that the collapse load is affected by the geometrical factors and material properties of the tube. Reid and Reddy [4] performed further investigations on strain hardening effects. They developed an accurate material model which considered both geometric and material strain hardening effects. The authors reported that the energy absorbing capacity can be maximized by choosing appropriate tube dimensions.

Gupta et al. [5] examined numerically and experimentally the lateral crushing of circular metallic tubes under quasi-static conditions. Aluminum and mild steel tubes with different diameter to thickness ratios were used in this investigation. The authors found that the energy absorbing capacity and mean collapse load increases with increase in thickness and decrease in diameter.

Increasing the energy absorption capacity of the tubular system by means of external constraints was applied by Reddy and Reid [6]. The authors built a tubular system with side constraints in which the horizontal diameter of the tube was prevented from

Abbreviations: FIU, flat plate indenter-unconstrained system; FISC, flat plate indenter-side constraints system; FIIC, flat plate indenter-inclined constraints system; CIU, cylindrical indenter-unconstrained system; CISC, cylindrical indenter-side constraints system; CIIC, cylindrical indenter-inclined constraints system; PIU, point indenter-unconstrained system; PISC, point indenter-side constraints system; PIIC, point indenter-inclined constraints system

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Nomenclature

e_g	crush efficiency
e_E	energy efficiency
W_{eff}	weight effectiveness
E	the energy absorption capacity
SEA	specific energy absorption capacity
F	collapse load

translating laterally. It was found that the energy absorbed by a system with side constraints was three times more than the system with no constraints.

The application of inclined constraints as an alternative to vertical ones also increases the energy absorbing capacity of tubes/rings. Reid [7] studied the effect of varying the inclination angle for the lateral compression of tubes. In general it was concluded that an externally constrained system is a viable method to increase its energy absorbing capacity.

The above studies were concerned with the compression of tubes under rigid platens. However, alternative ways of compressing these systems are possible by incorporating point-load indenters as shown by Reid and Bell [8]. The load deflection for this type of compression tends to be unstable once the collapse load has been reached. This behavior is termed deformation softening as opposed to deformation-hardening.

Instead of using flat plat or point-load indenter, Shim and Stronge [9] used cylindrical indenters to compress ductile, thin walled tubes. The authors investigated the post-collapse response of these tubes. The unstable response was also noticed for this kind of indenter.

In addition to circular tubes, various geometry shapes of tubes have been proposed by researchers to use as energy absorbers under lateral loading such as elliptical tubes [10,11] and oblong tubes [12].

Recently, researchers have utilized the finite element method (FEM) to predict the responses of energy absorption systems under quasi-static [12,13] and dynamic [14,15] lateral loading. Morris et al. [13] employed ANSYS to predict the responses of nested circular tubes compressed by two types of indenters and subjected to external constraints. Close agreements between the computational and experimental results were obtained.

Another numerical technique which is response surfaces method (RSM) was employed by researchers to seek an optimal design and to perform the multi-objective optimization design (MOD) of energy absorption system under pure axial [16,17], lateral [18] and oblique loads [19].

Much of the research on thin-walled tube energy absorbers crushed laterally has focused on those of circular cross section. However, the oblong tubes which are a modified form of circular tubes have received less attention. In the present work, the oblong tubes are proposed as energy absorption components. These tubes are expected to have high energy absorptions performance as they have a greater lateral displacement stroke compared with circular tube systems. The crushing responses of these tubes under quasi-static lateral loading have been investigated experimentally. The lateral compressions were applied through three types of indenters named as flat plate, cylindrical, and point-load indenter. Different variations of external constraints were incorporated into the oblong tube energy absorption system to increase the energy absorption capacity of these systems. In addition, with the aim of generating the design guidelines for such oblong tube as energy absorbing devices under lateral loading, the response surface method (RSM) for design of experiments (DOE) was used in conjunction with the finite element modeling (FEM). The FE model was developed using commercial finite element code (ANSYS) and validated using experimental techniques. The specific energy absorption capacity (SEA) and the collapse load (F) of the oblong tube were modeled as functions of geometrical parameters such as thickness (t), diameter (D), and width (W). Factorial study was performed to investigate the primary and interaction effects of geometric parameters on the specific energy absorbed and collapse load. Furthermore, Based on the developed models of the SEA and F, the approach of multi-objective optimization design was applied to find the optimal configuration of the oblong tube.

2. Experimental work

2.1. Material and geometrical properties

Mild Steel tubes were used in this work. The tubes were cold finished, manufactured according to the DIN standards (DIN 2393 ST 37.2) and containing around 0.15% carbon. Tensile tests were carried out in order to determine the mechanical properties of the tubes as shown in Fig. 1. Fig. 1 displays the true stress–strain curve of the tensile sample. Upon examination of this figure, it can be seen that the stress–strain curve displays unusual behavior in which strain softening occurred almost immediately after yielding with no evidence of strain hardening. This phenomenon is due to

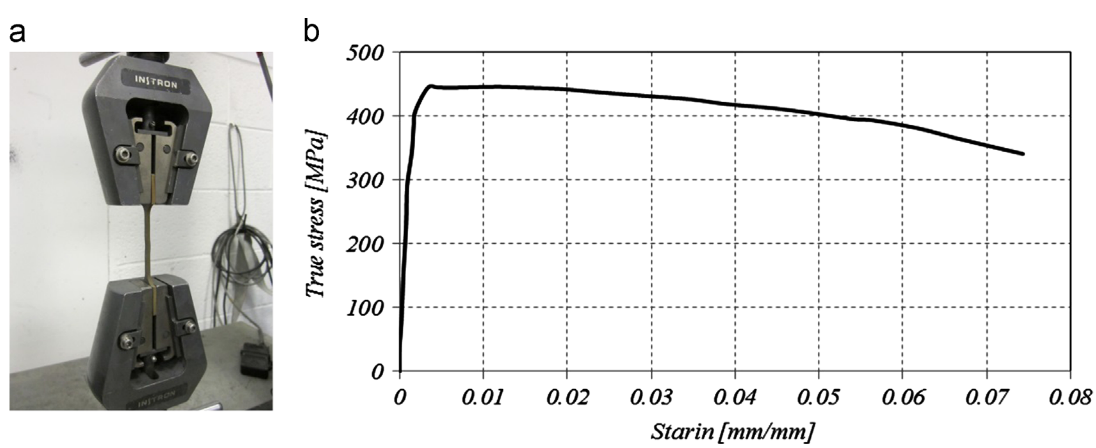

Fig. 1. (a) The tensile test procedure and (b) true stress–strain curves obtained from tensile tests.