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Crush analysis and multi-objective optimization design for circular tube under quasi-static lateral loading

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ABSTRACT

This paper addresses the energy absorption behaviour and crashworthiness optimisation of short length circular tubes under quasi-static lateral loading. Finite element (FE) models were developed using implicit FE code ANSYS to simulate the deformation behaviour and energy absorption of circular tube under lateral loading. These FE models were validated using experimental techniques to ensure that they can predict the responses of circular tube with sufficient accuracy. Response surface methodology (RSM) for design of experiments (DOE) was used in conjunction with finite element modelling to evaluate systematically the effects of geometrical parameters on the energy absorption responses of laterally crushed circular tubes. Statistical software package, design-expert, was used to apply the response surface methodology (RSM). The energy absorbing responses (specific energy absorbing capacity (*SEA*) and collapse load (*F*)) were modelled as functions of geometrical factors (tube diameter, tube thickness, and tube width). These developed functions allow predictions of the energy absorption response of laterally crushed tubes, based on their geometry parameters. Based on DOE results, parametric studies were conducted to generate design information on using the laterally crushed tubes in energy absorbing systems. Finally, the approach of multi-objective optimization design (MOD) was employed to find the optimal configuration of the proposed energy absorption structures. Design-expert software, which employs the desirability approach as optimization algorithm, was used for solving the MOD problem.

1. Introduction

In general, crashworthiness is the ability of a structure to protect itself and its occupants from serious injury or death when it is subjected to an impact load.

In the last few decades, there has been a continuous focus on crashworthiness as a primary requirement in the design of occupant–carrying structures.

Thin walled tubes have been extensively employed in crashworthiness applications, to absorb kinetic energy through plastic deformation and thus enhance the crashworthiness of the structure. The widespread use of thin walled tubes as energy absorbers is due to their good performance under dynamic loading, availability, low manufacturing cost, and efficiency. Many applications employ thin walled tubes to enhance the crashworthiness of structure such as energy absorption devices at the front of cars and trains [1], Aircraft sub floor structures [2], Rollover Protective Structures (ROPS) of heavy vehicles, such as bulldozers and tractors [3].

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. [4] and Alghamdi [5]. General information and discussion about energy absorption structures and materials can be found in book by Lu and Yu [6].

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 [7–11], lateral indentation [12,13], axial crushing [14–16], tube inversion [17], and tube splitting [18].

The axially loaded tubes have widely used as energy absorbing structures and have received considerable attention by the researchers due to the fact that axial crushing of tubes have comparatively high energy absorbing capacity. This behaviour is due to the fact that under axial loading most of the tube's material deforms plastically and participates in the absorption of energy. However, these structures have certain drawbacks such as the very large fluctuations of the collapse load about a mean load and the unstable deformation mode (global bending mode). 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. The main advantage of the

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laterally loaded tubes is that bending collapse mode generated from lateral loading results 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. In spite of these advantages of the laterally loaded structures, these energy absorbers have received relatively limited research attention in the literature.

In the past, the study and analysis of energy absorbing devices was performed by several methods such as experimental, empirical, and analytical techniques. In recent times, traditional techniques have been complemented with the finite element method (FEM), which is very powerful tool particularly for performing parametric studies. In addition to FEM, the factorial method is now employed by the researchers to conduct parametric studies. Factorial analysis is an alternative approach to investigate the responses of energy absorbing systems. It is considered as a very powerful tool for evaluating the main and interaction effects of the various parameters on the energy absorption responses. It is also used for conducting parametric studies, particularly if statistical approach such as design of experiments (DOE) is employed. The surrogate model method, such as response surface (RS) model, is considered as a common technique for performing factorial analysis of energy absorbing structures. Employing surrogate model method in the field of energy absorbing systems provides the ability to analysis and to perform multi-objective optimization design (MOD) of the energy absorbing structure. The optimization design can be achieved by using the surrogate models in the optimization algorithm, such as the multi-objective particle swarm optimization (MOPSO) algorithm and desirability approach. Many studies have used RSM with the optimization algorithm to seek an optimal design for the thin-walled tubes under pure axial [19–21], bending [22], and oblique loads [23].

Much of the research on the crashworthiness optimization of energy absorption structures has focused on those axially crushed devices. However, the crashworthiness optimization of circular tubes under lateral loading has received no attention in the literature.

This paper aims at addressing the design and optimization issues for the laterally crushed thin-walled circular tubes as energy absorption devices. An integration of finite element modelling (FEM) with the response surface method (RSM) for design of experiments (DOE) was employed for generating the design guidelines for such circular tube as energy absorbing devices. The FE model was developed using commercial finite element code (ANSYS) and validated using experimental techniques. The specific energy absorption (*SEA*) and the collapse load (*F*) of the oblong tube were modelled as functions of geometrical parameters such as thickness (*t*), diameter (*D*), and width (*W*). Parametric study was performed to investigate the primary and interaction effects of geometric parameters on the *SEA* and *F*. Furthermore, multi-objective optimization design (MOD) of the circular tube system is carried out by adopting a desirability approach to achieve maximum *SEA* capacity and minimum *F*.

2. Material and methods

2.1. Material properties

Mild steel tubes were used for manufacturing the empty and nested samples. The steel was cold finished, manufactured according to the DIN standards, DIN 2393 ST 37.2 and contain around 0.15% carbon. Tensile tests were carried out in order to determine the mechanical properties of the tubes. The dog bones samples (tensile samples) were prepared by flattening the tube and cut the specimens. Fig. 1 displays the procedure of tensile test along with the true stress–strain curve obtained. 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 as tension instability and the cold rolling process might be the reason for this.

Table 1 shows the mechanical properties of the mild steel material derived from the true stress–strain curve and used in the FE modelling. 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 [10,11].

2.2. Finite element modelling

2.2.1. FE model

An implicit finite element code, ANSYS [24], was employed for creating the FE models of thin-walled circular tubes under quasi-static lateral loading. Since the loading type was quasi-static where the loading rate was slow and there were no dynamic effects, the implicit code (ANSYS) was considered appropriate choice to model both material and geometric non-linearities of the circular tube under quasi-static lateral loading. Many researchers [10,11] used ANSYS software packages to predict the quasi-static response of the energy absorption systems. A 3D-structural solid element (solid 45) that had eight nodes with large strain, large deflection, and plasticity capabilities was used to model the tubes. The moving mass were modelled as rigid body and constrained to move vertically along the *y*-axis. The base was also modelled as a rigid body with all rotations and translations being fixed. A bilinear isotropic hardening material model was employed to define the material behaviour of the samples. The Young modulus, Poisson's ratio, and yield stress were determined depending on the results of tensile test as shown in Table 1.

A non-zero value of 1500 MPa was employed to represent the hardening modulus of this material. This value was selected due to limitation of ANSYS software in defining the softening stage in the bilinear material model, so the value was selected to be as low as possible. The same value of hardening modulus was used by [10,11] to define the softening stage of the same material. An augmented Lagrangian penalty option with a friction coefficient value of 0.2 was employed for all contact pairs. This contact algorithm employs a nonlinear surface to surface formulation to define contact between various interacting surfaces. All models were subjected to symmetry boundary conditions in order to reduce simulation solving times. Large strain deformation was included in the finite element model due to the test specimen experiencing significantly high displacement. The loads were defined by applying the predefined displacement on the pilot node, which was also used to gather the reaction force from each node. A mesh convergence study was performed to determine the mesh density. It was found that element size of 2 mm was able to produce a converged solution within a reasonable time. Fig. 3 shows the finite element mesh of the half model of the circular tube.

2.2.2. Validation of FE model

The numerical results for the circular tubes were validated against the results of the experiments carried out by using Instron machine. The validation was performed by comparing the load–displacement response, energy–displacement response, crush load, specific energy absorbing capacity, and the collapse modes. A prescribed velocity of 10 mm/min was applied to the moving crosshead of the instrument during the experiment to ensure that there were no dynamic effects. Many researchers [10,11] used velocities between 0.5 and 15 mm/min in the quasi-static lateral compression tests (Fig. 2).

Fig. 3 shows the comparison of the experimental and numerical force–deflection and energy–deflection responses for circular tube with an outer diameter of 101.6 mm, a thickness of 3.25 mm, and a width of 40 mm under quasi-static lateral loading. It can clearly be