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Analysis and optimization of sandwich tubes energy absorbers under lateral loading

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ABSTRACT

In this paper, the sandwich tubes, which consist of thin-walled circular tubes with aluminium foam core, were proposed as energy absorption devices. The sandwich tubes were laterally crushed under quasi-static loading conditions. Detailed finite element model, validated against existing experimental results, was developed using the explicit code (ANSYS-LSDYNA) to assess the energy absorption responses and deformation modes. Response surface methodology (RSM) was employed in parallel with the finite element models to perform both parametric studies and multi-objective optimization in order to establish the optimal configuration of the sandwich tube. Sampling designs of the sandwich tubes were constructed based on a D − optimal design of experiment (DOE) method. Factorial analysis was performed using the DOE results to investigate the influences of the geometric parameters on the responses of sandwich tubes. In addition, multi-objective optimization design (MOD) of the sandwich tubes is carried out by adopting a desirability approach. It was found that the tube with a minimum diameter of the inner layer and a maximum foam thickness are more suitable for use as energy absorbing components.

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1. Introduction

Empty thin-walled tubes crushed laterally have received a considerable amount of attention in the last four decades [1–11]. All investigations showed that the collapse mode of these components consisted of plastic bending conforming to the plastic hinge model of the lateral collapse of tubes. Since the strain energy is localised around the plastic hinges, the dissipation of energy through the lateral collapse is not structurally efficient [12]. Therefore, to improve the energy absorption performance, foam-filled components have been proposed. A light material such as a honeycomb, cork, wood, foam, and rubber can be used as a filler material in thin-walled components. Using filler materials along with thin-walled component enhances the absorption of energy of the whole structure. The structural and weight efficiencies of these structures make them practical for engineering applications. Using foams as filler material in thin-walled tubes provides several potential benefits for energy absorption. Much research has been performed to investigate crush and energy absorption responses of foam-filled thin-walled tubes under axial loading. Examples include foam-filled circular tubes [13–16], foam-filled square tubes [17–20], foam-filled conical tubes [21–24], foam-filled tapered rectangular tubes [25,26] and foam-filled hat sections [27,28].

Overall, researches on the collapse behaviour and energy absorption response of foam-filled tubes (either rectangular or circular cross-section) under lateral loading have been less reported in the literature. Considering the importance of such structures, a few numbers of studies have been performed to investigate the collapse behaviour and energy absorption response of foam-filled structures under lateral loading [12,29–32].

In the past, the study and analysis of energy absorbing devices were performed by using empirical and analytical techniques. Nowadays, traditional techniques have been complemented with the finite element method (FEM), which is a very powerful tool particularly for performing parametric studies. In addition to FEM, an alternative approach known as factorial design is also employed by the researchers to investigate the responses of energy absorbing systems. It is considered as an important facility for evaluating the main and interaction effects of the various parameters on the energy absorption responses. In general, the factorial analysis of

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energy absorbing structures can be performed by choosing a number of design variables (factors), which can pertain to the material, geometry, or loading parameters. Then specific levels for each variable are chosen, and the tests are run, either by experiments or simulations, using all the possible combinations and the corresponding design responses are calculated. The main and interaction effects can be specified accordingly. Main effects refer to change in the system's response with change in one factor (variable). The interaction effect occurs when the response is affected by the settings of two factors. Normally, the factorial analysis is carried out by using statistical based approach called design of experiments (DOE). The DOE technique provides the ability to construct surrogate models such as Response Surface (RS) models which relate the crushing and energy absorption responses to design variables. These surrogate models can then be used to analyse the responses of the energy absorbing structure and also to perform multi-objective optimization design (MOD) of it. The optimal 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 surrogate models with the optimization algorithm to seek an optimal design for empty and foam-filled thin-walled tubes under pure axial [20,33–38], bending [40,41], and oblique loads [42].

Much of the research on the optimization of foam-filled energy absorption structures has focused on those axially crushed devices. However, the laterally crushed sandwich tubes have received no attention.

In the present paper, numerical investigations into the quasi-static lateral collapse of sandwich tube systems have been performed. The FE model has been developed and validated against existing experimental results in the literature. An experimental design was created based on D-optimal design. The outer layer diameter (D_o), the outer layer thickness (t_o), the inner layer diameter (D_i), and the inner layer thickness (t_i) were applied as independent input variables. The specific energy absorption (SEA) and collapse load (F) were selected as the design responses. Factorial study was performed to investigate the main and interactive effects of geometric parameters on SEA and F. In addition, MOD study was performed to seek an optimal configuration for sandwich tube systems.

2. Numerical simulations

2.1. Material properties

As described by Fan et al. [29], the sandwich tubes were prepared by cutting the outer, inner and foam core separately and then assemble these three components together. These components were then adhered together by using thixotropic epoxy liquid glue (FORTIS AD825). The material of outer and inner layers is aluminium alloy AA6060T5. Foam core was prepared by using ALPORAS® aluminium foam. The mechanical properties of both AA6060T5 and ALPORAS® (Table 1) are the same as reported by Ref. [30]. As the loading type is quasi-static, the strain-rate effects are not taken into account in the finite element modelling Table 2.

Table 1
Component material properties of the sandwich tubes [30].

	Density (kg/m^3)	Young's modulus (GPa)	Poisson's ratio	Yield strength Rp0.2 (MPa)	Hardening modulus
AA6060T5	2760	69	0.3	150	345
ALPORAS®	230 ± 20	1.1 ± 0.1	0.33	1.5 ± 0.1	–

Table 2
Independent variables and experimental design levels used.

Variable	Unit	Code	Low	High
Outer diameter (D_o)	mm	A	100	150
Outer thickness (t_o)	mm	B	1.5	3
Inner diameter (D_i)	mm	C	80	130
Inner thickness (t_i)	mm	D	1.5	3
Constraint	$20 \leq (A-C) \leq 50$			

2.2. FE model

The commercial explicit FE code ANSYS-LSDYNA [45] was used for all finite elements modelling of sandwich tubes. Fig. 1 shows the finite element mesh of the half model of the sandwich tube. A 3D-structural solid element (solid 164), which has eight nodes with large strain, large deflection, and plasticity capabilities was used to model the foam core. A crushable foam model was used to define the ALPORAS® aluminium foam material. The moving top plate was modelled as rigid body and constrained to move vertically along the y-axis. The bottom plate was also modelled as a rigid entity, with all rotations and translations being fixed. Outer and inner aluminium tubes were modelled by using shell element (SHELL163) with Belytschko-Tsay element formulation. A bilinear kinematic hardening material model was employed to define the material behaviour of the outer and inner aluminium tubes. The mechanical properties of the foam and the aluminium tubes were the same as those listed in Table 1. An automatic 'surface to surface' contact type was used to define the contact between the outer tube and all rigid bodies. The perfect bonding between three components of the sandwich system was modelled by using a tied 'node to surface' contact type between the foam core and both the outer and the inner tubes. The mesh convergence analysis was performed to find the optimum mesh size. It was found that element sizes of 2 mm, 5 mm, for aluminium layers and ALPORAS® foam respectively, were able to produce accurate results. All models were subjected to symmetry boundary conditions in order to reduce simulation solving times.

The quasi-static loading was simulated by defining the motion of a moving rigid body through applying a prescribed velocity to it. The velocity was ramped up in a ramping time of $t_R = 12.5$ (ms)

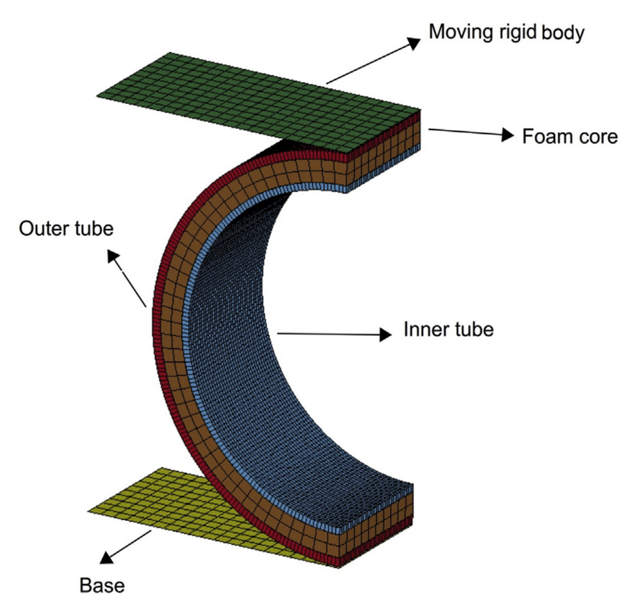

Fig. 1. FE model of sandwich tube.

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