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Collision performance of square tubes with diaphragms

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ABSTRACT

The energy absorption responses of conventional tubes and tubes with diaphragms are analysed here by means of finite element simulation. Numerical results show that tubes with diaphragms exhibit a relatively stable crushing process. The effect of imperfect energy absorption responses is also analysed, including the top shape of tubes and oblique loading. The strain rate affects the dynamic response of tubes with diaphragms. Four prototypes of these tubes were constructed and tested; however, sizeable differences were obtained between experimental results and the results of numerical simulation of the ideal structure in terms of process errors.

1. Introduction

Casualties and property losses caused by train collision accidents are a serious problem [1]. For instance, four carriages fell from a bridge and 40 people died in an accident on 23 July 2012 and on 28 April 2008 a two-train crash on the Jiao-Ji railway line killed 70 people and injured 416 in China. In order to avoid or at least reduce the losses caused by such accidents, many countries are conducting research on rail equipment crashworthiness and developing a robust structure for train protection as the primary means of passive protection. In other words, to ensure safety during a collision, it is necessary to allow the vehicle compartment itself to absorb kinetic energy in a controlled way, and reduce the acceleration acting on the car body as much as possible [2,3]. In order to improve the energy absorption capacity of the vehicle, sometimes energy absorbers are installed on the front end of the train [4,5].

The efficiency of a thin-walled energy absorber is influenced by many factors, such as material properties, cross-section configurations, modes of deformation, wall thicknesses, boundaries and loading conditions, etc. [6–8]. The capacity of a structure to absorb energy within its entire deformation (elastic and plastic) is a vital factor in crashworthiness applications. Numerous research have been conducted on columns with various cross-sections, such as circular, polygonal and taper [9–11]. The crushing response of foam-filled tube members under axial impact loading has also received increasing attention [12,13].

Over past several decades, various modes of plastic deformation of thin-walled structures such as tube crushing [14], expansion [15], necking [16], inversion [7] and splitting [6] have been discussed, but the most widely used is the tube longitudinal crush. Since longitudinal crush with progressive deformation in energy absorption is higher than transverse deformation by about one order of magnitude, a lot of research has been conducted on the crashworthiness of thin-walled structures under axial crush loads. Johnson and Reid [17] reported that the energy absorption efficiency of the devices was related to the deformation mode, load applied mode and material properties. Hamouda et al. [18] analysed the deformation of mild steel tubes and thin-walled composite square tubes under axial force with different l/w ratios (l=the length of the tube; w=the width of the tube). It was found that parameters such as thickness, type of fibre and length of tube have a considerable effect on the crushing characteristic of collapsed tubes. In fact, the deformation mode of the structure may also vary under the same conditions. It has been seen in previous studies [19] that mild steel tubes with uniform wall thickness throughout their height generally deform in three modes: symmetric crushing mode, extensional crushing mode, and general mixed crushing mode.

Several investigations aimed at increasing the energy absorption efficiency of thin-walled structures under axial load have been carried out. These investigations also aimed to improve the stabilisation of the collapse process. In order to control the collapse mode of thin-walled structures, circumferential grooves, which were cut alternatively inside and outside the tube at predetermined intervals, were introduced by Daneshi and Hosseinipour [20]. It was observed that this was an effective way to force the plastic deformation to occur at these predetermined intervals along the tube. Similarly,

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corrugated tubes were also studied [21] and corrugations introduced in the tube to force the plastic deformation to occur at predetermined intervals along the tube length.

A certain number of diaphragms are placed in the square tubes in this article. The introduction of diaphragms can improve the transverse strength of tubes. Therefore, the crushing mode can be altered so that better energy-absorbing performance can be achieved. In reality, computational modelling on occasions, however, cannot predict the result compared with test data. The discrepancy is attributed to modelling perfect geometry, whereas imperfections probably exist in the actual test specimens. The top surfaces of the components mentioned above were planar shell. As is mentioned in Section 6, contact error may also change the collapse mode of specimens.

In this paper, the axial crushing mode of a thin-walled square cross-section of tube with a diaphragm is studied under ideal and imperfection conditions. In the first part, a model of a tube with a diaphragm is proposed, including the geometry and a computational model. Different models are adopted for the numerical simulation of the quasi-static process and dynamic process. In the second part, the results of ideal structures are discussed. Axial crushing tests on prototypes are also conducted. Through numerical simulation the influence of different contact errors on tube response is investigated. In the third part, the dynamic characteristics of the specimens under different impact speeds are discussed.

2. Configuration of square tubes with diaphragms

Energy absorbers in this paper are thin-walled tubes with diaphragms and they have a square cross-section. All columns are of the same size: 600 mm long and 180 mm wide. Four diaphragms are uniformly distributed along the longitude and their intervals are 120 mm, as shown in Fig. 1. The diaphragm is a + shape, and the width of the welding edge connecting the diaphragm with the channel steel is 60 mm. The tubes are fabricated by two pieces of channel steel of different heights: 120 mm and 60 mm. The weld lines connecting the diaphragms with the big channel steel lie inside the square tube connected by a double-sided weld and there are four rectangular holes on the web plates of the small channel steel. The weld lines joining the diaphragms to the small channel steel lie outside the square tube. Thicknesses of diaphragms and side walls are identical for all columns. Both ends of the squares are closed by steel plates, which have the same thicknesses as the side wall.

3. Finite element modelling

Finite element analysis was conducted with the explicit nonlinear finite element code LS-DYNA. For accuracy and efficiency, 6 mm × 6 mm was chosen as the mesh size. Shell elements were modelled with the Belytschko–Tsay shell element, during the calculation, and four Gauss integration points were used to avoid hourglass energy. The AUTOMATIC_SINGLE_SURFACE contact was defined for the contact algorithm among all the parts including the rigid wall and the self-contact of the energy absorber; the static and dynamic friction coefficients were taken as 0.15 and 0.1, respectively. The axial quasi-static and dynamic crushing responses of tubes with diaphragms were studied too. The schematic diagram of the computational model is shown in Fig. 2 and Fig. 3 is the FEM model. The rigid wall was achieved by employing the *RIGIDWALL_PLANAR_MOVING command in LS-DYNA, by means of which a flat rigid surface is defined over the tube.

In the modelling of quasi-static and dynamic axial crushing, the bottom end of the tube was assumed to be built in and constrained in all degrees of freedom. The free upper end was impacted by the loading plate with a certain downward velocity.

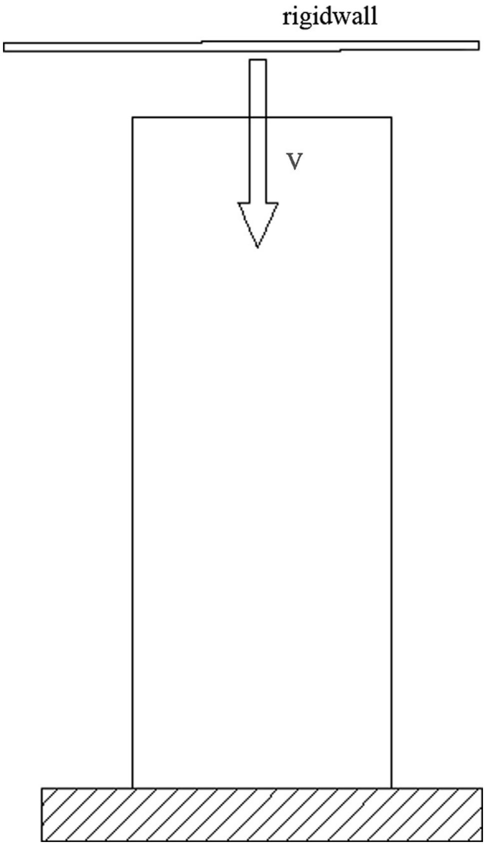

Fig. 2. Schematic of the computational model.

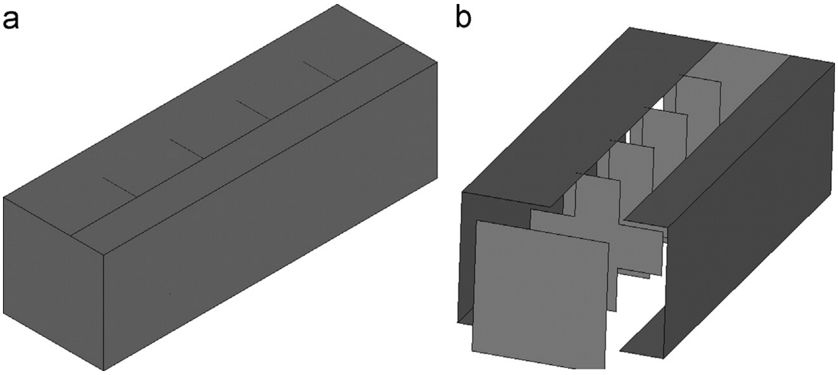

Fig. 1. Energy absorber structure ((a) external view and (b) explosive view).