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Dynamic lateral crushing of empty and sandwich tubes

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A B S T R A C T

The dynamic lateral crushing behaviour of short empty and sandwich circular tubes is examined in this paper. Unlike the conventional impact method, the specimens were placed on the bottom platen of an Instron machine with a constant upwards velocity and then the tube collided with the fixed upper rigid platen. Load-deflection curves of empty tubes were first obtained and analysed. From the viewpoint of deformation modes and plastic strain energy absorbed by the tube quadrants around the proximal surface and distal surface, a critical velocity of impact is determined which corresponds to a mode change. A relationship is found to exist between the critical velocity and thickness-to-diameter ratio as well as the yield stress and density of the material. To understand the dynamic crushing behaviour of short aluminium foam-filled sandwich tubes by two rigid platens, further tests and corresponding finite element analysis were performed, respectively. Similar to the observations in the quasi-static tests, the mode of dynamic collapse is bending, with the formation of plastic bending zones accompanied with core crushing. Corresponding FE models for ABAQUS/Explicit were developed and validated against the experimental observations. Detailed deformation features and energy absorption characteristics during the crushing process were identified. It was found that increasing the compression velocity leads to an increase in the total internal plastic energy dissipation for both empty and sandwich tube. The propagation of plastic bending in the form of double-moving-hinges is the main mechanism of energy dissipation, as opposed to the low velocity impact which involves stationary plastic deformation zones.

1. Introduction

Sandwich structures have attracted much attention in automotive and aerospace fields due to their higher strength-to-weight ratio, better impact resistance and associated energy absorption capacity [1]. Recent research on sandwich structures subjected to impact or blast loading has enhanced their potential in a wider range of crashworthiness applications than ever [2–4]. As typical energy absorbers, thin-walled tubes are usually crushed plastically under several loading conditions, such as axial crushing, lateral crushing, axial inversion and folding [5,6]. The load-deformation curves, especially under lateral compression, are desirable for energy absorption because of higher efficiency with plateau force over long stroke [6]. As a result, thin-walled tube systems are widely used as efficient energy absorbers in engineering fields [1]. On the other hand, cellular materials such as metallic foams have recently emerged as novel materials in energy-absorbing devices owing to their high specific stiffness and specific strength compared with traditional metals such as steels. Researchers have studied the axial crushing behaviour of foam-filled tubes [2,7], which have full advantages of both the thin-walled tubes and metallic foams. It was found that by combining the two structures, the energy absorption capacity is improved [8,9], though not necessarily weight-effective. Meanwhile, work on the lateral crushing behaviour of aluminium foam-filled tubes [10] showed that the foam filling advantage still existed under the transverse loading condition, in terms of better specific energy absorption. Thus, similar energy absorption enhancement might be expected for sandwich tubes under lateral crushing.

Investigations on the lateral crushing of empty tubes have been extensively conducted by many researchers [5,6,11–14]. All the investigations demonstrated that the crushing of those tubes involves plastic bending, which may be idealised as plastic hinges to model the lateral collapse of tubes. Because of the strain localization around the plastic hinges, it may not be structurally efficient to dissipate energy under this condition. Therefore, to further improve the energy dissipating performance, tubes with metal foam sandwiched might be an alternative structure. Previous research on the quasi-static responses has already identified this improvement in the crush strength and energy absorption

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capability [15]. The behaviour of sandwich tubes under dynamic lateral compression has been less reported in the literature. Moreover, metallic foams can be strain-rate sensitive [16,17] and have a higher plateau stress and a higher energy dissipation capacity under impact or blast loadings, compared with the quasi-static loading case.

In this paper, the dynamic response of empty and sandwich tubes under lateral compression is investigated. The effect of velocity is examined experimentally and by using finite element analysis. A series of tests on empty tubes and sandwich tubes were performed by using an Instron VHS8800 High Rate Test System, which enables a single shot test to be conducted at a constant crosshead speed, up to 10 m/s for compression. The specimens were placed on the bottom platen and then they moved upwards together, until they collided with the top platen, with very little change in the speed during the whole crushing process. The dynamic force and deformation histories were recorded simultaneously by a high-speed data acquisition package. Finite element code ABAQUS/Explicit was then employed to analyse the response of the tubes under higher velocities, up to approximately 100 m/s. Based on the deformation modes from FE analysis, a critical compression velocity was defined above which the tube deformation was localised around the impact end. A comparative study of the load-deflection curves under quasi-static and impact tests is described and the effect of velocity on the total energy absorption is studied.

2. Dynamic compression experiments

2.1. Material properties of specimens

Fig. 1 shows the specimens used in the tests. The sandwich tubes were manufactured by assembling together the individual components, i.e. the inner tube, the outer tube as well as the aluminium foam core. The aluminium tubes were made of AA6060-T5 and the length was fixed at 50 mm for each specimen. The stress–strain curves of the aluminium tubes were obtained from the standard uniaxial tensile tests [18], from which the average yield stress σ_y was 150 MPa. The density of tube ρ_s is 2760 kg/m^3. Hollow cylindrical tubes of aluminium foam were cut from an initial ALPORAS® aluminium foam block (400 × 700 × 2400 mm), with the nominal relative density of 9%, supplied by Gleich Ltd., Germany. The material properties of the foam core are the same as those reported in [17]. For bonding, a two-component thixotropic epoxy liquid adhesive (FORTIS AD825) was used to paste, separately, the two monolithic aluminium tubes with the aluminium foam core. Four empty tubes and seven sandwich tubes were fabricated and tested separately in the INSTRON VHS8800 machine and their details are listed in Table 1. The definitions of geometric parameters in the tests are shown in Fig. 2.

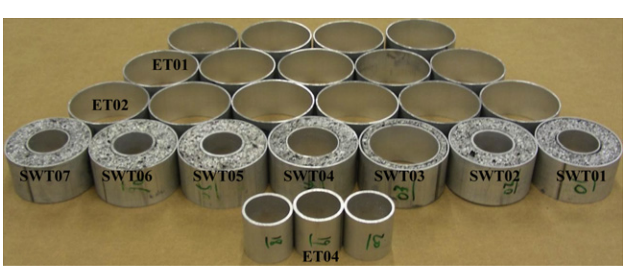

Fig. 1. Photograph of typical specimens for dynamic lateral crushing tests, including empty tubes and sandwich tubes.

2.2. Setup of dynamic experiments

All the lateral crushing tests were performed at a room temperature of 25 °C. The dynamic tests were performed using a High Rate Test System (INSTRON VHS8800). A photograph of the experimental setup is shown in Fig. 3. The top platen was fixed and the finishing position of the bottom platen was controllable. This system provides a feedback mechanism by its FastTrack™ VHS8800 controller package to adjust the drive profile of the hydraulic system according to the experimental condition. After some initial trials with several iterations, an almost constant loading rate could be achieved for the subsequent experiments. In our tests, for the bottom platen, a constant velocity of 1.0 m/s with a sampling rate of 50 kHz was used for low rate compressions and a constant velocity of 10.0 m/s (which was the maximum possible) with a sampling rate of 500 kHz for high velocity compression tests. The load history was measured by Kistler® load cell (Type 9071A) without data filter. The displacement history was measured by a linear variable differential transformer (LVDT) with data filter with a cut-off frequency of 1000 Hz. During the initial tests, the empty tubular specimen was placed either on the bottom platen or top platen, in order to explore the difference of these two arrangements. Subsequently, for all the tests with empty and sandwich tubes the specimen was placed on the bottom platen and then moved upwards together with the base platen. Double-sided tapes were used to stick the specimen on the bottom platen during the movement. A high-speed camera was used to track the deformation profile of the specimen during crushing.

The tube's contact forces with the top and the bottom platens are quite different in the presence of a tube's inertia. To study the possible difference, two kinds of impact methods were explored for the empty tubes. Impact method I was to attach the specimen to the bottom platen and then move together at a velocity, as sketched in Fig. 2a. The other, impact method II, was to fix the specimen with the top stationary platen, as depicted in Fig. 2b The load cell was mounted in the top platen and the displacement of the bottom platen was measured. The force–displacement curves of both the methods are plotted in Fig. 4, for specimens ET01 and ET02, respectively. The two methods resulted in different forces in the initial stage, but later the two forces were almost identical. For the second method, at the early crushing phase of small deflection, the magnitude of contact force was very small compared with that of the first one. This delay in experiencing the force by the load cell was due to the inertia of the tube. Also, a drop in the force after the initial small peak might indicate elastic bouncing of the tube from the top platen. As the displacement developed further, the tube wall started to interact with the top platen again, rendering a steeper increase of the force in the subsequent phase. This bouncing-back was also detected from the high speed photography. For all the tests reported here, method I was used.

3. Experimental results

3.1. Empty tubes

Fig. 5 shows the load-deflection results of several empty tubes (ET01, ET03 and ET04) from the quasi-static and dynamic tests with a crushing velocity of 10 m/s. Apart from the initial difference at the early deformation phase, the magnitudes of the crushing strength are nearly the same under each loading case. From the deformation profile recorded by the camera, the deformation modes of the empty tubular specimens were almost the same when they were subjected to a constant velocity. The progressive collapse has three phases, i.e., initial tube wall collision, steady dynamic collapse and unloading phase. In the first phase, the contact force had large