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Axial crushing analysis of empty and foam-filled brass bitubular cylinder tubes

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ABSTRACT

To reduce loss from collision, energy absorbers are used which dissipate energy upon deformation and folding in order to prevent damage to critical parts of a structure. In this study, the empty and polyurethane foam-filled bitubular tubes made from brass with circular section were subjected to quasi-static axial compression loading. Nonlinear dynamic finite element analyses are carried out to investigate the details concerning crushing process by using explicit finite element code ABAQUS. Satisfactory agreements are achieved between the finite element and the experimental results. The validated finite element model was then used for the parametric studies, in order to determine the effect of the empty and filler tube geometry parameters (i.e. wall thickness, semi-apical angle) and loading parameters (i.e. impact mass, impact velocity) on the Dynamic Amplification Factor. The results highlight the advantages of using the brass bitubular circular tubes as energy absorber.

1. Introduction

To protect structures under impact loading, it frequently necessitates the need for energy absorbers, devices designed to absorb impact energy in a controlled manner and eventually protect the structure under consideration. Energy absorbers are used in an extensive range of applications in industry, for example, in automotive structures, aircraft, train, helicopter skids and space capsule landing. Many researchers have surveyed the energy absorption capability of thin-walled structures, especially circular tubes. Few analytical models are proposed to predict the crushing behavior of these tubes. First, theoretical solution of circular tube under crushing loading was developed by Alexander to predict the mean crushing force and the energy absorption of circular tubes [1]. Wierzbicki and Abramowicz [2] presented a simple formula to predict the axial crash response of thin walled columns. Their method is based on the balance of external and internal work. In addition, a number of experimental and numerical studies have been conducted to validate these models and assess the crashworthiness parameters of these structures [3–5]. Several researchers used crashworthiness optimization technique to find the optimum tubes which have the maximum energy absorption capacity [6,7].

At the same time, various researchers attempted to increase the energy absorption of thin-walled tubes by using fillers [8–12]. To fill cellular materials such as polyurethane and aluminum foams in the tubular structures is a common method which can tremendously improve the energy absorption efficiency of the tubes. Not only the filler itself absorbs energy by plastic deformation, but also the interaction between tube and filler can change the original collapse mode of the tube into a more efficient collapse mode. Seitzberger et al. [13,14] and Chung Kim Yuen et al. [15] used a double-cell profile (two tubes with similar cross-section and one placed concentrically inside the other) arrangements, empty or filled with aluminum foam in order to increase the energy absorption capabilities of thin-walled tubes. Guo et al. [16–18] also carried out experimental and numerical investigations on the performances of this new topological structure under axial crushing and three point bending conditions. Chen and Nardini [19] investigated crushing behavior of closed-top-hat aluminum foam-filled sections including single-top-hat, double-top-hat and double-top-hat with a center plate. It was concluded in the same study that the thin-walled foam-filled members could be used as efficient crash energy absorbers. Seitzberger et al. [14] investigated the axial crushing of foam-filled square, hexagonal, octagonal and bitubular steel tubes. It was reported that considerable improvements with respect to energy absorption were obtained using foam filling particularly in bitubular configurations.

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Aktay et al. [20] studied quasi-static crushing of empty and foam-filled single, bitubular and constraint hexagonal- and square-packed aluminum tubes numerically and experimentally. They observed that many folds were formed, in addition, they increased using aluminum foam filling. Moreover, foam-filled bitubular tubes displayed different modes of deformation due to different types of foam filling. The tubes of hexagonal packing contacting the mold wall were deformed in elliptical while the central tube was deformed in hexagonal shape. In the square packing of empty tubes, tubes are changed into square in crass section. They found that the effect of foam filling in packed tubes is similar to single tubes. Hanfeng et al. investigated energy absorption characteristics of honeycomb-filled single and honeycomb-filled bitubular tubes numerically, moreover, they optimized specific energy absorption capacity and the minimum peak crushing force by adopting multi-objective particle swarm optimization algorithm [21]. The experimental and finite element analyses were performed on bitubular square thin-walled tubes using two different arrangements including parallel and diamond arrangements under quasi-static axial compression loading. Furthermore, the results revealed that the absorbed energy by the bitubular tubes was higher than the sum of the energy absorbed by the inner and outer tubes loaded separately [22]. In the recent years, researchers have carried out experiments as well as the FE analyses to investigate the behavior of concrete filled double-skin stub members and tested them against compressive forces [23–25].

The intention of the present study is to further contribute to the analysis of specialized bitubular tubes with respect to their energy absorption capacity when compressed axially at relatively low speeds. To accomplish this objective, the bitubular tubes made from brass having circular section filled with polyurethane foam are investigated experimentally and numerically. Subsequently, the validated finite element model was used to conduct a series of parametric studies on the empty and foam-filled brass bitubular tubes under quasi-static and dynamic loadings. The parametric studies were carried out to determine the effect of the empty and filler tubes geometrical and loading parameters such as wall thickness, semi-apical angle, impact velocity and impact mass on the Dynamic Amplification Factor.

2. Structural crashworthiness indicators

To evaluate the crashworthiness of the thin-walled structures, it is essential to define the crashworthiness indicators. Energy absorption (EA), specific energy absorption (SEA), mean crushing load (MCL) and crash load efficiency (CLE) are usually used as the important indicators to evaluate the crashworthiness. The EA of a structure subjected to the axial loading can be expressed as

$$\mathrm{EA}(d) = \int_0^d L(x)\,\mathrm{d}x \tag{1}$$

where d is the axial crushing distance and L denotes the axial crushing load. The mean crush load is an indicator of the energy absorbing capability of a structure when compared to the axial displacement required to absorb the energy. The mean crush load for a given deformation is defined as the total energy absorbed divided by the total deformation (d), numerically, as follows:

$$\mathrm{MCL}(d) = \frac{\mathrm{EA}(d)}{d} \tag{2}$$

The SEA is defined as the ratio of the absorbed energy to the mass of the structure. Thus it can be written as

$$\mathrm{SEA}(d) = \frac{\mathrm{EA}(d)}{M} \tag{3}$$

where M is the mass of the structure. Apparently, the higher is the SEA, the better is the EA capacity of a structure. As an energy absorber, the structure having high CLE is preferred in engineering. The CLE of a thin-walled structure can be given as

$$\mathrm{CLE}(d) = \frac{\mathrm{MCL}}{\mathrm{PCL}} \tag{4}$$

where the PCL represents the peak crushing load of a thin-walled structure. For an ideal energy absorber, the crush load efficiency should be as close to 100% as possible. From a crashworthiness point of view, peak crush load ratio is desirable. Commonly, an energy absorber is able to absorb a required energy, represented by the mean crush load; however, it may be impractical since the load required to initiate crush may be too high. Consequently, one possible approach to overcome this issue is to introduce a trigger mechanism in order to reduce the initial peak load (IPL), thus increasing the crush load ratio.

3. Experimental work

In this study, quasi-static analysis of the empty and polyurethane foam-filled brass bitubular tubes energy absorbers under axial loading is examined using experimental techniques. Although these devices are usually exposed to much higher velocities, it is primarily common to analyze the quasi-static response since the same pre-dominant geometrical effects will also occur under dynamic loading conditions. Many researchers have implemented quasi-static compression to survey the EA characteristic of metallic tubes [26–28].

3.1. Material and testing

The elastic and plastic behaviors of the brass materials were determined from typical quasi-static engineering tensile stress–strain curve of tube material tested in accordance with ASTM E8M standard. The true stress–plastic strain curve for brass material is shown in Fig. 1a. The elastic modulus, Poisson's ratio and initial yield stress of brass material were determined as 102 GPa, 0.33 and 236 MPa, respectively. The crush tests were carried out on the empty and polyurethane foam filled bitubular cylinder tubes as well. The polyurethane foam having density of 145 kg/m^3 was used. According to D1621-04 ASTM standard, uniaxial compression tests on square cubes of polyurethane foam were performed to determine the foams parameters. Fig. 1b shows typical compressive stress–strain curves of the foam having density of 145 kg/m^3. This curve indicates an initial elastic behavior (AB) followed by a plateau regimen in which the stress is nearly constant (BC), subsequently, a densification regimen is followed where the stress increases rapidly with the further increase of the strain (CD).

3.2. Quasi-static test

The empty and foam-filled bitubular cylinder tubes having cross sectional dimensions ($R1$ and $R2$) of 20 and 50 mm, wall thickness (t) of 1 mm and length (L) of 55 mm were subjected to quasi-static axial compression loading by using a 50-ton INSTRON hydraulic machine. During the compression tests, the specimens were compressed between the parallel steel plates of the test machine. To establish quasi-static conditions and to ensure that no dynamic effect was present, all the tubes were compressed at a rate of 5 mm/min until limited crush, which implies complete