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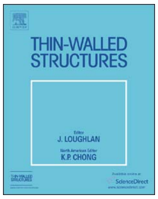

Full length article

Collapse behavior of thin-walled conical tube clamped at both ends subjected to axial and oblique loads

Sajad Azarakhsh[a,*], Ali Ghamarian[b]

[a] Young Researchers and Elite Club, Arak Branch, Islamic Azad University, Arak, Iran
[b] Young Researchers and Elite Club, Central Tehran Branch, Islamic Azad University, Tehran, Iran

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ABSTRACT

The structures of the vehicles during the crushing processes or accidents not only experience direct or axial collisions but sometime these structures are crushed off-axially. Therefore, it is very crucial to study whether or not a foam-filled tube is capable of supporting the oblique compression forces efficiently and effectively. In this paper, investigation of the axial and oblique loading collapse behavior of thin-walled conical tube clamped at both ends is presented. Several numerical simulations using ABAQUS finite element explicit code are carried out to study crashworthiness characteristics of empty and foam-filled thin-walled conical tubes clamped at both ends. In order to verify these numerical results, a series of quasi-static axial and oblique compression tests are performed. 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. semi-apical angle) and loading parameters (i.e. load angle) on the energy absorption and mean crushing load. The primary outcome of this study is to provide information for the use of foam-filled conical tubes as energy absorbers where oblique loading is expected.

1. Introduction

The increasingly interest in the safety and crashworthiness of vehicles has resulted in extensive researches on the structural response of thin-walled metallic tubes, which are the most conventional and effective energy-absorbing devices and have been widely employed in the vehicle design and manufacture. It was shown that the energy absorption capacity of thin- walled tubes is significantly affected by parameters such as cross-sectional shape, geometry and size of tubes, and loading conditions [1–5]. However, progressive buckling, inversion, and splitting of circular tubes were previously discussed by [3]. Furthermore, Alghamdi et al. [4] studied different structure's collapsibility as energy absorbers, namely circular and square tubes. Without too much increase in volume and weight, to improve the crashworthiness capability of thin-walled tubes, some researchers [6–9] used cellular materials, namely foams and honeycombs. The energy absorption capability of empty and foam-filled circular tubes was studied by Ghamarian et al. [10–13] and Ahmad et al. [14,15].

In a real-world vehicle collapse event, thin-walled tubes work, not only with pure axial or pure bending loads, but also with a combination of axial and oblique loadings; particularly in a bumper system. The energy absorption capabilities of thin- walled tubes reduce more under a combination of axial and oblique impacts, compared to pure axial loads. Han and Park [16] numerically examined the crush behavior of a square thin- walled extrusion subjected to oblique loads. A critical load angle was identified under which the deformation mode of the tube transitions from progressive to global bending collapse. The latter yielded a mean crush load, which was about 40% of that in pure axial collapse. Reyes et al. [17–19] experimentally and numerically investigated the quasi-static oblique loading behaviours of both empty [17,19] and foam-filled [18] AA6060-T4 and T6 columns. The studies revealed the drawbacks of straight thin-walled members under non-axial loading conditions, such as dramatically decreased load-bearing and energy-absorbing capacities, particularly at large load angles when global bending collapse dominates the column response. In view of this, the increased interest in designing energy-absorbing structures capable of sustaining oblique loads has led to several seminal works on the crushing behavior of tapered thin-walled tubes in which one or more sides of the tube are oblique to the longitudinal axis. For instance, Nagel and Thambiratnam [20–22] have shown that tapered thin-walled rectangular tubes are preferred over their straight counterparts in oblique impact scenarios. However, research information on the oblique loading of thin-walled tapered energy absorbers is still limited, despite their potential to be effective energy absorbers. Karbhari et al. [23] investigated the energy absorption characteristic of conical composite tubes under axial and off-axis loading over a load angle range of 5–35 deg. This study also showed that the angle of load orientation significantly reduces the energy absorption capacity of such

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[*] Corresponding author.

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tubes.

In this paper, an experimental programme on axial crushing and oblique loading of empty and foam-filled conical tubes clamped at both ends has been composed, and the main result from this investigation is represented. Towards this end, finite element models validated against experimental results were used to perform a series of parametric studies to evaluate the relative effect of each parameter on the tube response. The primary outcome of the study is to provide research information which will facilitate the design of conical tubes clamped at both ends as energy absorbers in applications where crushing energy must be absorbed under oblique loading.

2. Material properties

2.1. Aluminum conical tubes

Test specimens were made of the aluminum alloy 1050. Chemical composition was 99.5 A-0.4 Fe- 0.05 Cu- 0.05 Mn- 0.05 Mg- 0.07 Zn- 0.05 Ti- 0.03 others. In this study, to obtain accurate material information, typical quasi-static engineering tensile stress–strain curve has been tested in accordance with ASTM-E8M standard. It should be emphasized that, the stress–strain curve has been achieved for the strain rate of 1.42×10^{-3} (=10 mm/min). The elastic modulus of this material is E = 57.7 GPa, Initial yield stress is $\sigma = 83.3$ MPa, the density is $\rho = 2700$ kg/m3 and the Poisson ratio is $\vartheta = 0.3$. Based on the research results in literature [10–13], mechanical properties of aluminum alloy 1050 series is not sensitive to the strain rate.

2.2. Polymeric foam

Polymeric foams are largely used in industry because of their structural and energy absorbing capabilities combined with low weight. They can undergo large compressive deformations and absorb considerable amounts of specific energy. Energy is dissipated through the cell bending, buckling, or fracture, but the stress is generally limited by the long and flat plateau of the stress–strain curve. Therefore, in this study, polyurethane (PU) foam is used as the filler in thin-walled tubes. PU foam was prepared to use Polyol and Isocynate in the liquid forms. The foam liquids (Polyol and Isocynate) were mixed in temperature T = 15 °C, and the liquid mixtures were poured into aluminum conical tubes after mechanically stirred for 1 min in order to have homogenous cellular materials. Static uniaxial compression test was performed on PU foam. Fig. 1 shows a true stress–strain curve for rigid PU foam, obtained by compressing a cubic specimen quasi-statically along one direction in accordance with ASTM D1621–94 standard [24]. The elastic modulus of this material is E = 5.5 MPa, and its density is $\rho = 65$ kg/m^3. The curve exhibits three definite regions: linear elasticity, plateau, and densification. At small strains, usually < 0.05 the behavior is linear elastic, with a slope equal to the Young modulus of the foam. As the load increases, the foam cells begin to collapse by elastic buckling, plastic yielding, or brittle crushing, depending on the mechanical properties of the cell walls. Collapse progresses at roughly constant load, giving a stress plateau, until the opposing walls in the cells meet and touch, when densification causes the stress to increase steeply.

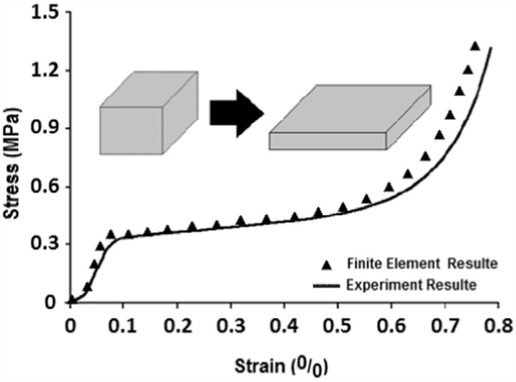

Fig. 1. Typical stress–strain curves for polyurethane foam with density 65 kg/m^3.

3. Terminology

Desired parameters in this research which are used for comparison and could be obtained from load–displacement curve are as follows:

3.1. Total absorbed energy (E_a)

The total energy absorption E_a, which describes the energy absorption capacity of each pair of specimens, is defined as the integration of the force vs. deformation curve:

$$E_a = \int_0^S F(u)du \tag{1}$$

where F(u) is the crushing force as a function of crush distance u, and S is the displacement before the end point.

3.2. The specific energy absorption (E_s)

The specific energy absorption, E_s, which is defined as the energy absorbed per unit mass, provides a way of comparing energy absorption capacity of structures with different masses and is given by:

$$E_s = E_a/m \tag{2}$$

Where m is the total mass of the pair of specimens.

3.3. Mean crushing load (MCL)

One of the most significant parameters for quantifying the behavior of axially compressed tubes is the mean crushing load, which is obtained by dividing the measured absorbed energy to the total crushing distance S.

$$MCL=E_a/S \tag{3}$$

4. Details of experiments

4.1. Specimens

The thin-walled conical tubes produced by spinning were found to yield the most consistent results in comparison with other production methods such as inversion. In this study, the conical tubes were manually spun using blanks of commercial aluminum sheet with 1 mm thickness. After the production, the investigations revealed that the thicknesses of tubes is mostly the same as the blank sheet while there is some thickness gradient on tube wall due to the blanks stretching over the die surface. The edge of the formed conical tubes on the open side was trimmed at the end of forming process by moving the cutting tool normal to the rotation axis of the samples. The geometry and dimensions of the tested specimens are illustrated in Fig. 2.

4.2. Boundary conditions

In most situations the bumper is fully clamped in a vehicle. As the present investigation was motivated by the behavior of bumper beams placed in the front and rear ends of vehicles, circular aluminum tubes are studied and fully clamped boundary condition were selected for the present study.

Boundary conditions arrangement on the conical tubes under axial