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Effect of initiator, design, and material on crashworthiness performance of thin-walled cylindrical tubes: A primary multi-criteria analysis in lightweight design

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ABSTRACT

Two major requirements for crush analysis of thin-walled cylindrical tubes are being lightweight and having good crashworthiness. Thin-walled cylindrical tubes, which are either empty or foam filled, can potentially be used in all vehicles and moving parts such as road vehicles, train, aircrafts, ships, lifts and machinery to protect passengers and the structure itself during impact. This paper discusses an idea of utilizing the initiator on the foam-filled thin-walled circular tubes with stiffened annular rings to increase the specific energy absorption (SEA) and prevent the sudden force applied to the main part of the automotive and its occupants. Effect of initiator, at the top of the foam-filled aluminum tube, different densities of rigid polyurethane foam, and number of annular rings under axial compression were described through energy absorption, crush force efficiency (CFE), and mass of structure. In order to verify the numerical results, a series of quasi-static axial compression tests was performed, and both load–displacement curves and deformation mechanism of the structure were analyzed. The results of multi-criteria decision analysis (MCDA), by incorporating numerical and experimental data, showed that in the considered material and geometry, the design with an initiator, four rings tube, and higher density of foam have superior performance in terms of energy absorption, CFE, and mass. More debate on effect of initiator would help to reach the simultaneous improved crashworthiness structure and lightweight design with greater degree of accuracy in the hope of reducing the occupant injury in a collision.

1. Introduction

Crashworthiness studies provide mechanisms by which a proportion of impact energy is absorbed by the collapsing structure, whilst a small amount is transferred to the passenger. Impact energy absorption systems are used to protect automotive and its occupants from the effects of sudden impacts which occurs during collisions. The global transportation industry is seeking lightweight solutions to its products to reduce the energy consumption. In this context, innovative structures and lightweight materials, such as aluminum alloys, are introduced into the automobile body to replace traditional steel components. However, weight reduction of the auto body requires the reevaluation or redesign of the structures [1]. In order to achieve the best crashworthiness design as well as light weight, different criteria must be satisfied at the same time. Many experimental and theoretical studies have been carried out for this design aim, particularly high energy absorption per-unit weight or volume, which is very important in vehicles. Energy absorbers can be categorized into two major groups, the first is the reversible energy absorber, like the hydraulic dashpot or elastic damper, and the second is irreversible energy absorber, like energy dissipation in plastic deformation of thin-walled with different cross sections such as cylindrical, pyramidal, square, rectangular, triangular, hexagonal and frusta. During the last two decades some essential studies have been carried out in the wide range of irreversible energy absorption devices such as thin-walled tube structures [2–7]. The results have shown that circular tubes have the most energy absorption capacity and mean crushing load among all cross sections. Recently, thin-walled structures have been filled with foams. Foams are a new class of materials with extremely low densities and unique combination of excellent mechanical properties which help the stability of the tubes and improving the energy absorption. Many studies were performed using foams under both quasi-static and dynamic axial crushing load [8–10]. For example an experimental study was carried out by Hanssen et al. in order to investigate the axial deformation behavior of triggered, circular aluminum extrusions filled with aluminum foam under both quasi-static and

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dynamic loading conditions [11]. The behavior of foam-filled thin walled tubes with different cross-sectional shapes under axial compression was investigated by Thornton [12]. The obtained results indicated higher mean crushing load of the foam-filled tube than the sum of those individual tubes and the foam due to the interaction effects between both components. The effect of filling thin-walled circular metal tubes with low density polyurethane foam under both quasi-static and dynamic axial loading was studied by Reid et al. [13]. They showed that the stability of crushing improves by using polyurethane foam. Therefore the crushing load will increase, either due to the crush resistance of the foam or because of its influence on changing the buckling mode of the tube wall from diamond or mixed mode to ring mode. Ahmad and Thambiratnam have investigated crushing response of foam-filled conical tubes by using experimental and numerical simulation [14]. They displayed that the energy absorption of foam-filled conical tubes were significantly higher than that of the tubes without foam.

In design of thin-walled tubes, the peak force or the highest load required to cause significant permanent deformation, is as important as energy absorption for two reasons. Firstly, no permanent deformation is acceptable in low-speed and low-energy impacts. Secondly, the peak load has a direct affect on the loading of the vehicle occupant, and in actual physical tests the peak load is measured off from the reaction force. Therefore, various methods have been presented to reduce the initial peak load and enhance the crush force efficiency, such as creating circumferential grooves in the outer and inner surface of tube [15–18]. Many thin-walled tubes have stiffened by annular rings in order to improve the energy absorption, specific energy absorption and to avoid Euler buckling [19–22]. Recently, the effects of added initiator were studied on both circular and rectangular empty tubes [23,24]. A schematic of buckling initiator in the circular and the square tubes has been shown in Fig. 1. These results indicate that by installing a buckling initiator attached at the impact end, the initial peak force of a circular and square tube could be effectively reduced, whilst its deformation mode, excellent stiffness and energy absorption capacity could be retained. To the best of the authors' knowledge, there have been no published studies addressing the crashworthiness and lightweight design of thin-walled foam-filled circular tube in connection with the initiator mechanism. Therefore, this study evaluates the effectiveness of adding initiator on the circular tubes reinforced with annular rings and rigid polyurethane foam under axial loading. Furthermore, it seems few attempts was made to balance conflicting objectives for design of thin-walled structures, although applying multi criteria decision making (MCDM) techniques in combination of simulation tools are an excellent aid to the engineers [25,26].

2. Energy absorbing structure

Energy absorbing systems in general must be cost-effective, minimal weight, and promote ease of manufacture and installation. Due to the difficulty of completely analyzing an entire energy absorbing system such as the frontal structure of cars, the study of individual components has been substantially conducted to understand their impact behavior and energy absorption capability. Thin-walled tubes of different geometry and materials have been prevalently used as collapsible energy absorbers in various kinds of structural applications. Such devices are designed to collapse progressively for absorbing impact energy in a controlled manner and converting kinetic energy to plastic strain energy in impact situations. To measure the energy absorbing characteristics, when a thin-walled structure is collapsed under axial compression, the following parameters are obtained with reference to Fig. 2.

2.1. Absorbed energy

The total energy absorbed, E_{abs}, in crushing the structure is equal to the area under the load–displacement curve, where:

$$E_{abs} = \int P d\delta \tag{1}$$

where P and δ are the crush force and crush distance, respectively.

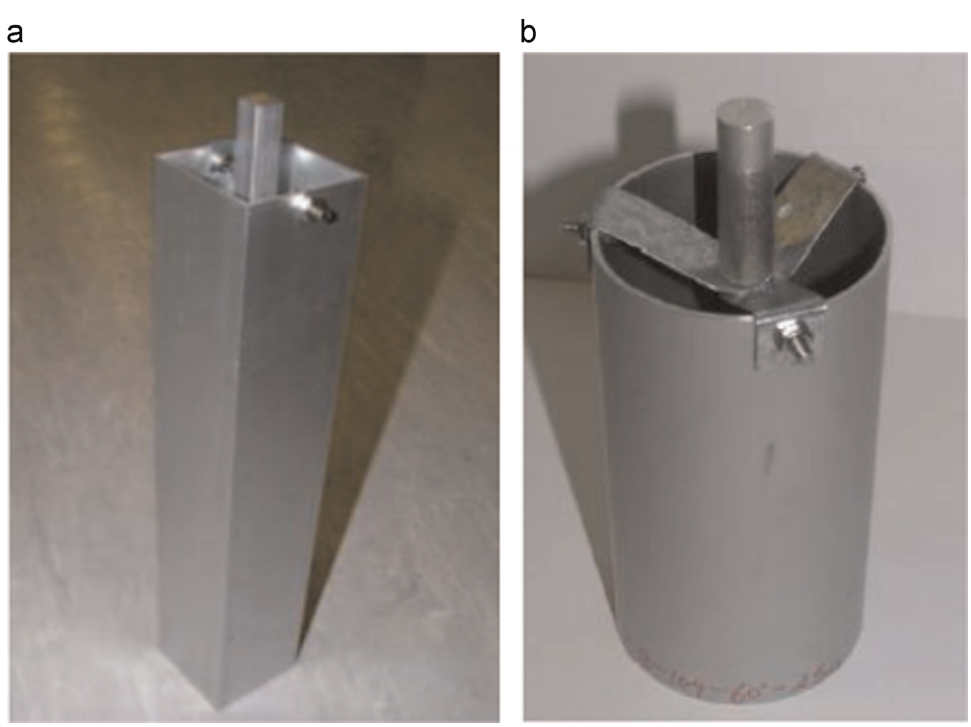

Fig. 1. Buckling initiator for the: (a) square tube and (b) circular tube [23,24].