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The effect of different shapes of holes on the crushing characteristics of aluminum square windowed tubes under dynamic axial loading

Hamid Nikkhah[a], Fenglin Guo[b], Youxiang Chew[c], Jiaming Bai[c], Jie Song[c,*], Pan Wang[c,*]

[a] Faculty of Engineering, School of Mechanical Engineering, University of Mohaghegh Ardabili, Ardabil 519911367, Iran
[b] School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiaotong University, Shanghai 200240, China
[c] Singapore Institute of Manufacturing Technology, Singapore 637662, Singapore

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ABSTRACT

In this paper, the crushing responses of tubes with different shapes of windows as well as the simple tube are investigated under axial and oblique loading conditions. Numerical model was constructed with FE code LS-DYNA and was validated by experiment. The model was then employed for the dynamic crush simulation of each tube at different load angles. The initial peak, crush force efficiency, energy absorption and specific energy absorption of windowed and simple tubes were compared and their overall crushing performances were evaluated by TOPSIS method. The results have proven the effectiveness of introducing windows to improve the tube's crushing performance and have showed that square and rectangle are the best window shapes.

1. Introduction

Energy absorbing devices provide protection over people and cargoes during crash events. By deforming irreversibly, such devices dissipate the impact energy and reduce the shock force that transmits to the people and goods. Usually the energy absorbing devices should exhibit low initial peak force which occurs in many axial and oblique loading conditions, and have high energy absorption (EA). Crush force efficiency (CFE) and specific energy absorption (SEA) are also used to evaluate the efficiency of the energy absorbing devices. More detailed description on the design criteria of energy absorbing devices can be found in Refs. [1,2]. If several design criteria are considered, multiply criteria decision making (MCDM) methods can be adopted, for example, the complex proportional assessment in Refs. [3,4].

Over the decades, numerous researches have focused on the crushing response of tubular structures under different kinds of loading conditions [5–8], in which tubes with regular shapes, e.g., square or circular cross-section, have received most attentions. As energy absorbers, tubular structures are easy to crush and their progressive collapse mode is advantageous in achieving high EA. To further improve their crushing performance, many modification techniques have been proposed. Singace and El-Sobky [9] introduced corrugation to the tube wall. They found that the quality and quantity of energy absorption could be controlled by the corrugation depth, and favorable crushing characteristics in terms of load uniformity and low deceleration pulse were observed. Song et al. [10] studied the axial crushing of tubular structures with origami pattern. Their results showed that the initial peak force was much smaller and the crushing process was more stable than that of the simple tube. Circular tubes with wide external grooves were studied by Salehghaffari et al. [11,12]. The ungrooved area functioned as external stiffeners and the grooved area became main body of the tube. They showed that the grooved tubes could achieve higher specific energy absorption and lower initial peak force.

Recently, tubes with patterned holes, so-called windowed tubes, have been found to have significant improvement in energy absorbing performance. The axial crushing test and simulation of windowed square tubes were conducted by Song et al. [13]. The results showed that windowed tubes could achieve up to 63% in the initial peak reduction and up to 54% in the SEA increment. Song [7] numerically investigated the crushing behavior of windowed tubes under oblique loading. It was found that by changing the size of windows at different locations of the tube, the windowed tube showed much higher energy absorbing capacity at large load angle, while at small load angle the energy absorption of windowed tube was the same as that of simple tube. An algorithm was also proposed to determine the size of windows at each section of the tube. Auersvaldt and Alves [14] studied the windowed square and hexagonal tubes under impact loading. They found that the windowed tubes presented significantly reduction in the initial peak load and that square windowed tubes could achieve higher SEA than the simple tube. However, for the hexagonal windowed tubes, the SEA was lower than that of the simple one.

Existing studies on windowed tubes focused mainly on those with

* Corresponding authors.
E-mail addresses: so0001ie@gmail.com (J. Song), wangp@SIMTech.a-star.edu.sg (P. Wang).

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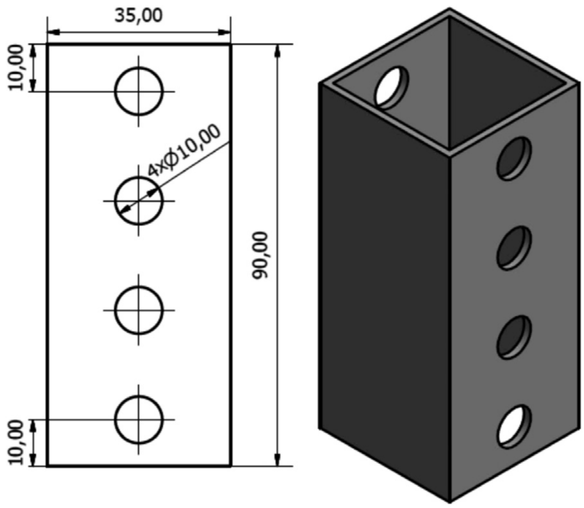

Fig. 1. Geometry of windowed tube with circular holes.

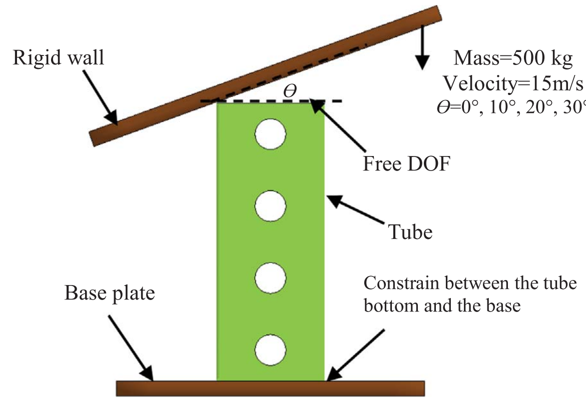

Fig. 3. Loading arrangement of the tube.

square or rectangular holes. In this paper, tubes with different shapes of holes under axial and oblique loading are studied, and their overall performances under various loading conditions are compared using a MCDM method called TOPSIS. This method compares different options through the evaluation of multiple criteria and ranks the options based on their scores. Details on the TOPSIS method can be found in Refs. [15–17]. The layout of this paper is as follows. First the geometries of the windowed tubes are presented. Next the FE model for the simulation of crushing process is described and is validated by the experiment. Then numerical results on the crushing responses of different windowed tubes as well as the simple tube are analyzed and their performances under different loading conditions are scored by TOPSIS method. The paper draws the conclusion at the end.

2. Geometry description

All the tubes considered are of square cross-section, with width being 35 mm, length being 90 mm and wall thickness being 2 mm. The geometry of the windowed tube with circular holes is shown in Fig. 1. There are 4 holes on each of the two opposite side walls, and the other two side walls are without holes. The holes, having diameter being 10 mm, are positioned on the wall with equal distance. The distance between the top (bottom) end of the tube and the center of the top (bottom) hole is 10 mm. Tubes with other shapes of holes have the same window arrangement as the one with circular holes, and the size of each hole is the same as the circular hole. The windowed tubes considered in the numerical simulation as well as the simple tube without windows are presented in Fig. 2.

3. Modeling and validation

3.1. FE modeling

FE code LS-DYNA was adopted for the axial and oblique crushing simulation. The sketch of loading arrangement is shown in Fig. 3. The bottom end of the tube is fixed onto the base plate and the top of the tube is free. The base plate is fixed. The rigid wall only moves in vertical direction and cannot rotate. The rigid wall, with mass 500 kg, impacts vertically onto the tube at an load angle, θ, which ranges from 0° to 30° at an interval of 10°. The mass was chosen to ensure that all the tubes could be fully crushed. The speed of impact is 15 m/s, which is a typical value used for the automobile crashworthiness application [18].

The tube was meshed with Belytschko-Tsay 4-node shell elements. Such element is suitable for the simulation of large structural deformation and has been adopted in previous studies on energy absorption [19,20]. The edge length of the element is 1 mm and there are 5 integration points through the wall thickness. Both the wall and the base plate were modelled as rigid body. Automatic single surface contact and surface to surface contact was adopted for the simulation of tube's self-contact and tube-to-wall contact respectively during the impact. The friction coefficient was 0.15. To take account the inevitable manufacturing error, small imperfection was introduced to the tube by superimposing the first four buckling modes onto the tube wall. Each buckling mode has a constant magnitude of 0.05 mm. As will be shown

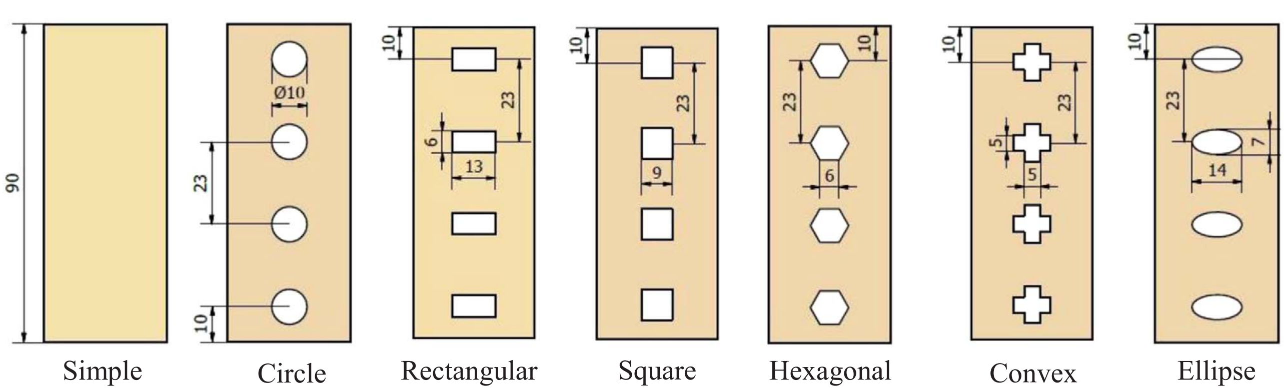

Fig. 2. Simple tube and windowed tubes with different shape of holes.