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Reprint of: Nested tube system applicable to protective structures against blast shock☆,☆☆

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ABSTRACT

Aiming at developing an efficient energy absorption component for protecting structures against blast shock, this paper proposes a triple-tube system (TT) consisting of three tubes. Its performance is studied experimentally and numerically, and compared with that of a double-tube system (DT) and a single-tube system (ST). The results show that the TT system can provide the highest energy absorption efficiency and the most stable deformation mode, so as to enhance energy absorption capacity for protecting structures. Then a parametric study is conducted to investigate the effect of the geometric parameters on the performance of the TT system and theoretical prediction of stage load is proposed to provide guidance for designing an effective TT system. Finally, the TT system is applied to a blast-resistance door used in civil air defense headquarters. The results demonstrate that the TT system can provide the most efficient impact force reduction and the lightest weight in protecting the structures from damage under blast shock wave.

1. Introduction

With the development of technologies, the lethality of the weapons is enhanced greatly. It is of a great demand to improve safety protection capabilities of civil air defense fortifications, especially the entrance gateway. Blast-resistant door is one of the choices for resisting blast load at the entrance. The traditional blast-resistant doors are usually designed in bulky and solid structures, which lead to poor operational performance and high costs [1]. Therefore, the door with high energy absorption and high buffering capacity is desirable.

Rings and tubes, due to simplicity in structure, easy manufacture and stable deformation mode, have been proven to be good energy absorption components. So far, rings and tubes have been investigated extensively. Burton and Craig [2] studied the performance of the ring under compression by rigid plates, showing a six-hinge deformation mode. DeRuntz and Hodge [3] proposed a four-hinge deformation mode and predicted the energy absorption performance under an assumption of ideal rigid-plastic material. Redwood [4] further studied the effect of strain hardening on the energy absorption performance. Reid and Reddy [5] assumed a short arc named plastica instead of a hinge, in attempting to obtain a more accurate prediction. Their theoretical prediction was more consistent with the experimental result. Silva-Gomes et al. [6] investigated the dynamic response of a ring system under impact load, and found that the response of the system could be obtained by analyzing the ring statically when the impact velocity was low. After that, Reid and Reddy [7] conducted further study about the response of ring system under high-speed impact. Based on the shock wave theory, the inerratic deformation of the ring system was analyzed, but there was a discrepancy between the theoretical prediction and experiment results because of wrap-around deformation mode.

As a simple and effective energy absorption component, tube still has great potential in various applications. To further enhance the capability of the ring system, Shen et al. [8, 9] prepared aluminium foam sandwiched tubes and conducted quasi-static lateral compression. Three major collapse patterns were observed. Olabi and his co-workers [10–12] proposed a nested two-tube system by putting a solid bar between two nested tubes, and demonstrated its effectiveness in enhancing the energy absorption capacity under quasi-static and lateral impact. Xiang et al. [13] studied the quasi-static bending behavior of sandwich beams with thin-walled tubes as core, and proved its high energy absorbing performance. Chen and Xue [14] proposed triple-tube system and analyzed its preliminarily features.

Due to TT system contains the geometrical parameters of three tubes, their sensitivity and the coupling effects on the performance of the TT system is important to achieve the objective

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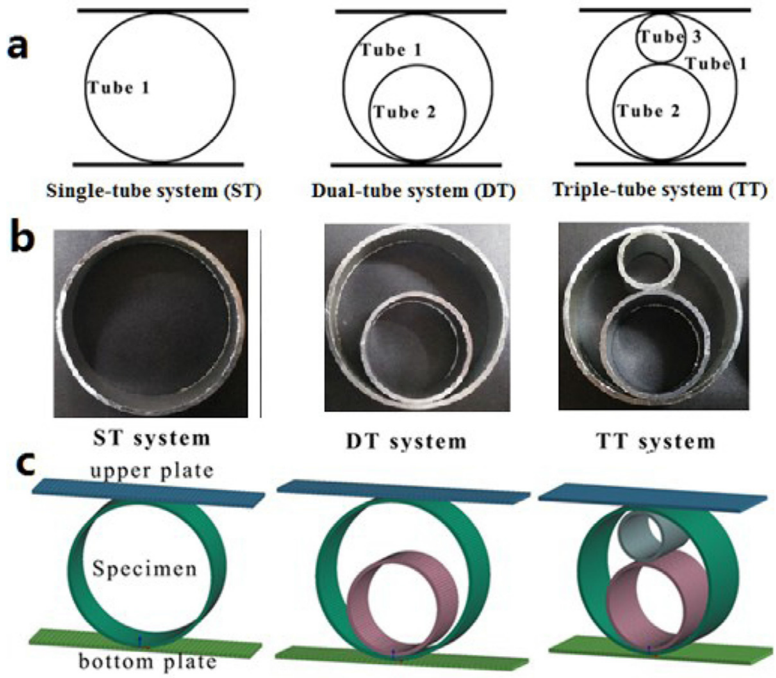

Fig. 1. Nested tube systems.

of protection. This paper further studies the TT system by investigating the effect of the geometric parameters on the performance of the TT system and provides theoretically guidance to design an effective TT system. Furthermore, the comparison with other two nested tube systems, i.e. single-tube system and double-tube system, are conducted and its energy absorption capacity is demonstrated. Finally, the TT system is applied to blast-resistance door for enhancing its resistance under blast shock wave.

2. Triple-tube system

Considering a tube with a diameter of D and thickness of t under compression between two rigid plates, its load can be predicted by [3]

$$P = P_0 / \left[1 - (\delta/D)^2\right]^{1/2} \quad (1)$$

where P_0 is initial collapse load, δ is the displacement of the compression. P_0 is given as:

$$P_0 = 2Yt^2L/D \quad (2)$$

Where Y is the yield stress of material, L is length of the tube. The energy absorbed can be obtained by integrating Eq. (1) over δ.

$$E_\delta = \int_0^\delta P_0 / \left[1 - (\delta/D)^2\right]^{1/2} d\delta = 2Yt^2L\sin^{-1}(\delta/D) \quad (3)$$

The energy absorption efficiency of tube can be evaluated by specific energy absorption (SEA). SEA is defined as the ratio of the absorbed energy by a structure to its mass and is given by:

$$SEA = E_\delta/m = 2Yt^2L\sin^{-1}(\delta/D)/\pi DLt\rho = 2Yt\sin^{-1}(\delta/D)/\pi D\rho \quad (4)$$

where ρ is the density. It indicates that the tube with smaller diameter and thicker thickness will have higher specific energy absorption. On the other hand, an ideal energy absorber should have long stroke, so keeping the large diameter for a tube system is necessary. Based on these two considerations, a nested triple-tube system is proposed, as shown in Fig. 1(a). In order to show its outstanding features, it is compared with the other two, i.e. single-tube system and double-tube system. The three types of nested tube systems are hereinafter referred to as ST, DT and TT system.

3. Experimental

3.1. Material and preparation of nested tube specimens

The studied tubes' systems were made of Aluminum alloy 6061-T6. The mechanical properties were provided by supplier as given in Table 1. Table 2 gave the tubes diameters of the three tube systems. The length of all these tubes was 15 mm, and the thickness of the tube wall was 1 mm. Fig. 1(b) showed the prepared specimens. The quasi-static tests were conducted using a universal test machine (MTS-810). The loading velocity is 10 mm/min.

3.2. Experimental results and discussion

Fig. 2 presents the deformed tubes of ST, DT and TT system which are observed from the experiments when deformation was 10 mm, 20 mm, and 30 mm, respectively. It could be observed that the ST system showed a typical four-hinge deformation mode in Fig. 2(a). The same deformation mode of two tubes in DT system was also observed, as shown in Fig. 2(b). It is because that the boundary conditions of each tube could be treated as that of compression by rigid plates. TT system gave a different deformation mode, as shown in Fig. 2(c). The tube 1 in TT system is a four-hinge deformation mode, while the tube 2 and tube 3 responded differently. The upper part of the tube 2 is deeply recessed, and the lower part of the tube 3 is convex. This is because that the initial collapse load of tube 3 is higher than that of tube 2.

Figs. 3 and 4 show the load-displacement curves and energy absorption of three tube systems. Obviously, the load of ST system was the lowest. The applied load of DT system was as the same as that of the ST system before the tube 2 was compressed. Once the tube 2 was compressed, a sudden increase in the load was observed,