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Dynamic response of self-locked energy absorption system under impact loadings

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ABSTRACT

The self-locked energy absorbing system can prevent lateral splash of tubes from impact loadings without any requirements for boundary constraints or inter-tube fasteners, thus breaking through the limitation of widely-used round tube systems. To reveal the mechanism of the impact response of self-locked systems, both impact experiment and FEM simulations are carried out. Based on the experimental and simulation results, a one-dimensional theoretical crushing model of the system is developed to analyze the dynamic response of the system, in which a plastic hinge model of the unit cell is proposed for the force-deformation relation. Three deformation modes of the system are predicted and observed, and moreover, the criteria to determine the deformation mode of the system are established analytically. A guideline on the design of the self-locked system is summarized, which is helpful in practical applications.

1. Introduction

Impact loadings may cause great damage to lives and properties due to their strong destructiveness and weak predictability, and accordingly, it is of great importance to understand the dynamic behavior of energy absorption systems subjected to impact loadings [1–6]. Previous studies on the dynamics response of energy absorption system mainly focus on metallic thin-walled round tube systems, because they have many advantages, such as easy manufacturability, low cost and high specific energy absorption [7–10]. For instance, Zhang and Yu analyzed the deformation mode and energy absorbing behavior of round tubes subjected to axial loading by both experimental and theoretical analysis [9]. Maduliat et al. proposed a yield line mechanism (YLM) model and investigated the energy absorption of circular tube under lateral impact loading [10].

Recently, researchers have made intensive efforts to improve the performance of round tube systems by geometry and material design. Langseth and Hopperstad studied the behavior of square thin-walled aluminum extrusions subjected to static and dynamic axial loadings by experiment [11]. El-Sobky et al. provided the optimum geometric conditions and appropriate constraints for the design of an efficient energy absorbing device based on frusta elements [12]. Liu et al. investigated the dynamic energy absorption characteristics of hollow microlattice structures by theoretical analysis and FEM simulation [13]. Wang et al. proposed a theoretical model of nested systems based on rigid, perfectly plastic material idealization [14]. Olabi et al. obtained the optimal design of nested system by experimental and numerical method [15]. Hanssen et al. investigated the energy absorption characteristics of the square extrusions with aluminum foam filler under static and dynamic crushing [16]. Song et al. investigated the axial impact behavior and energy absorption efficiency of composite wrapped metal tubes [17].

Although round tube systems are widely used in many fields, the weakness of round tube is obvious. Due to the extreme low rolling frictional resistance, the round tube systems require extra labor and time to assemble and fasten the tubes together, resulting in a slow response to the need of impact protection in emergencies. To improve the modifiability and reduce the response time of energy absorption systems, Chen et al. recently proposed a novel self-locked energy absorbing system, in which tubes can interlock with each other and thus avoid splashing and secondary damage under lateral compressive loadings [18–20]. Moreover, they developed plastic hinge models to investigate the energy absorbing performance of self-locked systems under static loading [18,19]. However, the dynamic energy absorption characteristics of the self-locked system are rarely studied. The investigation on dynamic characteristics is essential for energy absorbing systems in applications because it can provide comprehensive understanding into the mechanisms of the system response and give suggestions for the optimal design of the systems in impact protections.

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This paper is aimed at revealing the mechanisms of dynamic response of the self-locked systems under impact loadings and establishing a criterion to predict the dynamic behaviors of these systems. The paper begins with an impact experiment in Section 2, which presents the deformation mode of the self-locked system under a moderate-speed compressive impact. Subsequently, based on the experimental and simulation investigations, a theoretical crushing model of the system and a plastic hinge model of the unit cell are proposed in Section 3. Three dynamic deformation modes are revealed in Section 4, in which the factors that dominate the dynamic deformation mode are studied and the criterion to predict the deformation mode is built analytically. Suggestions on the system design are provided in Section 5 and conclusions are drawn in Section 6.

2. Impact experiment

An impact experiment is carried out in this section to reveal the dynamic response of the self-locked system, which presents the self-locking effect of the system as well.

2.1. Self-lock tube specimens

The self-lock tube specimens are manufactured by compressing large round tubes with suitable dies and cores following the process in Ref. [20]. A single self-lock tube is comprised of two open cylindrical shells and two parallel flat plates, and the geometry is determined by 5 parameters as shown in Fig. 1(a) and (b): the length L, the width of flat plates W, the spacing between the flat plates S, the thickness T and the mean diameter D. Here the mean diameter D is the average of the external and internal diameters of cylindrical shell. The average geometric parameters of single manufactured self-lock tube specimen are as listed in Table 1.

The specimens are made of 201 stainless steel, of which the material properties are listed in Table 2.

A multiple-tube energy absorption system can be assembled by stacking the single tubes in a staggered arrangement, so that the tubes can interlock each other and thus provide lateral constraint to each other to avoid splash and secondary damage when the system is subjected to lateral impact loadings. In the impact experiment, the self-locked system was assembled by stacking 72 single self-lock tube specimen in 16 layers, as shown in Fig. 1(c). The total mass, height and width of the self-locked multiple-tube system were 8.93 kg, 210 mm and 400 mm, respectively.

It should be noted that, the self-lock design not only provides inter-tube constrains to avoid splashing and secondary damage under lateral compressive loadings, but also brings good energy absorption properties, including low response force and high energy absorption efficiency of the system. The comparison between the self-locked system and the widely-used round tube system are provided in Appendix A.

2.2. Experimental setups

The impact experiment of the self-locked system was carried out by the DHR-1205 drop hammer rig, as shown in Fig. 2(a). The experimental setup is comprised of a drop hammer, a force transducer, an oscilloscope, a high rate photographic instrument, the loading and supporting plates and the specimens. The sketch of the experimental specimens with loading conditions is shown in Fig. 2(b). The mass of drop hammer ranges from 2 kg to 200 kg, and the maximum drop height is 30 m. The loading and supporting plates are both 58.2 kg, 90 mm in thickness, 580 mm in length and 150 mm in width. Taking both economy and stiffness into consideration, both plates are comprised of two layers connected by bolts: a main layer made of 1045 steel with thickness of 80 mm and a contact layer made of Cr12MoV with thickness of 10 mm. The loading plate is connected to the drop hammer by bolts. In this research, the total drop mass and the drop height were 133.34 kg and 8 m, respectively, corresponding to the initial velocity of 12.5 m/s. The supporting plate was fixed on the pedestal by bolts. The experimental specimens were stacked on the supporting plate and crushed by the loading plate. The force transducer was installed on the supporting plate to measure the reaction force of the supporting plate F_s, and a force-time curve can thus be recorded. The data were displayed and saved by the oscilloscope with the sampling frequency 50 kHz. Photographs of the self-locked system deformation were taken through the high rate photographic instrument of 1400fps.

Table 1
Average geometric parameters of self-lock tube specimens (mm).

L	D	T	S	W
100.4	20.97	0.88	2.61	38.01

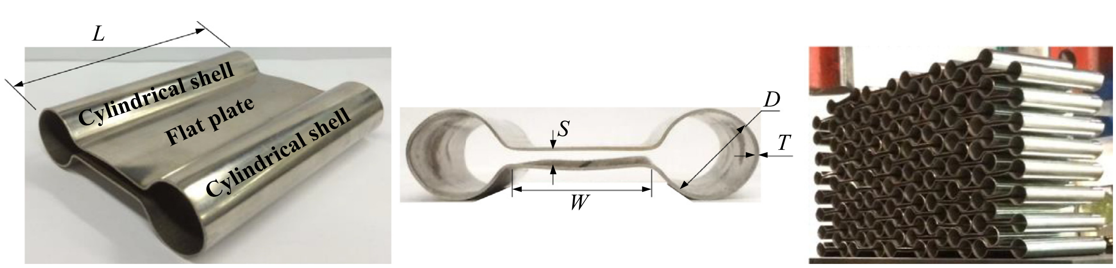
Table 2
Material properties of self-lock tube specimens.

Young's modulus E (GPa)	Poisson ratio ν	Initial yield stress σ_s (MPa)	Density ρ_m (kg/m^3)
191	0.26	322	7830

2.3. Results and discussion

The force F_s of supporting plate obtained from experiment is presented by the black curve with hollow squares in Fig. 3, and the deformed configurations of the self-locked system at points A–E in Fig. 3 are shown in Fig. 4(a)–(e). The FEM simulation is also carried out by ABAQUS/Explicit, with details in Appendix B. In the simulation, the tube parameters and loading conditions are exactly same as those in the impact experiment in order to make a comparison. The force-time curves of the loading and supporting plates as well as the energy of the system obtained from FEM simulation are presented in Fig. 3, and the deformation configurations are presented in Fig. 4(f)–(j).

The initial velocity of the loading plate was 12.5 m/s when the loading plate just contacted the system, as shown in Fig. 4(a). After that, the crushing progress entered stage I. In this stage, the crushing of the system was progressively developing from the loading plate towards



(a) (b) (c)

Fig. 1. Self-lock tube specimens: (a) a self-lock tube specimen and (b) the cross section of the tube with geometry parameters, and (c) the self-locked system with 72 tube specimens.