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A novel self-locked energy absorbing system

Yuli Chen [a,*], Chuan Qiao [a], Xinming Qiu [b], Shougen Zhao [a], Cairu Zhen [a], Bin Liu [b]

[a] Institute of Solid Mechanics, Beihang University (BUAA), Beijing 100191, China
[b] AML, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China

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ABSTRACT

Metallic thin-walled round tubes are widely used as energy absorption elements. However, lateral splash of the round tubes under impact loadings reduces the energy absorption efficiency and may cause secondary damage. Therefore, it is necessary to assemble and fasten round tubes together by boundary constraints and/or fasteners between tubes, which increases the time and labor cost and affects the mechanical performance of round tubes. In an effort to break through this limitation, a novel self-locked energy-absorbing system has been proposed in this paper. The proposed system is made up of thin-walled tubes with dumbbell-shaped cross section, which are specially designed to interlock with each other and thus provide lateral constraint under impact loadings. Both finite element simulations and impact experiment demonstrated that without boundary constraints or fasteners between tubes, the proposed self-locked energy-absorbing system can still effectively attenuate impact loads while the round tube systems fail to carry load due to the lateral splashing of tubes. Furthermore, the geometric design for a single dumbbell-shaped tube and the stacking arrangement for the system are discussed, and a general guideline on the structural design of the proposed self-locked energy absorbing system is provided.

1. Introduction

Convenient and effective protections against collision, impact and blast loadings can greatly save lives and properties from car accidents, projectile impact and explosions (Bazant and Su, 2015; Chen et al., 2009; Fleck and Deshpande, 2004; Hanssen et al., 2006; Mills et al., 2009; Neves et al., 2010; Su et al., 2015; Wasiowych et al., 1996; Xu et al., 2014, 2009; Yang et al., 2003). So it is of great importance to design stationary and temporary impact-resistant energy absorbing systems, which have attracted attentions of many researchers (Abramowicz, 2003; Alexander, 1960; Dharmasena et al., 2008; Evans et al., 2001; Ezra, 1972; Gibson and Ashby, 1997; Johnson and Mamalis, 1978; Jones, 2011; Jones and Wierzbicki, 2010; Langseth and Hopperstad, 1996; Lu and Yu, 2003; Qiu and Yu, 2011; Rawlings, 1974; Shukla et al., 2010). The basic principle of these systems is to dissipate kinetic energy by plastic deformation of structures (Alghamdi, 2001; Lu and Yu, 2003; Olabi et al., 2007). Well-designed energy-absorbing system attenuate the impact effect in a designed way: not only a certain amount of impact energy can be absorbed, but also the impact force and deceleration can be controlled within a desired range (Carney III, 2010; Liu et al., 2014b; Yu, 1986).

Metallic thin-walled tube is one of the most widely used energy absorbing structural elements in civil and defense

* Corresponding author.
E-mail address: yulichen@buaa.edu.cn (Y. Chen).

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engineering for its absorption characteristics and practical advantages, such as stable and long deformation process, small initial impact force, high specific energy dissipation, easy manufacturability, and low cost. Therefore, many existing impact energy absorbing systems are comprised of multi-row round tubes (Carney III, 2010; Shim and Stronge, 1986).

An early investigation on the lateral dynamic plastic flow buckling of a cylindrical metallic shell was carried out by Abrahamson and Goodier (1962), and the effect of tube wall thickness was considered in the lateral impact experiment of a single round tube. Later, the effect of elasticity as well as the strain-rate reversal was analyzed by Lindberg (1965), Lindberg and Kennedy (1975), Lindberg and Florence (1987) and Jones and Okawa (1976). Symonds (1965) discussed the impact of elastic waves on dynamic response of structures and indicated that the ultimate deformation mode is influenced by those waves. Through further research on the role of elastic waves and revision of the structural shock theory, a theoretical analysis performed by Reid and Bell (1984) revealed the significance of elastic waves on the deforming pattern and energy dissipation. Based upon these findings, Choi et al. (1986) investigated the strain-rate effect in steel tube clusters and indicated that neglect of strain rate would lead to underestimation of energy absorbing capacity. Duffey et al. (1990) and Florence et al,. (1991) analyzed the effect of impact velocity variance on the buckling of shells. The lateral compression of a tube between rigid plates was analyzed by DeRuntz and Hodge (1963) using a rigid perfectly plastic model with 4 plastic hinges, and Redwood (1964) included the strain hardening effect in DeRuntz and Hodge's model. A different collapse mode with 6 plastic hinges was proposed by Burton and Craig (1963). The effect of strain hardening was further studied by Reid and Reddy (1978) using plastic arc instead of plastic hinge.

Recently, researchers have been working on the improvement of the round tube system and proposed many new energy-absorbing devices based on round tubes. Shrive et al. (1984) introduced a cylindrical system comprised of two concentric rings and a series of smaller tubes welded in between. The rings did not completely flatten under the impact load and the maximum opposing forces agrees with results from quasi-static tests. Reddy and Reid (1979) investigated the effect of side constraints for closed systems. Nested tube system were examined by Morris et al. (2006, 2007) and Wang et al. (2015).

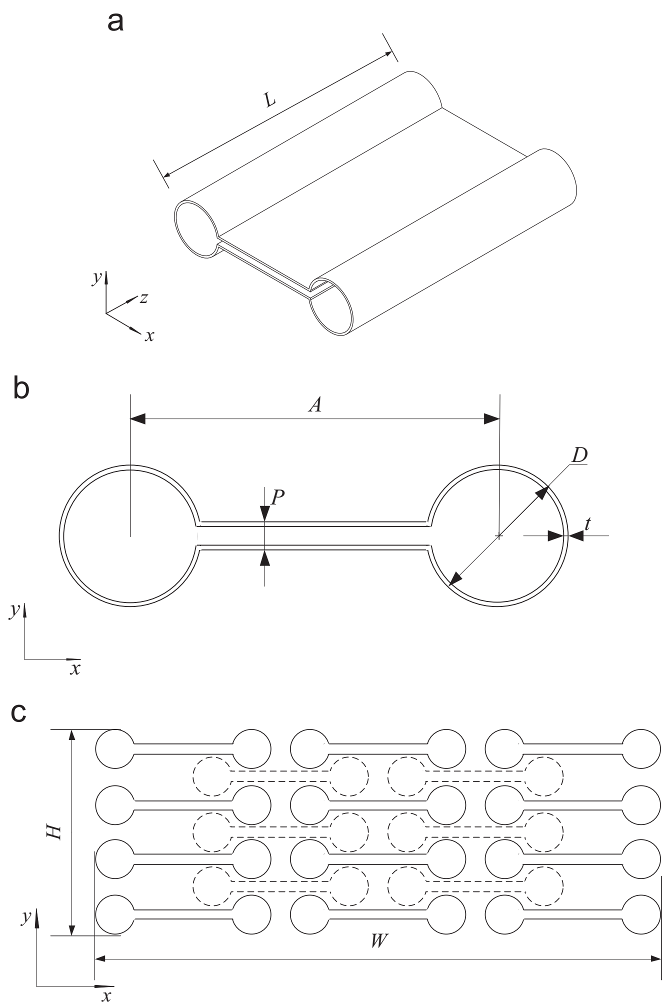

Fig. 1. Schematic of (a) a dumbbell-shaped tube, (b) the cross section of a dumbbell-shaped tube and (c) the self-locked energy-absorbing system.