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Approaching perfect energy absorption through structural hierarchy

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ABSTRACT

Energy absorbing efficiency of thin-walled tubular structures is restricted by the long-wave folding elements, which makes the mean crushing force (MCF) of the thin-walled tubular structure usually much smaller than its yielding strength. Hierarchical lattice topology increases the energy absorbing ability of tubular structure notably without increasing the weight. In an effort to reveal this advantage, hierarchical rectangular tubular structures are proposed in this paper. These proposed structures have multi-cellular structure and lattice sandwich cellular walls. During crushing of these structures, three typical folding styles, i.e., macro-cell folding, micro-cell folding and hybrid folding were observed in both experiments and finite element (FE) simulations. Micro-cell folding has relative short wave length depending on the dimension of the microstructure cells. Macro-cell folding has relative long wave length determined by the dimension of the overall tubular structure. Micro-cell folding notably increases the mean crushing force (MCF) while macro-cell folding decreases the MCF. However, the maximum MCF is associated with the hybrid folding style which is a transition from micro-cell folding to macro-cell folding. When the hierarchy level of the tubular structure is gradually increased, the MCF approaches the full-plastic strength of the matrix. Through high order hierarchical topology, extraordinary energy absorption can be achieved.

1. Introduction

Thin-walled structures are most commonly used as crash-resistant energy absorbing devices. Abramowicz and Jones (1984, 1986), Abramowicz and Wierzbicki (1989), Wierzbicki and Abramowicz (1983) and others proposed the crushing model of circular and square tubes. Hong et al. (2013) and Sun and Fan (2017) observed a new folding element, named as inward-contracted folding element, during the compression of triangle tubes, which is different from the two conventional plastic collapse elements, extensional and in-extensional folding elements. Wang et al. (2015) studied the collapse mechanism and energy absorbing ability of triangle tubes in lateral compression. These researches provide considerable insights into the energy-absorbing mechanisms of tubular structures.

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A limitation of the thin-walled tubular structure is that the MCF is usually much smaller than the peak force (PF) induced by long wave length of the folding. To increase the weight efficiency of tubular structures as energy absorbers, efforts were dedicated to multi-cell tubular structures. Birman (2014) improves energy absorption of cylinder through functionally graded structure. Chen and Wierzbicki (2001) studied single-cell, multi-cell and foam-filled thin-walled structures in energy absorption. It was found that the interaction effects between the foam core and the column wall contribute to the total crushing resistance by the amounts equal to 140% and 180% of the direct foam resistance for double cell and triple cell, respectively. Hong et al. (2014) designed multi-cell tubes with triangular and Kagome lattices to realize the progressive collapse mode and explore the folding mechanism of thin-walled multi-cell tubes. Zhang and Zhang (2014) studied the energy dissipation mechanisms of circular multi-cell columns and proposed theoretical models to predict the mean crushing force. Tran, Hou, Han, Tan, and Nguyen (2014) conducted crashworthiness optimization of multi-cell triangular tubes. Sun, Lai, and Fan (2016a) decomposed the multi-cell trianglular tubes into 3-panel angle elements, 4-panel angel elements and 6-panel angel elements, and derived the equations for the energy dissipation. Qiu et al. (2016) analyzed the mean crushing force for four different hexagonal tubes with multiple cells based on the simplified super folding element (SSFE) theory.

Some researchers investigated energy absorptions of hybrid structures (An & Fan, 2016). Deshpande and Fleck (2003) investigated energy absorption of an egg-box material. Xu, Qiao, and Chen (2014) mitigated impact/blast energy via a novel nanofluidic energy capture mechanism. Chen, Qiao, Shougen Zhao, Zhen, and Liu (2016) proposed a novel self-locked energy absorbing system to consume more impact energies. Zhang, Heyne, and To (2015) enhanced energy dissipation through biomimetic staggered composites. Foam-filled tubes (Wang, Fan, Chen, & Liu, 2016; Yang, Meguid, & Hamouda, 2017; Zheng, Wu, Sun, Li, & Li, 2014; Zheng et al., 2014) usually have better energy absorption than the linear summation of the components. However, when the cells are full-filled, the weight efficiency is decreased.

Hierarchy can make thin-walled structures even more weight-efficient (Fan et al., 2008; Sun, Zheng, Fan, & Fang, 2017). Lakes (1993) constructed hierarchical paper honeycomb whose plastic strength was 3.8 times higher. Fan et al. (2008) described the mechanism of hierarchical structure in improving the stiffness and strength, and proved that hierarchy can make thin-walled structures even more weight-efficient in energy absorption. Fan et al. (2012, 2013) and Zheng, Zhao, and Fan (2012) made hierarchical honeycombs using ductile woven textile composites. Their specific energy absorption (SEA) is even greater than those of metallic lattice trusses and honeycombs. Recently, progresses in manufacturing technology enabled scientists fabricate nano-lattice structures (He, Wang, Zhu, Wu, & Park, 2017; Meza, Das, & Greer, 2014; 2015; Schaedler et al., 2011; Zheng et al., 2014). Some of these lattices have excellent energy absorption profited from hierarchical lattice topology. But most of them are not ideal in energy absorption due to the brittleness of the matrix and the three-dimensional lattice topology.

Two-dimensional sandwich-walled triangular lattice tubular structures were designed and tested by Sun et al. (2016a, 2016b) to explore the energy-absorbing mechanism. Based on the tests, three mechanisms contribute to the enhanced crushing resistance of the hierarchical structure, i.e., hierarchical fold, shorter wave length and greater plastic bending moment of sandwich wall. However, the improvement will be trade off by the transition of folding mode from progressive folding to global bending. The MCF is still far below the full-plastic strength of the structure.

In order to further enhance the energy absorbing ability of tubular structures, higher order hierarchical lattice tubular structures are proposed in this paper. Energy absorbing mechanisms relating to hierarchy are investigated experimentally, numerically and theoretically.

2. Hierarchical lattice structures

2.1. Perfect energy absorbing structure

Here a structure can be considered as a perfect energy absorber if its mean crushing stress (MCS), σ_m, defined by the ratio of the MCF to the area of the structure, satisfies

$$\sigma_m = \frac{P_m}{A} = \rho^*\sigma_p \text{ or } P_m = P_p = \rho^*\sigma_p A, \tag{1}$$

where, σ_p is the full-plastic stress, $\sigma_p = (\sigma_y + \sigma_u)/2$ or $\sigma_p = \sqrt{\sigma_y\sigma_u}$. σ_y is the yield stress. σ_u is the ultimate stress. P_p is the full-plastic force of the structure. P_m is the MCF. A is the cross-section area of the tubular structure. s is the cross section area of solid walls. $\rho^*=s/A$ is the relative density. According to Eq. (1), the mass utilization efficiency is 100% for the perfect energy absorber.

Aluminium foams are always deemed as excellent energy absorbing materials, with (Gibson & Ashby, 1997)

$$\sigma_m = 0.3\rho^{*1.5}\sigma_y, \tag{2}$$

According to experiments of Kooistra, Deshpande, and Wadley (2004), MCS of aluminium tetrahedral lattice truss structures is given by Jiang, Sun, Zhang, and Fan (2017) as

$$\sigma_m = 1.224\rho^{*1.5}\sigma_p. \tag{3}$$

Meza et al. (2015) gave MCS of polymer second-order hierarchical nano-lattice as

$$\sigma_m = 0.316\rho^{*1.36}\sigma_y. \tag{4}$$