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Investigation of lateral crushing behaviors of hierarchical quadrangular thin-walled tubular structures

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ABSTRACT

Energy absorbing efficiency of thin-walled tubular structures is restricted by the folding of the ultra-thin walls, depressing the mean crushing force (MCF) of the tubular structure. Hierarchical topology increases the energy absorbing ability of tubular structure notably without increasing the weight. In an effort to reveal this advantage, hierarchical quadrangular tubes (HQTs) are proposed in this paper. These proposed structures have multi-cellular structure and sandwich cellular walls. During the crushing, two deformation stages, including crushing of the side walls and compression of the short vertical ribs in the horizontal sandwich walls, were observed in the experiments. The latter greatly increases the MCF of thin-walled quadrangular tubes (TQTs). Based on three typical folding elements and two energy absorbing mechanisms, the MCF can be consistently predicted. According to the research, extraordinary energy absorption can be achieved through hierarchical topology design.

1. Introduction

Thin-walled structures are most commonly used as crash-resistant energy absorbing devices. Abramowicz and Jones [1,2], Abramowicz and Wierzbicki [3], Wierzbicki and Abramowicz [4,5] and others proposed the crushing model of circular and square tubes. Hong et al. [6], Sun and Fan [7] 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.

Lateral crushing behaviors are also important for thin-walled tubes. Gupta et al. [7] presented experimental and computational investigations of the deformation and energy absorbing behavior of rectangular and square tubes of aluminum and mild steel under lateral compression. It is seen that the tube section collapses on account of formation of two sets of plastic hinges. Wang et al. [8] and Fan et al. [9] studied the collapse mechanism and energy absorbing ability of triangle tubes in lateral compression. Tran and Ton [10] investigated lateral crushing behaviors of thin-walled rectangular and square tubes.

A limitation of the thin-walled tubular structure is that the mean crushing force (MCF) is usually much smaller than the peak force (PF) induced by long wave length of the folding [11]. To increase the weight efficiency of tubular structures as energy absorbers, efforts were dedicated to multi-cell tubular structures. Tran et al. [12,13] studied lateral crushing behaviors multi-cell thin-walled triangular tubes under lateral loading. Hierarchy can make thin-walled structures even more weight-efficient. Sun et al. [14,15] 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. Two-dimensional sandwich-walled triangular lattice tubular structures were designed and tested by Sun et al. [14,15] 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. Qiao and Chen [16] numerically studied in-plane crushing behaviors of hierarchical honeycombs, whose walls are made of triangular lattices. The hierarchical honeycomb has an improved collapse stress in numerical simulation.

In order to improve the energy absorbing ability of tubular structures in lateral crushing, higher order hierarchical quadrangular tubular structures are proposed in this paper. Energy absorbing mechanisms relating to hierarchy are investigated experimentally and theoretically.

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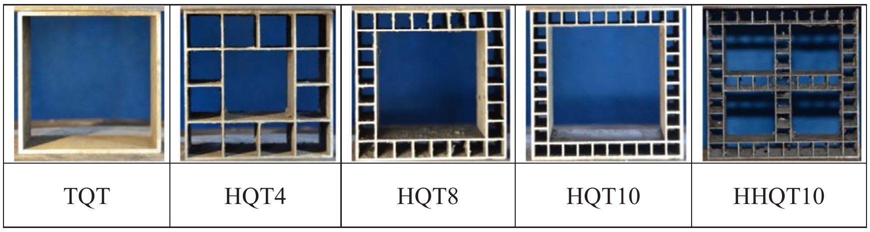


Fig. 1. Topology of thin-walled quadrangular tube, hierarchical quadrangular tube and high-order hierarchical quadrangular tube.

2. Hierarchical quadrangular tubes

For thin-walled quadrangular tubular structures, lower post-failure strength limits their energy absorption. Optimized topology can improve the post-failure strength. For this purpose, hierarchical quadrangular tubular structures are proposed that the side wall is turned into sandwich panel with micro-cells of thinner and shorter ribs, as shown in Fig. 1. Each side of HQT has N segments and there are N micro-cells in each sandwich wall. Another weight-efficient topology is high-order hierarchical quadrangular tube (HHQT). The tubular structure has a hierarchical structure with self-similarity. Each side has N segments and N micro-cells in each sandwich wall.

Based on the topology of hierarchy, TQT, HQT4, HQT8, HQT10 and HHQT10 were designed and fabricated, as shown in Fig. 1. The number denotes the cell number in each sandwich wall. All the specimens were manufactured by wire cutting from solid steel Q235 rod. The tensile stress-strain behavior of Q235 is tested according to GBT 228.1–2010. The Young's modulus E is 210 GPa. The yield stress σ_y is 343 MPa. The ultimate stress σ_u is 475 MPa. The Poisson's ratio υ is 0.3. All these tubes have identical mass. The tube length is 100 mm, the side length of the square tube is 120 mm, as listed in Table 1. For TQT, the wall thickness is 3.0 mm.

3. Experimental investigations of lateral crushing behaviors

3.1. Thin-walled quadrangular tube

The tubes were compressed under a universal test machine at a loading rate of 2 mm/min. As shown in Fig. 2, after elastic deformation the tube reaches its peak force (PF), P_f, 170.6 kN, then the load, P, drops down, accompanying with the buckling and folding of the two lateral sides. The quadrangular tube changes into a dumbbell shape. This process is called Stage A for thin-walled quadrangular tube. When

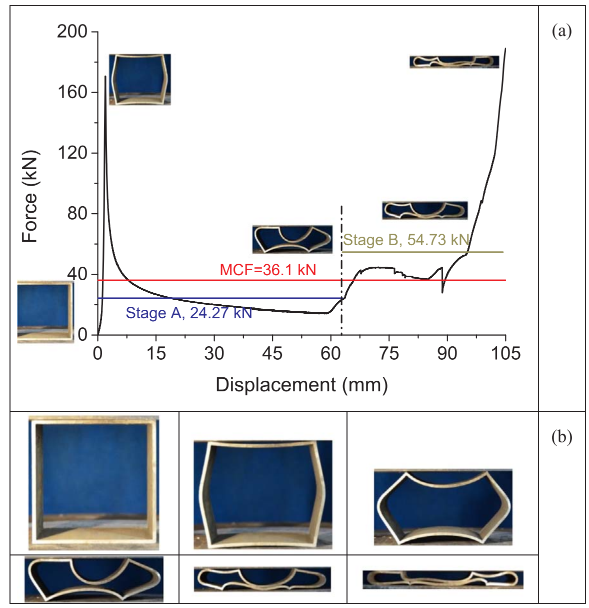
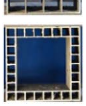
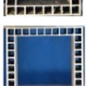
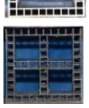


Fig. 2. Lateral crushing behavior of thin-walled quadrangular tube: (a) Displacement curve and (b) crushing styles.

the upper part of the lateral sides rotates to horizontal state and fully contacts with the loading plateau, meanwhile the two horizontal sides contacts with each other, Stage A ends. The deformation, Δ, is about 63 mm. The force then climbs up to a stable plastic state. This process is called Stage B until densification begins. The deformation at the densification, Δ_d, is about 104.3 mm, where the force is equal to the peak force, 170.6 kN. The MCF, P_m, is defined by

Table 1
Geometry and dimensions of thin-walled square tubes.

Tube		Side wall Segment number, N	Cell number	Side length, L (mm)	Wall thickness, t (mm)	Tube length, H (mm)	Cross-section area of solid walls, S (mm^2)
	TQT	1	1	120	3.0	100	1440
	HQT4	4	12	120	1.343	100	1440
	HQT08	8	28	120	1.145	100	1440
	HQT10	10	36	120	1.11	100	1440
	HHQT10	10	53	120	0.78	100	1440