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Multi-objective optimization of multi-cell tubes with origami patterns for energy absorption

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ABSTRACT

Three novel types of multi-cell tubular structures with pre-folded origami patterns were proposed in this paper, aimed at reducing the initial peak force and the crushing force fluctuation while maintaining or increasing the specific energy absorption during uniaxial crush. Experimentally validated finite element modelling was conducted to study the influence of geometric parameters on the mechanical properties. Optimal designs were obtained through multi-objective optimization. The results showed that predesigned origami patterns governed the buckling process of the tubes and quintuple-cell origami tubes could absorb the highest energy in crush with significantly reduced initial peak force and the crushing force fluctuation.

1. Introduction

Thin-walled metal tubes have been widely used as energy absorption structures due to their excellent energy absorption capacity and crashworthiness [1]. The energy absorption capacity of thin-walled metallic tubes under axial crushing loads has been intensively studied over decades. Among various types of tubes with different cross-sectional profiles, square tube is one of the most commonly used structural components for energy absorption. It has been reported in experimental studies that there are mainly two types of buckling modes for the axially crushed square tube, i.e., compact mode and non-compact mode. Compact buckling mode is a typical deformation mechanism for the square tubes during compression, while the non-compact buckling mode only occurs when the tube wall is substantially thin and, therefore, the crushed tube would be separated by several curved panels [2]. To further investigate the mechanical response of square tubes, Meng et al. [3] conducted a series of axial crushing tests on PVC square tubes and captured a collection of successive buckling procedure for the crushed specimen. In their studies, the buckling patterns observed in experiments were visually illustrated by paper models with travelling plastic buckling lines, showing a final inclination of about $\pi/4$ on the straight corner. Meanwhile, Wierzbicki and Abramowicz [4] proposed an analytical model for the axially crushed square tube based on the deformation procedure observed in physical tests, and presented the formulae for calculating the mean crushing load along with the energy absorption in compression.

Conventional thin-walled tubes are structurally simple with good energy absorption capacity. However, their collapse mode is highly sensitive to random defects accompanied by high initial peak force and violent fluctuations in the plateau region of the force-displacement curve, which increases the risks of whiplash injuries and submarining effects in accidents. To overcome the shortcomings of conventional tubes, many approaches have been proposed in the design. A common method is introducing geometric imperfections. Singace and Ei-Sobky [5] introduced sinusoidal corrugations to conventional tubes to guide the buckling process along with improved uniformity of the plateau force when subjected to axial crushing load. Based on this research, Wu et al. [6] experimentally and numerically studied the influence of wavelength and amplitudes of the sinusoidal corrugations on the energy absorption capacity. It was found that the pre-defined corrugations could guide the buckling process of the tube along with flattened load-displacement curves. However, the energy absorption capacity was reduced simultaneously because of the weakened resistance in the loading direction. Except of the introduction of geometric imperfections, the applications of origami patterns also aroused much attention in this field. Ma and You [7] developed a special square tube with origami patterns in the corner, which was designed to guide the collapse mode and increase the plastic travelling lines simultaneously. Ma et al. [8] later studied the energy absorption of another type of tube with Miura-ori patterns. Inspired by the work of Ma and You [7], Yang et al. [9] proposed another type of origami tube with Yoshimura-pattern, which was observed in the crushing tests of conventional circular tubes [10]. The experimentally verified numerical results showed that the pre-designed origami patterns could assist to lead the collapse process

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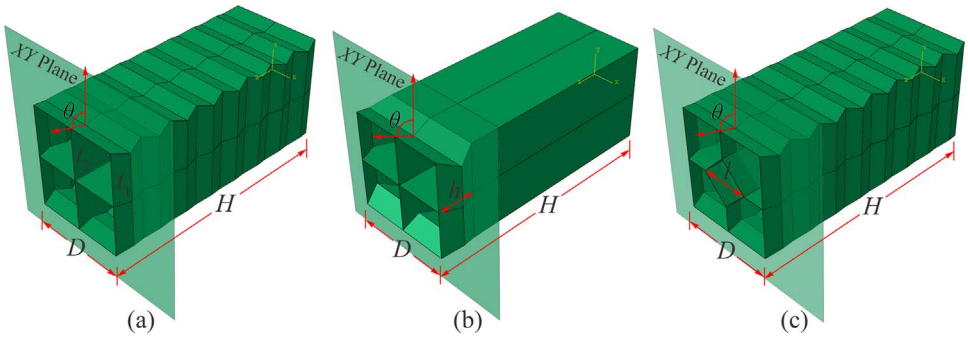

Fig. 1. Geometric models for (a) origami-patterned quadruple-cell tube, (b) origami-triggered quadruple-cell tube, and (c) origami-patterned quintuple-cell tube.

along with increased energy absorption capacity as compared to conventional circular tubes. It should be noted that manufacturing the origami-patterned tube might be more cost-effective by applying origami mechanism technique proposed by Zhou et al. [11], in which, steel plates were stamped by a specially designed mould to create half origami tubes. The half origami tubes were then welded and post-processed by heat treatment to reduce the residual stress.

As compared to the designs by adjusting geometric parameters in single-cell tubes, it has been found that tubes with multi-cell sections could achieve higher efficiency in energy absorption due to the fact that travelling plastic hinge lines and in-plane stretch of walls in corner regions accounted for two thirds of the total energy absorbed by an axially crushed square tube [4,12]. Chen and Wierzbicki [13] analytically and numerically studied the mechanical response of double-cell and triple-cell square tubes, and observed evident increase in the specific energy absorption in comparison with that of conventional square tubes. Kim [14] proposed a special type of multi-cell square tube with four square elements at the corner and found that the specific energy absorption was evidently increased as compared to conventional tubes. Similar advantages were also witnessed in cylindrical tubes with multi-cell sectional profiles [15]. Hong et al. [16] designed and manufactured a type of multi-cell tubes with triangular and Kagome lattice patterns, which showed higher weight-efficiency in the energy absorption than the single-cell tubes. Based on triangular multi-cell tubes, Sun et al. [17] developed a type of hierarchical tubular structure and found that its mean crushing force was higher than that of the triangular multi-cell tube. Based on the Super Folding Element theory [12], Zhang et al. [18] derived a theoretical solution to quantify the crushing resistance of axially crushed multi-cell square tubes, which agreed well with the numerical results. The formula for the mean crushing force was improved later on by Nia and Parsapour [19], taking into account the unequal-cell square tubes. To investigate the influence of cross-sectional shapes on the mechanical properties, Zhang and Zhang [20,21] studied the axially crushed multi-cell tubes with different sections experimentally, numerically and theoretically. The theoretical predictions of the mean crushing load proposed in their work showed good agreements with the numerical and experimental results. Zhang and Zhang [22] also studied the influence of the cell geometrical dimensions of quadruple-cell square tubes by numerical simulations and physical experiments. Unlike the aforementioned studies, Hou et al. [23] performed optimizations on the hexagonal thin-walled tubes with different sectional profiles for maximizing the specific energy absorption or reducing the initial peak force. After that, their team [24] performed multi-objective optimizations on square thin-walled tubes with different number of elements to find the optimal designs with high energy absorption and small initial peak force. However, no experiments have been conducted in their studies to verify the obtained optimal solutions.

In this paper, three novel types of multi-cell thin-walled tubular structures with pre-folded diamond origami patterns were proposed. The influence of various structural parameters on the mechanical properties and energy absorption capacities were systematically investigated via experimentally validated numerical simulations. Based on the numerical results, multi-objective optimizations were performed on the specially designed tubes by linear weighted average method [25], aiming to find the optimal designs with low initial peak force, high specific energy absorption and small fluctuation of the crushing force. Response surface method (RSM) was utilized in the optimizations to formulate the objective functions. Theoretical analyses were proposed based on simplified buckling models and a theoretical solution for the mean crushing force was derived.

2. Computational simulation and experimental validation

2.1. Different design approaches

Fig. 1 illustrated the three novel types of tubes composed of quadruple and quintuple cells, i.e., origami-patterned quadruple cells (Fig. 1(a)), origami-triggered quadruple cells (Fig. 1(b)) and origami-patterned quintuple cells (Fig. 1(c)). The internal rib walls of these tubes were straight and flat without origami patterns, while the external walls were predesigned into different shapes. In the origami-patterned tube with quadruple cells, the external tube wall was folded in diamond origami patterns, similar to a typical buckling mode observed in axial crushing tests of square tubes [3]. The aim for the predesigned origami patterns is to induce the buckling procedure and reduce the fluctuations of crushing force in compression. Generally, the pre-folded origami pattern should have smaller wavelength than the theoretical values of conventional multi-cell tubes, i.e., more plastic folding lines and more materials being involved in the deformation procedure to increase the energy absorption in compression. The origami-triggered quadruple-cell tube was pre-folded with a single origami trigger at the top end of the tube external surface, for the purpose of reducing the initial peak force. In the origami-patterned quintuple-cell tube, the external surfaces were pre-folded in origami patterns similar to quadruple-cell tubes. However, rather than using cross rib walls, an additional diamond cell was designed to replace the cross aiming to distribute the load more evenly in crush. The origami tubes were designed to have the same height (H) of 100 mm and the same mean diameter (D) of 40 mm. To ensure the same mass of all tubes, different values of wall thickness were predefined in this study. A series of finite element (FE) simulations were conducted on different types of tubes to investigate the influence of the typical geometrical parameters on their mechanical response and energy absorption capacity, including the ratio of the internal stiffener wall thickness to the surface wall thickness (t_2/t_1) for the origami-patterned quadruple-cell tube, the height of the pre-folded pattern (h) for the origami-triggered quadruple-cell tube, and the diagonal length of the diamond cell (l) for the origami-patterned quintuple-cell tube. The pre-designed folding angle (θ), as the key geometrical parameter, was investigated for all the three types of tubes. As the benchmark for comparison, conventional quadruple-cell square tube with identical overall size and mass to origami tubes was studied by numerical simulation and validated by experiments.

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