Energy absorption of thin-walled tubes with pre-folded origami patterns: Numerical simulation and experimental verification

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ABSTRACT

Thin-walled tubes are widely used as energy absorption components. In this study, two different origami patterns were introduced to circular tubes. The influence of the origami patterns on the energy absorption capacity and the deformation mechanism of tubes under uniaxial loading were investigated both numerically and experimentally. The results showed that the initial peak force of origami tubes would be significantly reduced, while the energy absorption capacity could be improved or maintained. Brass tubes with and without origami patterns were fabricated using 3D printing and were tested to validate the finite element models.

1. Introduction

Thin-walled metal tubes are commonly used as energy absorption components due to their high manufacturability and low cost [1,2]. Under uniaxial compressive loadings, thin-walled tubes deform in a manner of progressive buckling, which may dissipate a great amount of energy. Tubes in different shapes have been widely studied, among which circular and rectangular tubes are most popular due to their simplicity and predictable buckling modes. Nevertheless, traditional tubes still have essential defects such as high initial peak force.

The study on the axial crushing behaviour of circular tubes can be traced back to a few decades ago [3,4]. Alexander [4] experimentally investigated the mechanical response of circular tubes under quasi-static axial loadings by a simplified buckling mode with solely axial-symmetric (concertina) folding patterns. In the study, the analytical solution of mean crush load $P$ was derived according to concertina buckling mode. However, this solution was not applicable to non-symmetric (diamond) buckling models. Later, this research was improved by Abramowicz and Jones [5], who considered both concertina and diamond buckling modes when deriving mean crush load of axial-loaded circular tubes with various heights. For diamond buckling mode, Thornton and Magee [6] suggested several semi-empirical relationships to specify the specific energy absorption. Andrews et al. [7] investigated the crushing mode and energy absorption capacities of circular tubes through quasi-static compressive tests, with a classification graph presented. The graph could be used to estimate the crushing mode and energy absorption capacity of tubes. Further investigations have been done by Guillow et al. [8]. In their work, parameters and analytical solutions proposed by Andrew et al. [7] were expanded and experimentally validated. It is acknowledged that concertina buckling mode may bring much higher energy absorption capacity than diamond mode. The buckling modes could be changed by proper structural design. For example, Kavi et al. [9] found that foam fillings could change the buckling mode of circular tubes from diamond to concertina regardless of the type of foam. They also found that increasing wall thickness could be more efficient to increase specific energy absorption than foam filling. Similarly, Wang et al. [10] investigated the compressive behaviour of luffa-filled tubes and found that the deformation would change to concertina mode with the increase of luffa density.

Lower initial peak force and enhanced energy absorption capacity are critical in the design of tubular structures for safety protection purpose. However, it is difficult to achieve the two goals simultaneously. Extremely high initial peak forces commonly exist when conventional tubes are axially crushed, which shall be avoided or minimized as it may bring serious potential hazard. Many methods have been tried to reduce the initial peak force. A frequently used method is to introduce geometric imperfections in conventional tubes [11,12]. However, imperfections could also reduce the energy absorption capacities of tubes. In order to...
Adachi et al. [13] modified circular tubes to buckle in concertina mode by employing ribs along the circumferential direction, which showed higher energy absorption capacity (approximately 30%) than those tubes that buckled in diamond mode [7]. Lee et al. [14] designed square tubes by using a controller to restrain the deformation in a certain pattern and successfully increased the energy absorption capacity. Zhang et al. [15,16] used multi-cell columns instead of single-cell ones to achieve superior energy absorption efficiency after investigating the mechanical behaviour of square and circular multi-cell tubes with different shapes of cross-section. Although these methods could increase the energy absorption capacity of tubes, the initial peak forces were not lowered.

To increase the energy absorption capacity and simultaneously reduce the sharp initial peak force, several strategies were proposed in the past. One approach was to change the wall thickness to form functionally graded structures, such as the work done by Sun et al. [17] and Zhang et al. [18,19]. Another strategy was to prefabricate proper patterns on tube walls to induce the tube to collapse in predictable modes. Zhang et al. [20] introduced pentahedron patterns to thin-walled square tubes and observed diamond buckling mode in experiments. However, the modified tubes in experiments were very sensitive to imperfections and the predicted octagonal mode was not always observed. Ma and You [21] improved Zhang’s design by introducing pre-folded diamond patterns in the corners of the square original tube and significantly reduced the sensitivity of tubes to imperfections. In the work by Ma and You [21], rigid origami pattern was also applied, which could be spread out completely to a flat sheet. It is indeed very interesting and meaningful to introduce origami pattern for energy absorption purpose, which is usually used in kinetic engineering. Buckling modes may significantly affect the energy absorption capacity of tubes. By introducing origami patterns to conventional tubes, predesigned buckling modes could be achieved. Therefore, it is highly possible to design tubes with higher energy capacity and lower initial peak force simultaneously.

In this paper, based on the research done by Ma and You [21], we introduced diamond patterns including its special case (so-called full-diamond patterns) to circular tubes and investigated their influence on energy absorption capacities. Octagonal origami tubes were folded in diamond and full-diamond patterns to approximate circular tubes. The energy absorption capacities of three types of tubes (diamond, full-diamond and circular tubes) were...