International Journal of Mechanical Sciences 121 (2017) 58–66

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

The imperfection-sensitivity of origami crash boxes

Bo Wang*, Caihua Zhou

State Key Laboratory of Structural Analysis for Industrial Equipment, Department of Engineering Mechanics, Dalian University of Technology, Dalian 116024, China

ARTICLE INFO

Keywords:
Origami crash box
Energy absorption
Axial crushing
Imperfection

ABSTRACT

A novel thin-walled tube, named as origami crash box, is recognized as a promising energy absorption device. Experimental results reveal that unintentional imperfection could trigger the symmetric mode with low mean crushing force rather than a high-performance mode, known as complete diamond mode. Therefore, the imperfection-sensitivity of origami crash boxes is investigated in this paper. Appropriate geometric imperfection which is regarded as a substitution of the real defect is introduced into finite element models to trigger the symmetric mode. Numerical simulation shows that the specific energy absorption SEA declines with the increase in imperfection amplitudeA_i. And a critical value of ratio A_i/t that is just able to trigger the symmetric mode is obtained. A detailed parametric analysis indicates that a suitable geometry is beneficial to improve the compliance of origami crash box, leading to stable collapse behavior with higher performance in terms of energy absorption. Moreover, a bulkhead reinforced origami crash box is proposed as a low imperfection-sensitivity energy absorption device. And an optimal wall thickness ratio t_1/t is obtained through numerical analysis.

1. Introduction

Various energy absorption devices are designed to absorb kinetic energy during a collision. Thin-walled structures, like circular or square tubes, have been deeply studied for over one hundred years and wildly used in vehicles [1,2]. Nevertheless, as the most common energy absorptions devices, circular and square tubes are undesirable for their high peak force and unstable deformation [3,4]. In order to investigate the energy absorption characteristics of those tubes, the factors which could influence the energy absorption performance are listed as follows [5]:

- Geometry: length, width and thickness of the member.
- Material properties: elasticity modulus, yield stress and strain hardening.
- Boundary conditions: clamped, pinned or free.
- Impact velocity: strain rate and inertia effects.
- Imperfections: amplitude and shape.

Based on the investigation of those factors, some approaches are adopted to enhance the energy absorption capacity. For instance, thin-walled tubes with foam filler [6–8], multi-cell [8,9] and variable thickness walls [10–12] are good candidates as energy absorption devices. In addition, introducing specific imperfections is another effective approach. There are many types of imperfections, including corrugated shape [13–16], grooved shape [17–19], indentation trigger [20], patterned windows [21], stiffeners [22], and pattern [23–27]. The studies on those imperfections prove that the intentional imperfection could intensely control the collapse behavior.

However, imperfection is a double-edged sword. Because there are always some unintentional imperfections existing in tubes. Although the advanced manufacture technology could reduce the magnitude of those imperfections, they still have a strong influence on collapse mode, thereby affecting the energy absorption properties [28]. Therefore, a large amount of works focus on the effect of imperfections. For instance, the imperfections in circular tubes were measured with a laser sensor in Ref. [28]. And the results showed that an increased value of imperfection amplitude could weaken the energy absorption capacity. Belingardi et al. [29,30] have made a number of comparisons between experimental tests and numerical studies to assess the effect of geometrical imperfections on thin-walled beams. Grzebieta [31] presented an approximate method for determining the range of load oscillations and load-deflection behavior of circular tubes. While the accuracy of this method depends on estimating the correct of tube imperfection due to that the circular tubes are notoriously imperfection-sensitive structures [32]. Considering that many structures are imperfection-sensitive, the influence of imperfections on axially loaded tubes is taken into account in Eurocode 9 “Design of aluminium structures” [33].

Recently, Ma and You [25] proposed a novel origami crash box as a high efficient energy absorption device. However, this origami crash box was proved as a imperfection-sensitive structure in the following

* Corresponding author.
E-mail address: wangbo@dlut.edu.cn (B. Wang).

http://dx.doi.org/10.1016/j.ijmecsci.2016.11.027
Received 5 September 2016; Received in revised form 11 November 2016; Accepted 27 November 2016
Available online 28 November 2016
0020-7403/

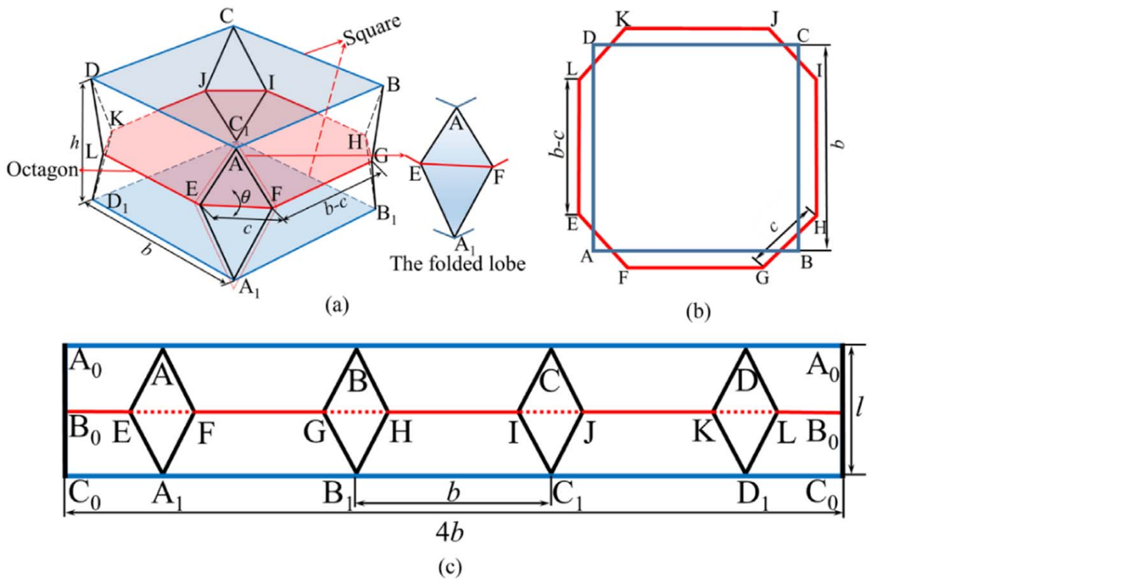

Fig. 1. The origami crash box. (a) A module of the origami crash box. (b) Top view of the module of origami crash box. (c) A modules of the origami pattern for origami crash box.

work [34]. Therefore, the influence of geometric imperfection on origami crash box is analyzed in this paper. Detailed geometric parameters analysis and a novel bulkhead reinforced origami crash box are presented to guide the application of origami crash boxes. The layout of this paper are as follows: First, the geometry of origami crash boxes is described in Section 2. Subsequently, the motivation to investigate the imperfection-sensitivity is illustrated in Section 3. Numerical simulation is presented in Section 4. Results and analysis, including the effect of imperfection amplitude, tube geometry and bulkhead are elaborated in Section 5. Summary is found in Section 6.

2. Geometry

A module of origami crash box is shown in Fig. 1(a). The most important geometric feature of origami tube that distinguishes it from a conventional square tube is the folded lobes at each corner. There are two merits of those folded lobes. First, they are regarded as geometric imperfections to reduce the peak crushing force. Second, they are supposed to trigger a desirable collapse mode known as the complete diamond mode [25]. The upper and lower boundaries of the module are squares. The middle cross-section of this module is an octagon as shown in the top view in Fig. 1(b). A module of origami crash box can be folded by a flat sheet, as shown in Fig. 1(c), the solid lines in the figure stand for hill creases and the dashed ones stand for valley creases. Therefore, the manufacturing of origami crash box is of lower complexity because of the developable geometry. The relationship among dihedral angle θ, module length l and corner width c is described as follow:

$$\cos\theta/2 = (\sqrt{2}-1)c/l \tag{1}$$

In reality, an energy absorption device could be a long tube which can be obtained by stacking a number of modules axially. In this case, the height of an origami crash box equals to Mh, where, M is the number of modules in one tube, h is the height of a module, as shown in Fig. 1(a).

3. Motivation

Numerical simulation was carried out by Ma and You [25] to prove that the complete diamond mode is an efficient collapse mode. In the optimum case, as much as a 92.1% increase in the mean crushing force is achieved, while a peak force reduction of 20.9% is obtained in the same design compared with the conventional square tube. Similar conclusions were drawn from a great number of experiments performed by Wang and Zhou [34]. In addition, experimental results show that the mean crushing force of origami crash boxes with longer modules ($l/t=60$) is larger than that with shorter modules ($l/t=40$) when the origami crash boxes deform in complete diamond mode [34], where t is wall thickness. Therefore, the origami crash boxes, which are assembled by stacking two longer modules ($l/t=60$, $M=2$) axially, as shown in Fig. 2, are investigated in this paper.

However, the origami crash boxes with longer modules are more inclined to deform in symmetric mode (denoted by "S") rather than complete diamond mode (denoted by "C"), as shown in Fig. 3[34]. In other words, the compliance of those origami crash boxes, which is defined as the characteristic of tube to collapse following the pre-manufactured origami pattern (collapse in complete diamond mode), is unsatisfactory. The experimental results suggest that the mean crushing force of symmetric mode is much lower than that of complete diamond mode [34]. The reason why the origami crash boxes are likely to deform in the symmetric modes is due to the local buckling caused by geometric imperfection in the slender region between two modules [34], as shown in Fig. 2. Considering the undesirable performance of symmetric mode, the characteristics of the origami crash boxes with geometric imperfections are investigated in the following analysis. In addition, to avoid deforming in symmetric mode, effective measure has to be taken to reduce the imperfection-sensitivity of origami crash box.

In order to evaluate the performance of the tubes, some relevant energy absorption indices including the initial peak force P_{max}, the mean crushing force $\overline{P}_m$ and the specific energy absorption (SEA) [10,35] are

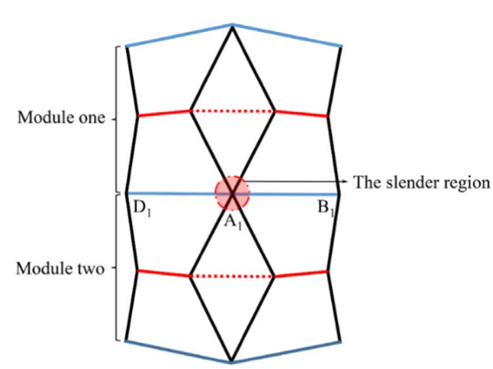

Fig. 2. The origami crash box with two longer modules.