International Journal of Mechanical Sciences 118 (2016) 1–12

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Dynamic axial crushing of origami crash boxes

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ARTICLE INFO

Article history:
Received 20 July 2016
Received in revised form
29 August 2016
Accepted 1 September 2016
Available online 1 September 2016

Keywords:
Origami crash boxes
Energy absorption
Axial crushing
Basic folding element

ABSTRACT

Thirty-three dynamic tests on thin-walled tubes including conventional square tubes and two types of origami crash boxes were conducted on a drop hammer rig. All of the origami crash boxes have identical thickness t and surface area A to those of conventional square tubes. Experimental results validate that origami crash boxes perform better than the conventional square tubes. And the mean crushing force of origami crash boxes with longer modules ($l/t=60$) is larger than that with shorter ones ($l/t=40$). Complete diamond mode as well as two new collapse modes, which are local buckling mode and symmetric mode, were observed in tests. The comparison among those three collapse modes suggests that the complete diamond mode is the most efficient one and the symmetric mode is the most inefficient one in terms of energy absorption. The effect of local buckling on the mean crushing force is presented to analyze the characteristics of those three collapse modes. It is found that the mean crushing force decreases with the increase of the number of buckling points.

1. Introduction

Traffic accidents have drawn considerable attention recently [1]. Those accidents result in substantial loss of life and property. This situation may become much more serious along with the rapid development of transportation industry [2]. Therefore, the safety performance of vehicles is what engineers and designers should invest more effort in.

Compared with designing a new body-in-white (BIW) with safer performance, designing some specific energy absorption devices to absorb the huge kinetic energy is an easier method. Circular, square and triangular tubes are the most common energy absorption devices.

Circular tubes are known to be efficient energy absorbers [3]. Alexander [4], Yoshimura [5], Pugsley [6], Johnson [7], Wierzbicki [8] and Singace [9] are pioneers in the field. Guillow [10] presented a mode classification chart for circular tubes through plenty of experiments. Diverse performance of circular tubes deforming in axi-symmetric mode, non-symmetric mode, mixed mode and Euler mode was investigated in [10].

The foundation research of square tubes were performed by Wierzbicki and Abramowicz including the super folding element theory [11,12], the effective crushing distance [13] and the material strain rate sensitivity [14]. A large sum of experiments were conducted to validate the quality of those theoretical prediction [15,16]. Two new collapse modes, known as asymmetric mixed mode A and B, apart from the symmetric collapse mode were observed in those experiments. Further investigation revealed the diverse characteristics of square tubes folding in different collapse modes [16].

The triangular tubes are widely used in some structures as bridges, cranes and steel building [17]. Chattopadhyay investigated the buckling modes of triangular tubes [18]. Finite element analysis of triangular tubes was carried out by Cui and Shen [19]. Recently, two collapse modes (diamond mode and rotational symmetry mode) of triangular tubes under large axial plastic deformation was studied by Fan [17].

The researches above indicate that different collapse modes influence the performance of those conventional tubes (circular, square, and triangular tubes). Therefore, some methods were proposed to control the collapse modes. For instance, introducing foam filler [20–22], multi-cell [22,23] and variable thickness [24–26] to thin-walled structures have been proved to be effective to enhance the energy absorption capacity. In addition, a large number of researchers devoted themselves to the discovery of new collapse mode. For example, Zhang and Cheng [27] have found a novel mode known as the complete diamond mode (also be named as octagonal collapse mode) based on the research of square tubes with patterns. But the collapse mode is not stable. Ma and You [28,29] designed a novel crash box named origami crash

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http://dx.doi.org/10.1016/j.ijmecsci.2016.09.001
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box which can collapse in complete diamond mode steadily under axial crushing.

This paper focus on the performance of origami crash boxes under low velocity impact tests with different geometries, loading rates and mass of the tup. The characteristics of two new collapse modes (local buckling mode and symmetric mode) will be discussed in detail. The layout of this paper is as follows. First, the geometry of a module is given in Section 2. Subsequently, the experimental details are outlined in Section 3. The experimental results are presented in Section 4. Detailed analysis of the results is elaborated in Section 5. The summary is found in Section 6.

2. Geometry of a module

Fig. 1(a) shows a module of origami crash box. Four pre-manufactured origami patterns known as folded lobes at each corner in Fig. 1(a) are designed to fulfil two main functions which are collapse mode inducer and geometric imperfections. Considering the fabricating cost, the origami crash boxes are designed to be developable. That means a module of origami crash box can be folded by a flat sheet material which is illustrated in Fig. 2. Top view of module is shown in Fig. 1(b) from which it can be seen that the upper and lower boundaries of a module are two squares with the length of sides equals to b. Therefore, an origami crash box can be just one module or be assembled by several modules end to end. The cross-sections of module are octagons with changing side values along the height of module. Three parameters which can decide the geometry of the module are listed as follows: the width of folded lobe c, the width of the tube b and the module length l. The relationship among the three parameters is described as follows:

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

3. Experimental details

3.1. The experiment system for low velocity impact tests

The low velocity impact tests reported herein were conducted in the Suzhou Automotive Research Institute, Tsinghua University Institute of Lightweight Vehicle. Fig. 3 shows the drop hammer test rig which was produced by Beijing Paishengsida Machinery Manufacturing Co., Ltd. This rig has a variable tup mass from 36 to 225 kg, as shown in Fig. 4. The maximum height that the tup can rise to reaches up to 7 m which means that the initial impact velocity can get to 12 m/s and the initial kinetic energy can reach up to 15,000 J. A simple level was used to guarantee the levelness of the square tup, as shown in Fig. 4.

An accelerometer (model 7201-10) produced by Endevco Corporation was mounted on the top of mounting frame, as shown in Fig. 4. Special strain gauge-type force transducers which were composed by four strain gauges was placed in the middle of the specimen support plate and the base of the drop hammer test rig, as shown in Fig. 3. The dynamic strain meter (model LK2107B/LK1432) was used to collect electrical signals. Considering the complexity of impact environment (e.g., the short impact time (about 10 ms) and the vibration noise), two signals obtained by accelerometer and strain gauge-type force transducers respectively were applied to perform mutual authentication to ensure the validity of data.

A high-velocity camera (SA1.1) produced by Photron. Ltd was employed to record the crushing process, as shown in Fig. 3. A sheet of paper filled up with unordered speckles was pasted in front of the mounting frame, as shown in Fig. 4. The digital image correlation (DIC) method [30] was employed to calculate the displacement of tup by tracing the speckles on the paper. Meanwhile, the displacement can be calculated by Eq. (2), as follow

$$\delta = vt - \iint P_t/m_t dtdt \tag{2}$$

where, P_t is crushing force which can be obtained from accelerometer (multiply acceleration by the mass of tup) or strain gauge-type force transducers. The displacement obtained by different methods was employed to perform mutual authentication to ensure the validity of data.

3.2. The geometry of specimens

The complete diamond mode of origami crash boxes has been triggered successfully in numerical modelling [28] leading to high mean crushing force and low peak crushing force in the axial crushing. Therefore, the complete diamond mode of origami crash boxes is regarded as an more desirable collapse mode than the symmetric mode of the conventional square tubes [28]. The features of complete diamond mode that distinguish it from the symmetric mode of square tube are the two super folding elements [12] formed in one corner of a module due to the folded lobes, as shown in Fig. 1(a). Theoretically, the size of area swept by travelling hinge lines in super folding elements could greatly decide the characteristics of energy absorber [12,31]. Consequently, two types of origami crash boxes with different length of module l were manufactured, as shown in Table 1. The origami crash box with longer module (l/t=60) was supposed to perform better than that with shorter module (l/t=40) due to the larger area swept by

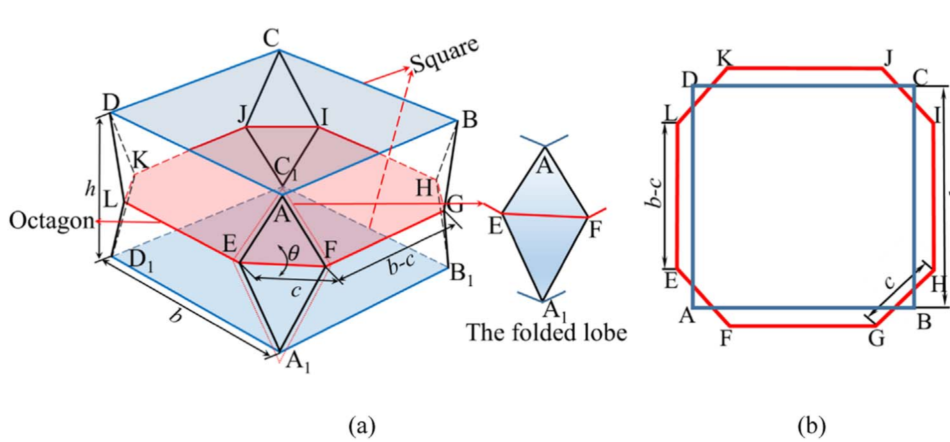

Fig. 1. The origami crash box. (a) A module of the origami crash box. (b) Top view of a module.