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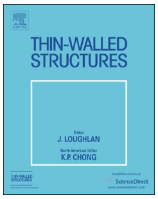

Full length article

Quasi-static axial crushing of thin-walled tubes with a kite-shape rigid origami pattern: Numerical simulation

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ABSTRACT

This paper presents a novel thin-walled tube design with a pre-folded kite-shape rigid origami pattern as an energy absorption device. Numerical simulation of the quasi-static axial crushing of the new device shows that a smooth and high reaction force curve can be achieved in comparison with those of conventional square tubes, with an increase of 29.2% in specific energy absorption and a reduction of 56.5% in initial peak force being obtained in the optimum case. A theoretical study of the energy absorption of the new device has also been conducted, which matches reasonably well with the numerical results.

1. Introduction

Thin-walled energy absorption devices have been widely used in transportation vehicles accompanying the rapid development of modern transportation industry which results in increasingly rigorous safety standards on vehicle structural crashworthiness and impact protection. They are designed to irreversibly convert kinetic energy into material plastic energy during impact accidents, so as to protect the costly structures and people inside. Among all the structural forms, thin-walled tubes are widely adopted in the design of energy absorption devices because they show excellent performance under axial loading in terms of weight efficiency, stroke distance and total energy absorption [1].

The axial crushing behaviors of thin-walled tubes have been extensively studied by researchers. It has been found that tube geometry has pivotal effects on the collapse mode, and corresponding energy absorption properties, of a tube. Circular tubes could be crushed in a ring mode [2], a diamond mode [3–5] or a mixed mode [6,7], mainly depending on tube diameter D to wall thickness t ratio, D/t. Similarly, four collapse modes, i.e., symmetric or inextensional mode, extensional mode and mixed modes A and B [8,9], could be obtained in square tubes by varying tube width b to wall thickness t ratio, b/t. Regarding theoretical work, a mathematical model of circular tubes collapsing in the ring mode was first proposed by Alexander [10] to calculate the mean crushing force, which was further modified by Abramowicz [11] and Wierzbicki et al. [12]. For square tubes, an theoretical expression of the mean crushing force for a tube collapsing in the symmetric mode were derived by Wierzbicki and Abramowicz [13], and Abramowicz and Jones [8,9], and that for a tube collapsing in the extensional mode by Abramowicz and Jones [8].

Despite the desirable features demonstrated by thin-walled tubes as energy absorption devices, they also have the disadvantage that the crushing force is not uniform during the deformation process, especially with the existence of a high initial peak force and subsequent fluctuation. Introducing corrugation on the surface of circular tubes could generate a lower initial peak force and a more uniform crushing process, with the side effect of reduced total energy absorption [14]. Zhang et al. [15] numerically studied the crushing of two square tube designs with pyramid patterns, and reported energy absorption improvements by 15–33% and 54–93%, respectively. However, experimental results revealed that tubes with the pyramid patterns were imperfection sensitive and thus the desired mode was difficult to be induced [16].

Recently, the application of origami patterns on tubular structures has received increasing attention. It has been found that, if the surface of a tube is pre-folded according to an origami pattern, the collapse mode of the tube can be altered, leading to changes in energy absorption performance. Ma and You [17] proposed a new device, referred to as the origami crash box, which was made through pre-folding the surface of a square tube according to a specially designed origami pattern. Both a reduction of over 20% in

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initial peak force and an increase of over 50% in energy absorption were achieved in one design. Song et al. [18] applied a kind of origami pattern on square tubes to minimize the initial peak force. Their study showed that the patterned tubes exhibited a lower initial peak force and a more uniform crushing load compared to those for conventional square tubes, while no total energy absorption gain was achieved.

In this paper, a new type of thin-walled tube which has a kite-shape rigid origami pattern pre-folded on its surface [19] is proposed as a potential energy absorption device. The pattern is constructed by joining two pieces of the well-known Miura-Ori pattern [20]. The performance of the new device subjected to axial crushing is studied numerically and theoretically. The layout of the paper is as follows. Section 2 gives a detailed geometrical analysis of the new origami tube. Numerical simulation results of the quasi-static axial crushing of the new tube are presented and discussed in Section 3. A theoretical investigation of the collapse mode and energy absorption of the new tube is conducted in Section 4. Finally is the conclusion in Section 5, which ends the paper.

2. Tube geometry

The kite-shape rigid origami pattern that is pre-folded on the surface of the new tube consists of two elements designated as P1 and P2 shown in Fig. 1(a–b), each of which is composed of a single vertex with four congruent parallelograms. Note that the solid lines represent hill fold lines and the dashed ones represent valley fold lines in the figures. Folding P1 and P2 along the fold lines and joining free edges A_1D_1 and A_2D_2, D_1G_1 and D_2G_2, C_1F_1 and C_2F_2, and F_1I_1 and F_2I_2, an origami tube shown in Fig. 1(c) is obtained. The tube constructed this way satisfies the condition of rigid folding, and thus is rigidly foldable with only one degree of freedom (DOF) [19]. Moreover, what is presented in Fig. 1(c) can be seen as a single unit, and a tube with multiple units can be obtained by stacking them axially. In this case, all of the units in a tube must be folded simultaneously in order for the condition of rigid folding to be satisfied.

The geometry of the pattern can be parameterized in the following way. Element P1 in the flat configuration can be described by side lengths a_1, c_1, and angle γ_1, as shown in Fig. 1(a), and l_1 is related to a_1 and γ_1 through the following equation

$$l_1 = a_1 \sin \gamma_1 \tag{1}$$

Similarly, side lengths a_2, c_2, and angle γ_2 define the geometry of element P2 in the flat configuration as shown in Fig. 1(b), and the following equation applies

$$l_2 = a_2 \sin \gamma_2 \tag{2}$$

To join P1 and P2 to form a unit of an origami tube, the following geometrical relationship should be satisfied

$$a_2 = a_1 \tag{3}$$

In addition, the pre-folding angle of P1, i.e., the dihedral angle between face $A_1B_1E_1D_1$ and face $D_1E_1H_1G_1$, θ_1, the pre-folding angle of P2, i.e., the dihedral angle between face $A_1B_2E_2D_1$ and face $D_1E_2H_2G_1$, θ_2, the angle between lines E_1F_1 and D_1F_1, ψ_1, the angle between lines E_2F_1 and D_1F_1, ψ_2, and the angle between lines A_1D_1 and F_1D_1, ξ, can be calculated through the following equations

$$\tan \psi_1 = \tan \gamma_1 \cos(\theta_1/2) \tag{4}$$

$$\tan \psi_2 = \tan \gamma_2 \cos(\theta_2/2) \tag{5}$$

$$c_2 \cos \psi_2 = c_1 \cos \psi_1 \tag{6}$$

$$\sin \psi_2 \tan(\theta_2/2) = \tan \xi \tag{7}$$

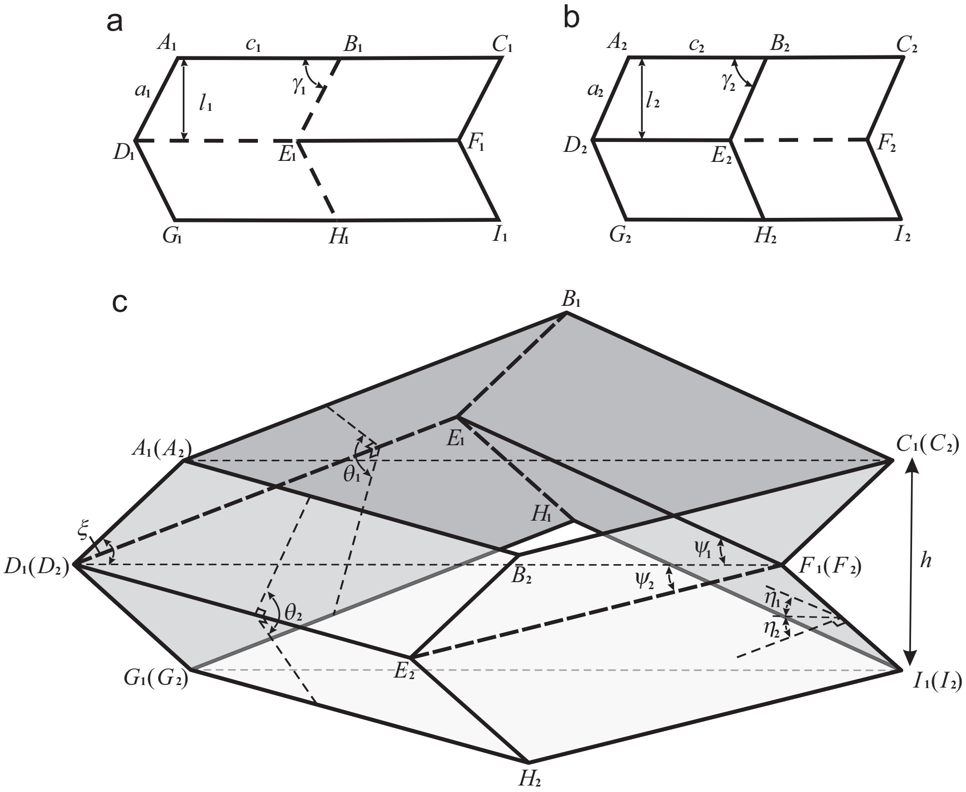

Fig. 1. (a) Element P1 of the kite-shape pattern, (b) element P2 of the kite-shape pattern, and (c) a unit of an origami tube with the kite-shape pattern.