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Inward-contracted folding element for thin-walled triangular tubes

Fangfang Sun [a], Hualin Fan [a,b,*]

[a] State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
[b] State Key Laboratory of Constructional Machinery, Zoomlion Heavy Industry Science & Technology Co., Ltd., Changsha 410013, China

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ABSTRACT

Extensional and in-extensional folding elements are two conventional plastic collapse mechanisms for thin-walled tubes to predict their anti-crushing behaviors. In the compression experiments of triangular tubes, a new folding element, named as inward-contracted folding element, was observed. Accompanying with this folding mechanism, double zigzags and half-shortened wavelength were observed in the corresponding deformation curve compared with the deformation curves of tubes collapsing at conventional modes. This inward-contracted folding element always follows behind the extensional folding to form a hybrid folding element. A plastic model was proposed, through which the mean crushing force (MCF) and the folding wavelength are predictable.

1. Introduction

Thin-walled structures are the most commonly used anti-crash energy absorbing devices. Extensional and in-extensional folding elements [1–3], as shown in Fig. 1 [4,5], have been suggested and widely applied to analyze the crushing of polygonal thin-walled tubes. Meanwhile, some attention has been paid to polygonal tubes with odd number of sides [6–8]. A typical example is the equilateral triangular tube [4, 9], which is widely used in such structures as bridges, cranes and steel building, etc. [10]. Because of the particular geometrical shape, it is important to further explore the collapse modes of triangular tubes under large axial plastic deformation. Crushing behaviors of multi-cell triangular tubes [6–8], laterally compressed triangular tubes [11,12] and expandable tubes [13,14] were also discussed. Elastic buckling characteristics of triangular tubes under uniaxial loading were revealed by Chattopadhyay et al. [15]. Hierarchical triangular tubes have been proved to have much more excellent anti-crushing behaviors than thin-walled or even multi-cell triangular tubes [16,17].

The super-folding element theory [1,2,18] is applicable to the polygonal tubes. However, when it comes to the triangular tubes, acute angles between each side would affect the deformation mode of triangular tubes. Hong et al. [4,19] studied the crushing behaviors of triangular tubes. They revealed three deformation modes [4,19], as shown in Figs. 1 and 2. In mode I, one side moves inward and the other outward, as shown in Fig. 2(a). Mode I denotes a typical in-extensional folding element (Fig. 1(a)). In mode II, the two side move outward simultaneously, as shown in Fig. 2(b). Mode II denotes a typical extensional folding element (Fig. 1(b)). In mode III, the two side move inward simultaneously, as shown in Fig. 2(c). Mode III denotes a new folding element, which was named as inward-contracted folding element here. This folding element was also observed by Fan et al. [9]. They proposed a plastic model to predict the anti-crushing behaviors of the triangular tubes, as shown in Fig. 3.

In this paper, quasi-static axial crushing behaviors of triangular tubes were researched by experiments and theoretical predictions.

2. Traditional folding elements

Abramowicz and Wierzbicki [20] and Hayduk and Wierzbicki [21] analyzed the basic folding element model and offered the method to calculate the mean crushing force. The energy, E_1, absorbed by the type I basic folding element, as shown in Fig. 1(a), is

$$E_{\mathrm{I}} = M_0\left(16I_1\frac{Hb}{t} + 2\pi c + 4I_3\frac{H^2}{b}\right) \tag{1}$$

with

$$I_1(\psi,\overline{\alpha}) = \sin\overline{\alpha}\int_0^{\beta(\overline{\alpha})}\frac{\mathrm{d}x}{\sqrt{\tan^2\psi+\cos^2 x}} - \left[\frac{\pi}{2} - \psi - \arctan\left(\frac{\cos\beta(\overline{\alpha})}{\tan\psi}\right)\right], \tag{2}$$

$$I_3(\psi,\overline{\alpha}) = \cot\psi\int_0^{\overline{\alpha}}\left(\cos\alpha\sqrt{\tan^2\psi+\sin^2\alpha}\right)\mathrm{d}\alpha, \tag{3}$$

* Corresponding author at: State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China.
E-mail addresses: fhl02@mails.tsinghua.edu.cn, fhl15@nuaa.edu.cn (H. Fan).

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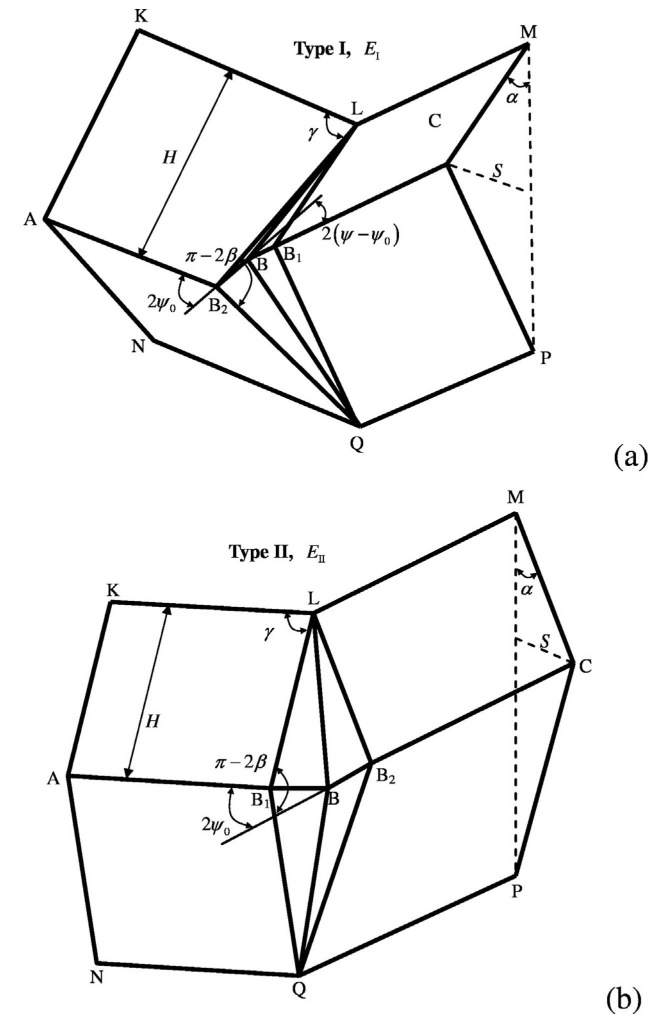

Fig. 1. Traditional (a) in-extensional (Type I, E_I) and (b) extensional (Type II, E_{II}) folding elements [4].

and

$$M_0 = \frac{1}{4}\sigma_0 t^2, \tag{4}$$

where b is the radius of the toroidal shell element in the kinematically admissible velocity field, t is the wall thickness, $2H$ denotes the initial distance between plastic hinges at top and bottom of a basic folding element, c is the length of side of a triangular cross-section and σ_0 is the mean value of plastic flow stress of the material. For triangular tubes, $I_1 = 0.33$ and $I_3 = 0.61$.

The energy, E_{II}, absorbed in the type II basic folding elements, as shown in Fig. 1(b), is given by [6]

$$E_{II} = M_0\left(\frac{2}{3}\pi H + 2\pi c + \frac{8}{3}\pi\frac{H^2}{t}\right). \tag{5}$$

With two basic folding elements and three angles, there should be four collapse modes for triangular tubes combined by (a) three type I basic folding elements, denoted by $3E_I$; (b) three type II basic folding elements, denoted by $3E_{II}$; (c) two type I basic folding elements and one type II basic folding element, denoted by $2E_I + E_{II}$; and (d) one type I basic folding element and two type II basic folding elements, denoted by $E_I + 2E_{II}$ [4].

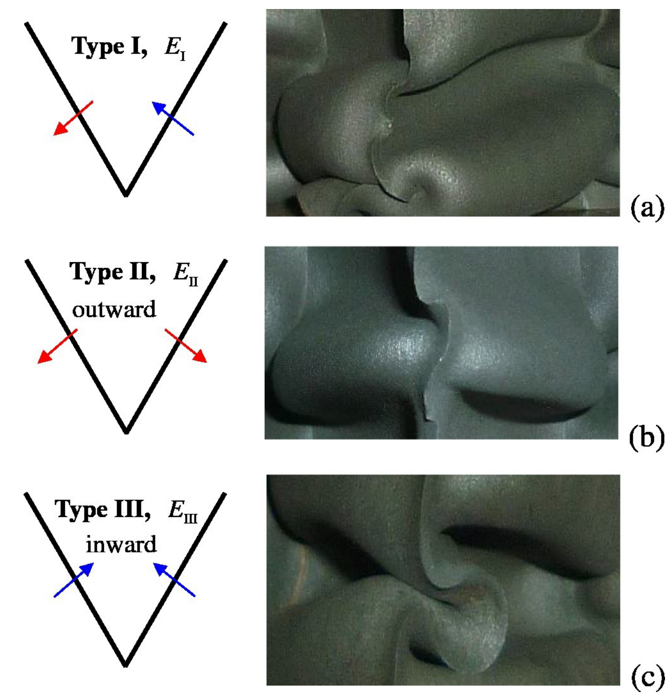

Fig. 2. Folding mechanisms of node in (a) in-extensible mode (Type I, E_I), (b) extensible mode (Type II, E_{II}) and (c) inward-contracted mode(Type III, E_{III}).

3. Inward-contracted folding elements

3.1. Observations in experiments

In experiments [4,19], three typical deformation modes were observed, as shown in Fig. 2, decided by the relative motion of neighboring sides. When the two sides move both to the same direction, one inward and the other outward, as shown in Fig. 2(a), mode I is the traditional inextensional deformation mode. When the two sides move both outward, as shown in Fig. 2(b), the tube will deform at traditional extensional deformation mode (mode II). The third deformation mode (mode III) was also observed as shown in Fig. 2(c), where the two sides move both inward and adhere to each other before folded. Contrary to the extensional and inextensional deformation styles, the tube will contract inward. So mode III is named as inward-contracted (anti-extensible) folding mode in this paper. This mode has been early reported by Hong et al. [4] and Fan et al. [9] in 2013.

Based on the results from finite element simulations and cardboard models, theoretical inextensional collapse modes were proposed to describe the plastic progressive collapse of thin-walled equilateral triangular tubes by Fan et al. [9], as shown in Fig. 3.

More details about the deformation mode were revealed by experiments reported by Hong et al. [4,19]. Three experiments were analyzed here to reveal the deformation characteristics.

ST1 specimens [4] were fabricated by Q235 steels. All specimens have same wall thickness of 1.0 mm, breadth of 50 mm and length of 150 mm. In compression, contracted fold was observed firstly at the end as shown in Fig. 4. Then extensional deformation was observed, but the extensional fold was not fully developed. Beneath the extensional area, the tube contracted. The neighboring two sides contracted inward. At the corner, the two sides adhered together and then were folded. Beneath the contracted area, there was another extensional deformation area. In compression, extensional mode and contracted mode shaped in succession. Accompanying with the contracted mode, deformation curve would have more zigzags with shorter wavelengths. For the first contracted fold at the upper end, the wavelength is 14.4 mm. The succeeding limited developed extensible fold has a wavelength of 18.4 mm. The second contracted fold has s wavelength of 18.5 mm. In