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Axial crushing and optimal design of square tubes with graded thickness

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ABSTRACT

Introducing thickness gradient in cross-section is a quite promising approach to increase the energy absorption efficiency and crashworthiness performance of thin-walled structures. This paper addresses the deformation mode and energy absorption of square tubes with graded thickness during axial loading. Experimental study is firstly carried out for square tubes with two types of thickness distributions and numerical analyses are then conducted to simulate the experiment. Both experimental and numerical results show that the introduction of graded thickness in cross-section can lead to up to 30–35% increase in energy absorption efficiency (specific energy absorption) without the increase of the initial peak force. In addition, structural optimization of the cross-section of a square tube with graded thickness is solved by response surface method and the optimization results validate that increasing the material in the corner regions can indeed increase the energy absorption efficiency of a square tube.

1. Introduction

Square and circular tubes are most commonly used energy absorber since they are cheap and efficient for absorbing energy. Accordingly, they received most extensive studies [1–5] including theoretical analyses, numerical simulations, experimental investigations and optimizations. To increase the crashworthiness performance of them, filling the structures with cellular materials including foams and honeycombs [6–10] has attracted wide research interests in the scientific community since 1980s. Introducing internal webs and making the section multi-cell [11–18] is found to be another efficient approach that can significantly increase the energy absorption efficiency of thin-walled structures. In the present work, another approach by optimizing the material distribution in the cross-section is proposed to increase the energy absorption efficiency of thin-walled structures.

Square tubes may deform in many different collapses modes including inextensional (or symmetric) mode and extensional mode, mixed mode and global Euler buckling. When inextensional mode is developed, the mean static crushing force P_m can be calculated by [19]

$$P_m = 13.06\sigma_0 b^{1/3} t^{5/3} \tag{1}$$

where σ_0 is the flow stress of the material, b and t are width and thickness of the square tube. The exponent of thickness t is concerned with the ratio of energy for bending and extension. As shown in Fig. 1(a), the basic folding mechanism defined by Wierzbicki and Abramowicz [19] consists of four trapezoidal elements, two horizontal cylindrical surfaces, two inclined conical surfaces, and a toroidal surface. Three deformation mechanisms including bending at stationary hinge lines, rolling at moving plastic hinge lines and extensional deformations in the small toroidal region were reported to each dissipate one-third of the plastic energy. Since rolling and extensional deformation are basically confined in the corner regions, most of the plastic energy of a square section is believed to dissipate in the four blue boxed corner regions as indicated in Fig. 1(b). With this in mind, a natural idea to increase the energy absorption efficiency of a square tube is to increase the material in the corner regions and accordingly decrease that in other regions.

The idea of adopting graded thickness in thin-walled tubes to increase the crashworthiness performance is not novel. The inversion-buckling of taped circular tubes with variable thickness along the axial direction was firstly studied by Chirwa [20] and significant efficiency increase (up to 50%) was reported when compared to a constant thickness tube with the same mass. As the advance in material

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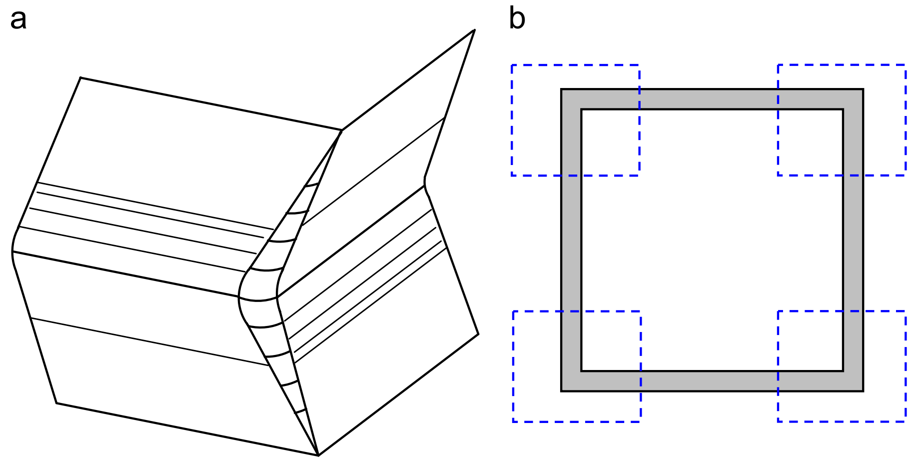

Fig. 1. (a) Collapse mechanism proposed by Wierzbicki and Abramowicz and (b) corner regions of square section. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

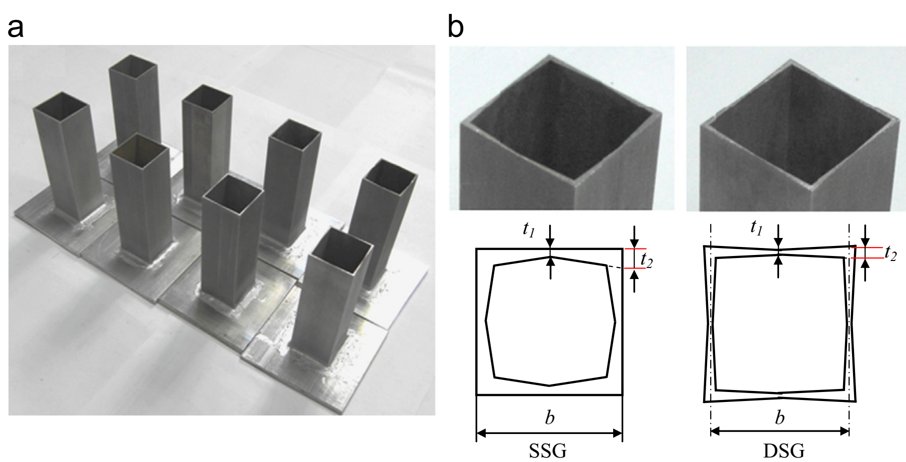

Fig. 2. (a) Square specimens with uniform and graded thickness for experimental tests and (b) dimensions of two types of graded thickness distributions.

processing technology, the manufacture of metal plates with continuous thickness changes is not difficult any more. For instance, tailor rolled blank (TRB) technology [21,22] is now employed to produce vehicle components with lighter weight. Researchers [23,24] are also adopting the thickness variables as design variables to optimize the vehicle components with better crashworthiness performance. However, up to now, there is still no relevant study in the open literatures to investigate the influence of material distribution in the cross-section of thin-walled structures on the energy absorption efficiency of them.

From the view of a designer, the structures with variable thickness have a bigger design space and will definitely offer a better solution than structures with constant thickness. This is similar to the adoption of tapered tubes [25–28] which bring better energy absorption characteristics than those of straight tubes. It is also similar to the employment of functionally graded foam which gets better crashworthiness performance than that of uniform counterparts [29–31]. Therefore, adopting graded thickness in cross-section is quite promising to significantly increase the energy absorption efficiency and crashworthiness performance of thin-walled structures. An ideal energy absorber should dissipate the kinetic energy with an almost constant force response (high crushing force efficiency: the ratio of the mean force to the maximum force [9]) and high SEA (specific energy absorption:energy absorption per unit mass of material) value. It will be found in the present work that by introducing the graded thickness in square tubes, the mean force will be increased without the increase of the maximum force and the energy absorption will be increased with almost no increase of the mass of the square tube.

In this paper, the energy absorption characteristics of square tubes with graded thickness are studied during axial loading. Square tubes with two types of thickness distributions including single surface gradient (SSG) and double surface gradient (DSG) are experimentally tested to investigate the influence of graded thickness change on deformation mode and energy absorption capacity. The square tubes with constant thickness are also tested and compared with those with graded thickness to validate the better crashworthiness performance of the latter. Numerical analyses are then conducted to simulate the experimental tests by using explicit nonlinear finite element code LS-DYNA. The numerical results including deformation modes and crushing force responses are compared with experiment and some discussion about the energy absorption of tubes with graded thickness is presented. Finally, a preliminary study is carried out to optimize the cross-section of a square tube with graded thickness in order to maximize the energy absorption efficiency of it.

2. Experimental test

2.1. Experimental setup

The specimens tested in the present work were fabricated by Wire cut Electrical Discharge Machining (WEDM) technique with the precision to be $\pm 20\,\mu m$. The specimens are shown in Fig. 2(a) and they are made of aluminum alloy material AA6061 O which is strain