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Bending collapse of square tubes with variable thickness

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ABSTRACT

This paper aims to study the bending collapse behavior of thin-walled square tubes with variable thickness in the cross-section. Three-point bending test is carried out for thin-walled square beams with different thickness for flanges and webs. The relative strength of the flanges versus the web plates is found to have significant influence on the force response and deformation pattern. Numerical simulation of the experimental test is also performed and the numerical results compared very well with the experimental results. Moreover, the difference between the quasi-static and dynamic responses of the square tubes under transverse loading is analyzed. A response surface method is finally employed to optimize two thin-walled beams under impact loading. The optimization results show that putting less material in flanges and more in the web plates is an efficient way to improve the bending resistance of the beams under transverse loading. Adopting graded thickness in the web plates is an effective and promising approach to further increase the energy absorption efficiency of the beams.

1. Introduction

Thin-walled metallic tubes are widely applied as structural components in various engineering fields, especially in moving vehicles such as automobiles, ships, aircrafts and etc. The performance of them under accidental impact events is therefore of interest to the researchers for the occupant safety considerations. The energy absorption characteristics of metallic tubes under various load conditions [1] have received extensive investigations including axial crushing [2–5], lateral crushing [6–9], transverse bending [10–16] and etc. Various approaches were proposed by researchers to improve the performance of them under impact loading. For example, introducing multi-cells [4,5], foam filler [10–13], grooves [17,18], reinforced ribs [19] and et al. The purpose of these methods is generally to increase the energy absorption efficiency of them during deformation and to attenuate the peak force which might cause damage or injury.

Recently, introducing thickness variables in thin-walled structures to improve their crashworthiness performance has attracted increasing interests in the researcher community [20–27]. The reason is twofold: first, the manufacture of such structures becomes more and more cheap and convenient. New emerging material processing technology, such as tailor rolled blank (TRB) [20] or tube tapering machine [21], can easily produce plates or tubes with graded thickness. Actually, early studies were performed by researchers [28,29] to investigate the inversion of circular tubes with variable thickness. However, the uncontrollable thickness distribution hampered further investigations and applications. Second, the performance of structures with variable thickness is definitely not worse than that of those with uniform thickness due to larger design domain. This has been validated by recent experimental or numerical studies that investigated thin-walled tubes with graded thickness in the cross-section [22] or along the longitudinal direction [23–27].

Under transverse loading, the bending collapse mechanisms of square tubes are similar as those subjected to axial crush. The energy is primarily dissipated by bending along static hinge lines, rolling at moving hinge lines and stretching in toroidal regions [2,14–16]. The theoretical model proposed by Kecman [14] is shown in Fig. 1(a). It can be noticed that the deformation is not uniformly distributed in different regions of the tube. For axial crush, the contribution of each plate in energy dissipation of a square tube is approximately equal, while the webs of the tube apparently dissipate more energy than the top and bottom flanges during bending since the latter just bends along static hinge lines. Therefore, a natural idea to increase the energy absorption efficiency of the tube is to put more material in the webs and accordingly reduce that in top and bottom flanges.

In the present work, the bending collapse of square tubes with variable thickness in the cross-section is investigated. Three-point bending test for square tubes with uniform but different wall

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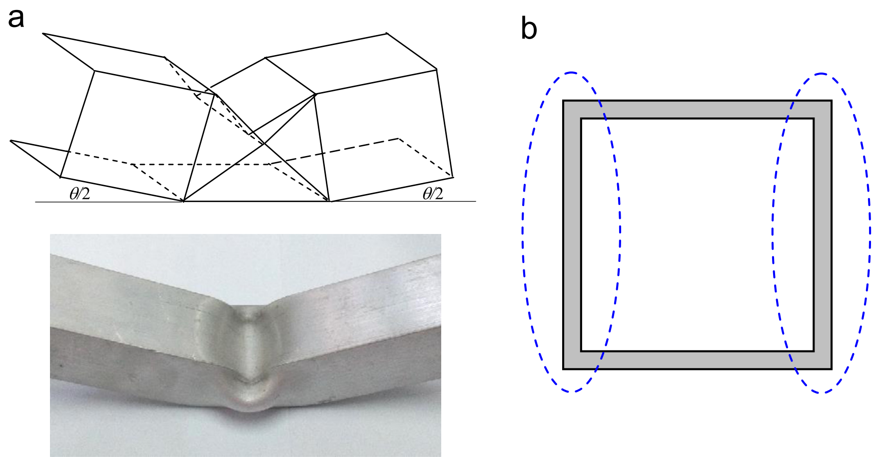

Fig. 1. (a) Collapse mechanism proposed by Kecman, (b) Web plates of square tubes.

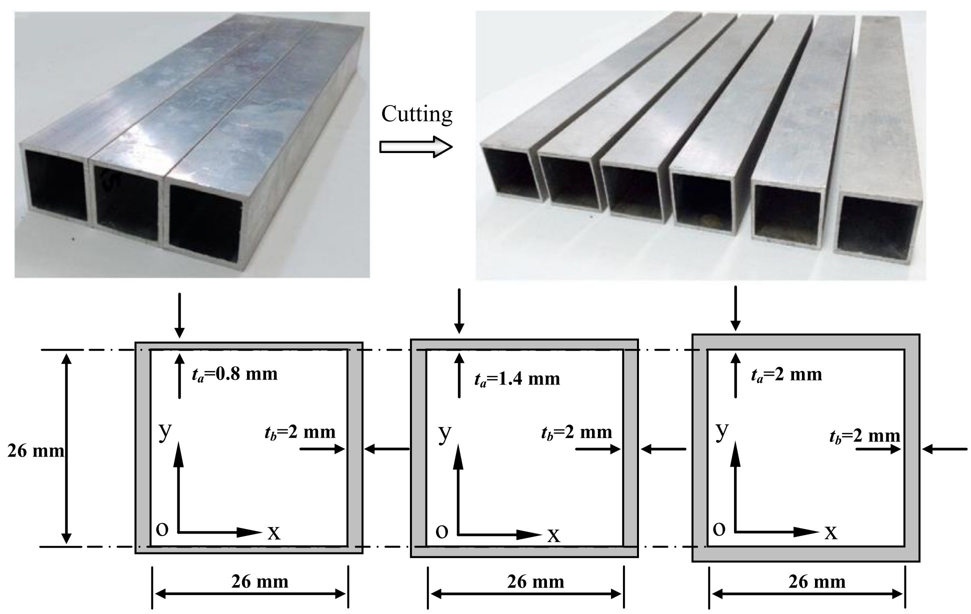

Fig. 2. Specimens of square tubes with different wall thickness for side plates.

thickness in the four side plates are firstly conducted. The nonlinear explicit finite element code LS-DYNA is then employed to simulate the test and the numerical model is validated by the experimental results. The dynamic analyses of square tubes under transverse loading are then performed and the influence of load speed is analyzed. Two relevant optimization problems are formulated for square tubes under impact loading and the optimal designs of thickness variables (distribution of the material) in the cross-section are finally found out by a surrogate optimization method. The advantage of tubes with variable thickness over those with uniform thickness is revealed and some suggestions are offered for design of structures against transverse loading.

2. Specimen preparation and experimental setup

Square tubes with uniform but different wall thickness in the four side plates are experimentally investigated in this section. To keep the symmetry of structure during deformation, same thickness is assigned to the opposite side plates of the tube. The thin-walled square beam specimens are fabricated by using commercial square tubes with inside width $b=26$ mm and wall thickness $t=2$ mm. The tubes are firstly cut to $L=250$ mm and the thickness of two opposite side plates of the tubes is then reduced by a Wire cut Electrical Discharge Machining (WEDM) technique. The precision of the cutting is below 20 μm. The original square tube and the specimen after cutting are shown in Fig. 2. Three different wall thicknesses t_a: 0.8, 1.4 and 2 mm are investigated here and three specimens are prepared for each case. The sectional dimensions of the specimens are also presented in Fig. 2.

The structural material of the square tubes is aluminum alloy AA1100-O. The tensile test is performed on a 10 kN capacity Zwick Z010 universal testing machine to obtain the stress–strain relation of the material. The specimens are taken parallel to the axial direction of square tubes and standard dimensions as specified in the ASTM E8M-04 for tensile test are adopted [30]. The tests are conducted in room temperature and the engineering stress–strain characteristics of the material are shown in Fig. 3. The mechanical properties of it are given as follows: Young's modulus $E=68.0$ GPa, initial yield stress $\sigma_y=30.5$ MPa, the ultimate stress $\sigma_u=90.5$ MPa, Poisson's ratio $\nu=0.33$.

Quasi-static three point bending tests are also performed in ZWICK Z010 machine with computer control and data acquisition systems. The experimental setup and geometry for three-point bending test are shown in Fig. 4. The diameter of the cylindrical punch and supports is 10 mm and the span between the supports