International Journal of Mechanical Sciences 103 (2015) 30–39

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Some problems on the axial crushing of multi-cells

Xiong Zhang [a,c], Hui Zhang [b,*]

[a] Department of Mechanics, Huazhong University of Science and Technology, Wuhan 430074, Hubei, PR China
[b] School of Mechanical Engineering and Automation, Wuhan Textile University, Wuhan 430073, Hubei, PR China
[c] Hubei Key Laboratory of Engineering Structural Analysis and Safety Assessment, Luoyu Road 1037, Wuhan 430074, China

ARTICLE INFO

Article history:
Received 13 June 2015
Received in revised form
4 August 2015
Accepted 21 August 2015
Available online 8 September 2015

Keywords:
Multi-cells
Axial crushing
Energy absorption
Geometric compatibility
Theoretical analysis

ABSTRACT

Multi-cell structures are highly efficient energy absorber under axial crushing. The present work aimed to resolve some problems concerned with energy absorption of a type of quadruple cells. These problems include influence of geometric compatibility among elements, type of trigger, structural parameter or topology change on crush resistance of the structure. Experimental study was conducted first and numerical simulation was then carried out by using commercial explicit finite element code. Theoretical prediction for the mean crushing force of the quadruple cells was also performed by the existing theoretical models. The results showed that when the structural parameter in the section was varied, the geometric compatibility problem became severe if the discrepancy of folding wavelength among constituent elements was large. However, it generally had limited influence on crush resistance of the multi-cell structure and the existing theoretical models can still predict the crush resistance of the section with good accuracy.

1. Introduction

Cellular materials and structures are widespread in nature and widely applied in various engineering fields. They exhibited many good properties such as low-weight, high efficiency and multi-function. In the aspect of structural crashworthiness, the cellular configuration of structures also gets their merits [1]. Thin-walled single tubes are good energy absorbers and researchers are still trying different ways [2–7] to further improve their performance. However, in the past decade, multi-cell tubes were found to be much more weight efficient in energy absorption than single-cell tubes [8–22] and the mechanisms for this high efficiency attracted increasing interest from the research community.

Earlier works on the energy absorption of multi-cells under axial crushing resorted to numerical analyses by commercial finite element codes [8–16] and more and more experimental studies [17–24] were carried out recently to demonstrate the high efficiency of multi-cells or to validate the accuracy of theoretical models. The section of multi-cells could be quite multifarious and complex. To predict the crush resistance of a multi-cell, the energy dissipated during deformation has to be analyzed for all the constituent angle elements in the section. Recently, Zhang et al. [23–28] carried out a series of works on the crush resistance of different types of constituent angle elements. These constituent elements are constituted by a number of plates or shells connected with various angles and by different edge connectivity. Theoretical models have been established for different collapse modes of these elements. However, there are still many problems to be investigated and solved before the theoretical models can be well applied to a complex section.

Theoretically, when the energy dissipation of each constituent element is determined, the crush resistance of the whole structure can be obtained by summing up the contribution of every element. However, the deformation of one constituent element must interact and coordinate with that of other elements and therefore, the energy absorption mechanisms of the same element may be different in different cases. This is so-called geometrical or deformation compatibility. There is rarely any discussion about this problem. According to Abramowicz and Wierzbicki [29], additional energy will be dissipated by this mechanism. Therefore, the geometrical compatibility could make some trouble in the prediction of crush resistance of multi-cells.

Although it has been validated that multi-cell tubes are more efficient in energy absorption than single-cell tubes, it is not clear that how the crush resistance of a tube varies when it transforms from a single-cell to a multi-cell. For example, Fig. 1 illustrates the transition from a single square section to a regular quadruple cell. Two adjacent cell walls in the square section have double thickness $2t$ and the double thickness cell walls are split into two uniform cell walls with thickness t and an interval d. With the increase of interval d, the section finally transforms to a regular quadruple cell. How would the crush resistance of the section vary

* Corresponding author. Tel.: +86 27 87543538; fax: +86 27 87543501.
E-mail address: zhanghuiwtu@126.com (H. Zhang).

http://dx.doi.org/10.1016/j.ijmecsci.2015.08.026
0020-7403/

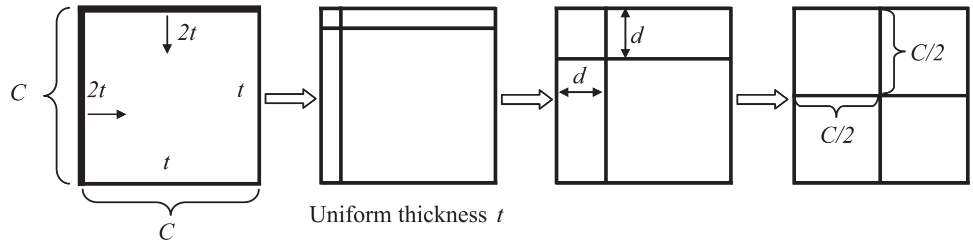

Fig. 1. Transition from a single cell to a regular quadruple cell.

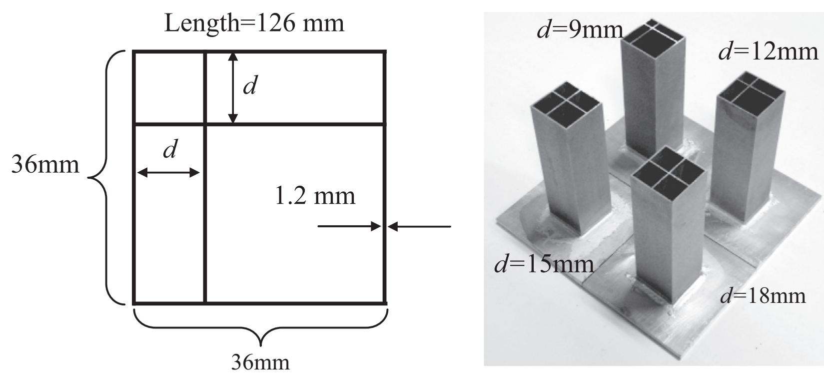

Fig. 2. Dimensions and picture of quadruple cell specimens.

in this transition? Is it possible to predict the crush resistance of such a section with arbitrary parameter *d*? In fact, this problem can be deemed as a parametric study on interval parameter *d* and it is also a topology variation problem when *d* approaches 0. In addition, this problem is also associated with the geometrical compatibility problem which becomes more severe among different elements when parameter *d* is small.

This paper tried to probe and solve the above mentioned problems. Experimental study was carried out first to observe the deformation and force responses of quadruple cell tubes with different dimensions. Numerical model was then validated by the experimental results and employed to further study the influence of geometric parameters on the crush resistance of the structure. Finally the discussion on the geometric compatibility and theoretical prediction was made and some suggestions were offered. The paper is organized as follows: In Section 2, experimental tests and results are firstly presented and the finite element models employed to simulate the tests are described in Section 3. Further numerical analyses and discussion on geometric compatibility problem are also given in this section. Theoretical aspects are offered in Section 4 and finally, Section 5 summarizes the present study.

2. Experimental test

Axial crushing test of a group of quadruple cell specimens was performed in this section to observe the variation of crush resistance and deformation mode when parameter *d* in Fig. 1 was changed. The dimensions and specimens are shown in Fig. 2. The width *C* and length *L* of the tubes are 36 mm and 126 mm, respectively. The wall thickness *t* of all the flanges is kept constant to be 1.2 mm. Four *d* values with an interval of 3 mm are employed. As limited by the fabrication process, the minimum value of *d* is set to 9 mm and the maximum value is 18 mm due to the symmetry of the section. The specimens were fabricated by cutting of aluminum alloy blocks made of AA6061 O. The cutting was performed by Wire cut Electrical Discharge Machining

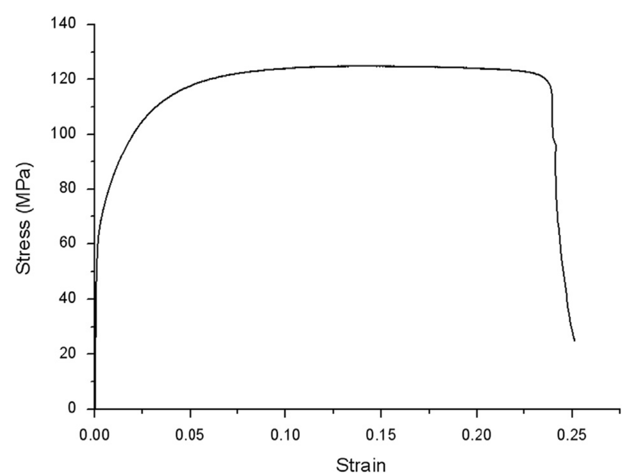

Fig. 3. Engineering stress–strain curve of AA6061 O.

(WEDM) technique with the precision to be ±20 μm. Quasi-static axial crush tests were carried out by using a 100 kN capacity universal materials testing machine with computer control and data acquisition systems. The testing was displacement controlled with the top platen of the machine being moved vertically downward to compress the specimens and the loading speed was 1 mm/s.

The tensile engineering stress–strain curve of AA6061 O is shown in Fig. 3 which was measured by a 10 kN capacity Zwick Z010 universal tensile tester with the standard tensile specimens as specified in the ASTM E8M-04 [30]. The mechanical properties of it are as follows: Young's modulus E=68.9 GPa, initial yield stress σ_y=63.3 MPa, the ultimate stress σ_u=125.0 MPa, Poisson's ratio ν=0.33. Aluminum alloy is strain rate insensitive and strain rate effect is not considered here.

The measured force response and energy absorption curves with respect to the load displacement are presented in Fig. 4 (a) and (b) for quadruple cells with different *d* values. It is noted