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Axial crushing of circular multi-cell columns

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ABSTRACT

Multi-cell columns are highly efficient energy absorbing components under axial compression. However, the experimental investigations and theoretical analyses for the deformation modes and mechanisms of them are quite few. In this paper, the axial crushing of circular multi-cell columns are studied experimentally, numerically and theoretically. Circular multi-cell columns with different sections are axially compressed quasi-statically and numerical analyses are carried out by nonlinear finite element code LS-DYNA to simulate the experiments. The deformation modes of the multi-cell columns are described and the energy absorption properties of them are compared with those of simple circular tube. Theoretical models based on the constituent element method are then proposed to predict the crush resistance of circular multi-cell specimens. The theoretical predictions are found to be in a good agreement with the experimental and numerical results.

1. Introduction

Thin-walled structures are always applied in the vehicle systems as energy absorbing devices to avoid injuries or damages during accidents and the weight of them is expected to be as light as possible for the sake of cost efficiency when safety is guaranteed. The specific energy absorption (SEA, energy absorption per unit mass of material) is therefore the most extensively adopted index to evaluate the efficiency of energy absorption devices although other indices proposed by researchers are also important and useful [1]. Since 1980s, filling the structures with cellular materials including foams and honeycombs has attracted wide research interests in the scientific community as an important approach to increase the SEA value of thin-walled energy absorber.

In the past decade, the employment of multi-cell sections was found to be an effective way to increase the energy absorption efficiency of thin-walled structures and it could be more efficient than filling the structure with cellular filler [2]. The double-cell and triple-cell aluminum extrusions were firstly studied by Chen and Wierzbicki [3] in 2001 and multi-cell columns with different sections were then investigated by Kim [4], Zhang et al. [5] and Najafi and Rais-Rohani [6]. All these studies reported that the SEA values of multi-cells were significantly higher than that of single-cell under axial loading and theoretical analyses were also conducted by these researchers to predict the crush resistance of the multi-cell columns. The theoretical analysis of multi-cell is a quite difficult and challenging task and a basic idea to solve this problem is to divide the multi-cell into a group of basic constituent elements.

No matter how complex the section of a multi-cell column is, it is constituted by a number of shells or plates connected with various angles and by different edge connectivity. Determining the energy dissipation of each element separately and summing up the contribution of every element, the crush resistance of a multi-cell section can be obtained. Recently, the crush resistance of angle elements made up of plates was studied by Zhang and Huh [7] and Zhang and Zhang [8–12]. The influence of central angle on crush resistance was investigated numerically for edge connectivity Ze (the number of plates or shells connected by one intersection line) ranging from 2 to 8 [7,8] and significant impact of it was reported. Theoretical models were also established for angle elements of different types [9,11], including corner element (Ze = 2), Y-shaped element (Ze = 3) and X-shaped element (Ze = 4). As edge connectivity Ze increases further, the deformation modes and corresponding analytical models were also presented and experimental studies [8,12] were carried out to validate the above proposed theoretical models for different angles and different edge connectivity. However, up to now, there is still no relevant research about the energy absorption of multi-cell structures consisting of shells or both shells and plates.

In this paper, the axial crushing of circular multi-cell metal structures is investigated. Axial compression tests are carried out

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for circular columns with single, double, triple and quadruple cells to study the deformation behavior and energy absorption characteristics of them. The T-shaped element and cruciform element which can be deemed as internal filler of multi-cell columns are also tested. Numerical simulations of the experimental tests are then conducted by explicit nonlinear finite element code LS-DYNA. The numerical results including deformation modes and crushing force responses are compared with those of experiments. Finally, theoretical analyses based on the constituent element method are carried out to predict the mean crushing force and energy absorption of circular multi-cell structures.

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 ±20 μm. The circular multi-cell specimens and the relevant T-shaped and cruciform element are shown in Fig. 1 and the specimens are made of aluminum alloy material AA6061 O. The tensile stress–strain curve of AA6061 O is obtained by using a 10 KN capacity Zwick Z010 universal tensile tester with the standard tensile specimens as specified in the ASTM E8M-04 and it is shown in Fig. 2. The mechanical properties of it are as follows: Young's modulus $E = 68.0$ GPa, initial yield stress $\sigma_y = 71$ MPa, the ultimate stress $\sigma_u = 130.7$ MPa, the rupture strain $\varepsilon_r = 0.22$, the power law exponent $n = 0.18$, Poisson's ratio $\nu = 0.33$ and density $\rho = 2.7$ g/cm^3.

The dimensions of the cross section of circular multi-cell specimens are shown in Fig. 3. The length L of all the specimens is 120 mm, while the diameter D of the circular columns is 36 mm. The thickness t of all shells and plates is 1.2 mm, which means the outer diameter of the circular columns is 37.2 mm. The bottom of each column was welded to a 6 mm aluminium plate of the same material to clamp the column during the test. Argon arc welding technique was applied to join the multi-cell columns to the base plate. Quasi-static axial crush tests were carried out by using a 100 KN capacity INSTRON 5882 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 0.5 mm/s.

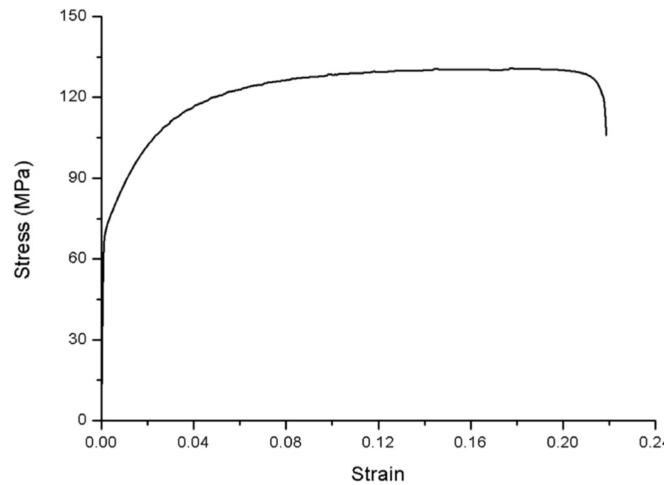

Fig. 2. Engineering stress–strain curve of AA6061 O.

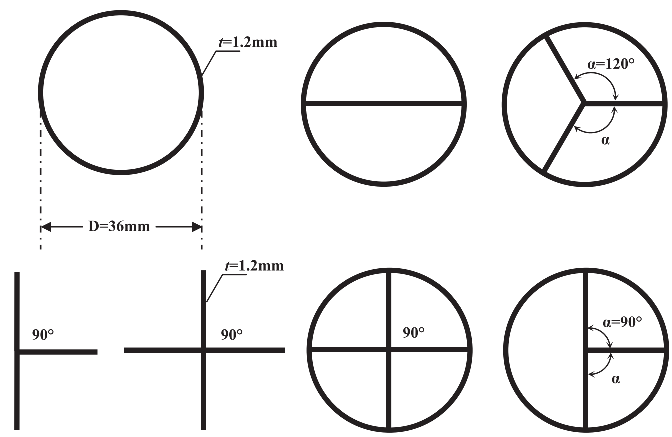

Fig. 3. Cross section of circular multi-cell columns and relevant specimens.

2.2. Experimental results

2.2.1. Deformation mode

The deformed shapes of the hollow circular tube and multi-cell columns are presented in Figs. 4–8. The concertina mode is

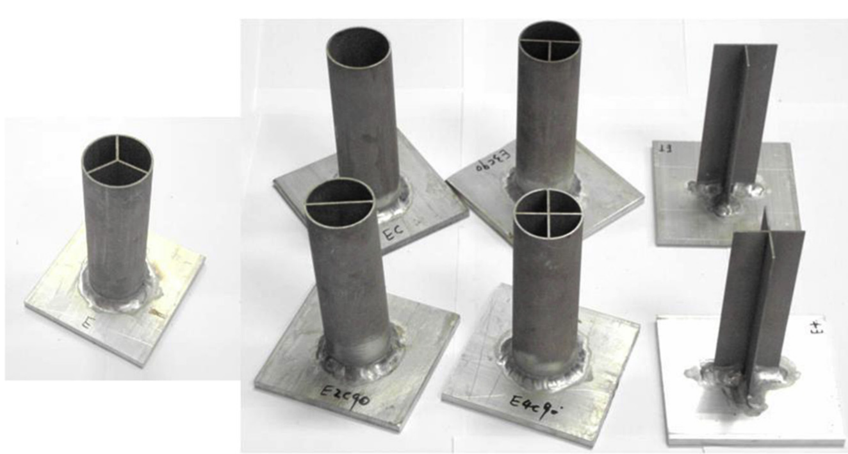

Fig. 1. Circular multi-cell columns and relevant specimens for experimental tests.