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Energy absorption of multi-cell stub columns under axial compression

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ABSTRACT

Multi-cell metal columns were found to be much more efficient in energy absorption than single-cell columns under axial compression. However, the experimental investigations and theoretical analyses of them are relatively few. In this paper, the quasi-static axial compression tests are carried out for multi-cell columns with different sections. The significant advantage of multi-cell sections over single cell in energy absorption efficiency is investigated and validated. Numerical simulations are also conducted to simulate the compression tests and the numerical results show a very good agreement with experiment. Theoretial analyses based on constitutive element method are proposed to predict the crush resistance of multi-cell columns and the theoretical predictions compare very well with the experimental and numerical results.

1. Introduction

Thin-walled metal tubes are known to be efficient energy absorbing components and enormous efforts have been made by researchers to understand the deformation behavior of them under axial compression. The plain circular and square tubes are most commonly used and received most concerns. The classification of possible collapse modes of them [1–3] and the analytical models for energy absorption of these modes [4,5] have been addressed and validated by the researchers. With the advance in the analytical and numerical methods, the columns with more complex sections become the focus of attention.

Over the past decade, the multi-cell metal columns were found to be much more efficient than single-cell columns. Chen and Wierzbicki [6] investigated numerically the behavior of double-cell and triple-cell aluminum extrusions under axial loading and a simplified theoretical model was proposed to predict the mean crushing force of them. A new multi-cell profile, with four square elements at the corner, proposed by Kim [7] was reported to increase the specific energy absorption (SEA) by 190% over the conventional square column. Based on the theory of Chen and Wierzbicki [6], Zhang et al. [8] analyzed the energy absorption of square multi-cell columns by dividing the section to three types of elements. Zhang and Cheng [9] compared the energy absorption efficiency of multi-cell columns with that of foam-filled columns and the performance of multi-cell sections were found to be very much better. However, up to now, the studies on the axial compression of thin-walled multi-cell structures were primarily concentrated in the theoretical and numerical aspects. Almost no experimental investigations were found in the open literatures to validate the theoretcial models and numerical simulations.

Experimental tests are carried out in the present work to study the energy absorption characteristics of multi-cell columns. The SEA of single square columns and multi-cell columns are compared to better understand the extent of increase in energy absorption efficiency for multi-cell columns. Numerical simulations and theoretical predictions are also conducted and the relevant results are compared with experimental results to validate the numerical and analytical models. The present work is organized as follows: in Section 2, quasi-static axial compression of multi-cell columns are described and relevant experiment results are presented. Finite element models are introduced in Section 3 and numerical simulations are carried out to analyze the deformation modes and energy absorption characteristics of multi-cell columns. Section 4 gives a discussion in the theoretical aspect of the crushing resistance of multi-cell columns under compression. A comparison among theoretical, numerical and experimental results is also given in this section. Finally, Section 5 summarizes the present work.

2. Experimental test

The multi-cell columns with the sections that have been numerically and theoretically studied by Chen and Wierzbicki [6]

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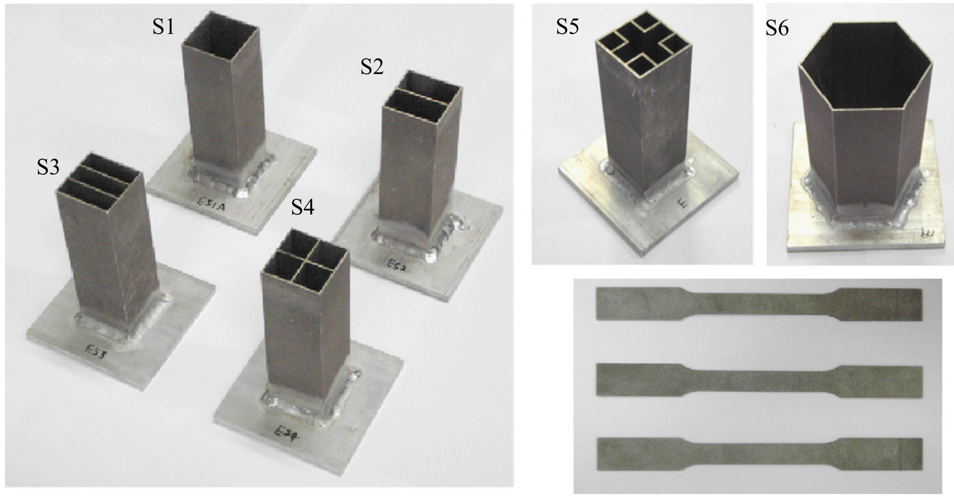

Fig. 1. Multi-cell and tensile specimens for experimental tests.

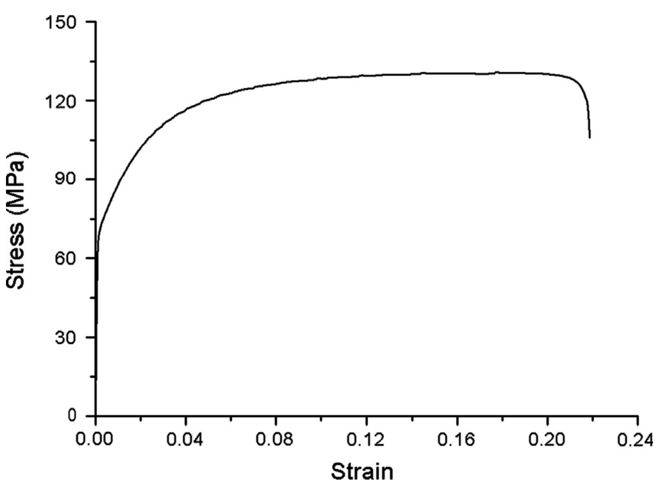

Fig. 2. Engineering stress–strain curve of AA6061 O.

and Kim [7] are experimentally investigated in the present work. In addition, the plain square and hexagonal columns are also tested. The polygonal columns were recently tested by Zhang and Zhang [10] to analyze the influence of central angle on the crush resistance of corner elements. In their work, the side wall of the specimens were fabricated by welding and the influence of the weld lines is hard to evaluate although it is expected to be small. In the present work, the specimens were fabricated by Wire cut Electrical Discharge Machining (WEDM) technique with the precision to be ± 20 um. The influence of central angle on energy absorption of corner element is therefore validated again.

The multi-cell specimens are marked from S1 to S6 as shown in Fig.1 and the material of the specimens is AA6061 O. The engineering stress–strain curve of the material was obtained by using the tensile specimens with dimensions as specified in the ASTM standard E8M-04. The tensile specimens are also given in Fig. 1 and uniaxial tensile measurements were performed on a 10 KN capacity Zwick Z010 universal tensile tester. The tensile stress–strain curve of AA6061 O is shown in Fig. 2 and the mechanical properties of it are given here: Young's modulus $E=68.0$ GPa, initial yield stress $\sigma_y=71$ MPa, the ultimate stress $\sigma_u=130.7$ MPa, Poisson's ratio $\nu=0.33$ and the power law exponent $n=0.18$.

The dimensions of the cross section of multi-cell specimens are shown in Fig. 3. The length L of all the specimens is 120 mm, while the width C of the side wall of the columns is 36 mm. Although the length L is not very long, the number of lobes developed for the specimens is enough for the progressive buckling deformation analysis. The internal webs are located in the equal divisions of the side walls and the thickness t of all constitutive plates is 1.2 mm. The bottom of each column was welded to a 6 mm aluminum 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. The experimental set-ups for both tensile test and axial compression test are shown in Fig. 4.

The deformed shapes of the multi-cell columns are presented in Fig. 5. It can be found that the folding lobes are increased with the increase of internal webs. The number of lobes is 5 for S1, while it is increased to 10 for S4 and 13 for S5. This is due to the decrease of folding wavelength and the mechanism is similar as the employment of foam fillers to increase the energy absorption efficiency of single-cell columns. The only difference is the replacement of foam fillers by the internal webs here and the later was found sometimes more effective [9]. Both the hollow square and hexagonal columns developed inextensional mode and the number of lobes is 5. It should be mentioned that almost all corner elements of the multi-cell columns deform in inextensional mode except for some corner elements in specimen S5. The corner elements in the internal region of the columns develop extensional mode as denoted by the dashed circle in Fig. 5.

The force–displacement curves are shown in Fig. 6 in the left and the integration curves of the force–displacement responses, namely the energy absorption–displacement curves, are given in the right. To make the curves clear, the results of specimens 1–3 are shown in Fig. 6(a) and those of specimens 4–6 are plotted in Fig. 6(b). The relevant energy absorption parameters including effective crushing distance (ECD), energy dissipation and mean crushing force P_m are listed in Table 1. One extra specimen is tested for S1, S2 and S4 to check the repeatability and data dispersion. The difference of the mean crushing force between two specimens is about 5% which is acceptable. The coefficient of effective crushing distance κ should be calculated by dividing the ECD by the length L of the column. However, the welding seams between the multi-cell columns and base plates have some influence on the effective length of the columns. As shown in