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Crashworthiness analysis of multi-cell prismatic structures

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ABSTRACT

This paper presents a numerical and experimental study of several configurations of multi-cell columns compared to single-walled and double-walled columns subjected to dynamic axial impact forces. The impact of the columns was numerically analysed using FEM and also verified by experimental testing. The effect of the column mass and thickness of the multi-cell columns compared to single- and double-walled columns was also studied. The results showed that, by analysing a group of columns with the same thickness and weight, the energy absorption efficiency can be significantly improved by introducing internal ribs to the double-walled columns. The results showed that the crushing force of the middle ribs (MR) multi-cell columns was the highest, followed by the corner ribs (CR) multi-cell columns, the double-walled (DW) columns and the single-walled (SW) columns, respectively.

1. Introduction

The axial crushing resistance characteristic of single-cell thin-walled columns has long been the subject of extensive research, since single thin-walled prismatic columns were identified as a very efficient impact energy absorption system within the space-frame concept of cars [1, 2], train structures [3, 4] and helicopter subfloors [5, 6]. Usually, the focus of investigation is on increasing the energy absorption performance of a column by varying the cross-sections, such as square, circular, octagonal, hexagonal, top hat and double hat.

Apart from the single-cell concept, the multi-cell column has also been considered as an alternative solution to increase the energy absorption performance. Chen and Wierzbicki [7] presented theoretical solutions to calculate the mean crushing force of single-cell, double-cell and triple-cell columns, as can be seen in Fig. 1(a). The results showed that the energy absorption efficiency of double-cell and triple-cell columns is higher than that of single-cell columns. Furthermore, Kim [8] carried out an optimization process of a new multi-cell profile with four square elements at the corner, as shown in Fig. 1(b), as well as developing an analytical solution for calculating the mean crushing force of the column. The specific energy absorption (*SEA*) of this new multi-cell structure was reported to be 1.9-times larger than that of the conventional square box column of the same cross-sectional area [8].

Recently, Zhang et al. [9] developed a theoretical solution to calculate the mean crushing force of several configurations of square multi-cell columns, as shown in Fig. 1(c), and concluded that a significant increase in energy absorption efficiency would be achieved when a square single-cell column is divided into a multi-cell column. Zhang and Cheng [10] showed a comparative numerical study of energy absorption characteristics between foam-filled square columns and multi-cell square columns, as can be seen in Fig. 1(d). The results showed that multi-cell columns are 50–100% more efficient in absorption energy than foam-filled columns.

To improve energy absorption efficiency and minimize the initial crushing force of thin-walled aluminium columns with single-, double-, triple- and quadruple-cell columns, Hou et al. [11] optimized the structures by using single-objective and multi-objective optimizations. The single-, double-, triple- and quadruple-cell column configurations are shown in Fig. 1(e).

Furthermore, Zhang et al. [12] reported the energy absorption comparison between a single column, a foam-filled column and an optimized design of a rib-reinforced column, as shown in Fig. 1(f). The results showed that the optimized design of the rib-reinforced column would increase energy absorption and reduce the initial peak force.

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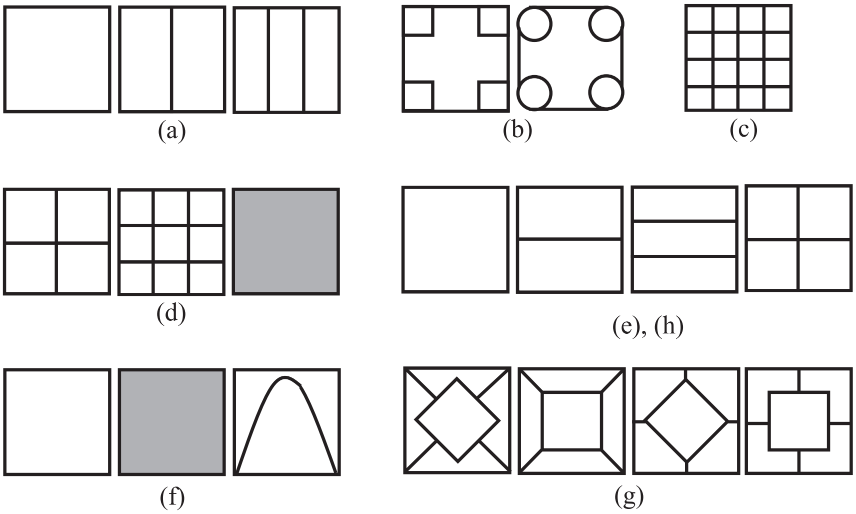

Fig. 1. Cross-sectional geometry of multi-cell prismatic columns, (a) Chen and Wierzbicki [7], (b) Kim [8], (c) Zhang et al. [9], (d) Zhang and Cheng [10], (e) Hou et al. [11], (f) Zhang et al. [12], (g) Najafi and Rais-Rohani [13], (h) Zhang and Zhang [14].

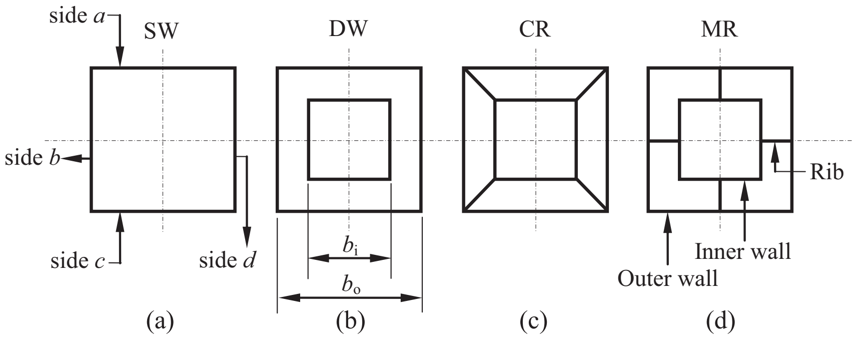

Fig. 2. Cross-sectional geometry of (a) single-walled (SW), (b) double-walled (DW), (c) corner ribs (CR) multi-cell and (d) middle ribs (MR) multi-cell columns.

Najafi and Rais-Rohani [13] presented an analytical mean crushing force calculation of axially crushed thin-walled aluminium columns with different multi-cell, multi-corner configurations, as can be seen in Fig. 1(g), and then compared the results with quasi-static nonlinear finite element simulation. The results showed that multi-cell columns have less crushing force fluctuation than the associated single-walled column with an equal mean crushing force. They also showed that the crushing force and energy absorption depend greatly on how the walls of the inner square tube are attached to those of the outer tube.

Very recently, Zhang and Zhang [14], carried out quasi-static experimental investigations, numerical simulations and theoretical analyses of multi-cell columns with different sections, as shown in Fig. 1(h). The findings in Ref. [14], as also found in the above-mentioned literature, show that there is a significant advantage of multi-cell sections compared to single-cell in terms of energy absorption efficiency.

Table 1
Geometrical detail of the single-walled, double-walled and multi-cell columns Set 1 (Numerical and Experimental Analysis).

		Single-walled (SW) [15]				Double-walled (DW) [15]			
		Outer wall thickness t_o (mm)	Outer wall width b_o (mm)	Inner wall thickness t_i (mm)	Inner wall width b_i (mm)	Outer wall thickness t_o (mm)	Outer wall width b_o (mm)	Inner wall thickness t_i (mm)	Inner wall width b_i (mm)
Side	*a*	1.05	45.90	–	–	1.03	46.27	1.00	27.15
	b	1.05	46.40	–	–	1.00	46.05	1.03	27.12
	c	1.08	46.10	–	–	1.00	46.48	1.02	27.12
	d	1.00	46.30	–	–	1.05	46.03	1.05	27.13
		Corner ribs multi-cell (CR)				Middle ribs multi-cell (MR)			
		Outer wall thickness t_o (mm)	Outer wall width b_o (mm)	Inner wall thickness t_i (mm)	Inner wall width b_i (mm)	Outer wall thickness t_o (mm)	Outer wall width b_o (mm)	Inner wall thickness t_i (mm)	Inner wall width b_i (mm)
Side	*a*	1.00	45.70	0.95	26.88	1.13	45.12	1.05	27.15
	b	0.98	45.33	0.93	27.00	1.20	45.23	0.98	27.00
	c	0.98	45.88	0.95	26.88	1.28	44.83	0.98	27.15
	d	1.02	45.23	0.93	27.05	1.10	45.08	0.93	26.85