International Journal of Impact Engineering 78 (2015) 81–97

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

The crush resistance of four-panel angle elements

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, PR China

ARTICLE INFO

Article history:
Received 6 June 2014
Received in revised form
27 September 2014
Accepted 15 December 2014
Available online 23 December 2014

Keywords:
Multi-cell columns
Energy absorption
Angle elements
Crush resistance
Experimental test

ABSTRACT

Four-panel angle elements are frequently encountered in multi-cell sections. To predict the energy absorption of such sections under axial loading, theoretical models have to be established for possible collapse modes of these elements. In this paper, four-panel angle elements are classified into four types: corner element, K-shaped, X-shaped and tree-shaped element. The influence of geometric parameters and type of triggers on collapse modes and crush resistance of these elements was firstly investigated numerically by using LS-DYNA. Theoretical models were then established for most commonly developed collapse modes of each type of four-panel angle elements. Elements with different width, thickness and angles were analyzed to validate the proposed models and the theoretical predictions by these models showed good agreement with numerical results. In addition, axial crushing test of two multi-cell sections with K-shaped elements was carried out quasi-statically and the experimental results validated the good accuracy of the present numerical and theoretical models.

1. Introduction

Thin-walled metal tubes with square, circular or hat-shaped sections are known to be efficient energy absorbing components under axial compression and they have been widely applied in the various engineering fields. In order to further increase the energy absorption efficiency of metal tubes, researchers tried many different approaches, for instance, filling the tubes with cellular materials including honeycombs and foams. Recently, thin-walled metal columns with multi-cell sections were found to be significantly more weight-efficient than single-cell tubes in energy absorption and attracted extensive research interests [1–7].

Due to highly nonlinear features during axial loading, it is a really challenging task to predict the crush resistance of multi-cell columns with complex cross-section. The basic idea to obtain the crush resistance of a multi-cell section is to divide the section into a number of representative constituent elements, determine the crush resistance of each individual element and finally sum up the contribution of every elements [8,9]. However, to achieve this goal, first of all, we have to study the crush resistance of different types of angle elements. Angle elements are constituted by a number of plates or shells connected with various angles and by different edge connectivity. The influence of all these factors should be taken into consideration in the analysis of crush resistance of angle elements.

In the early study of multi-cells, the influence of central angles on crush resistance was not considered. Theoretical analysis of multi-cells was firstly carried out by Chen and Wierzbicki [1]. The crushing strength of single-cell, double-cell and triple-cell aluminum profiles under axial compression was investigated by them numerically and theoretically. The triple-cell and double-cell sections were found to be much more efficient than single-cell section, and a simplified theoretical method was developed to calculate the mean crushing force of the structures. Based on their methods, Kim [2] derived an analytical solution for the mean crushing force of a multi-cell profiles with four square elements at a corner. The specific energy absorption (SEA) of the proposed multi-cell section was reported to be increased by 190% over the conventional square box column. In the simplified method proposed by Chen and Wierzbicki [1], the membrane energy of each plate was assumed to be the same, which may be oversimplified. Zhang et al. [3] then developed a theoretical solution for square multi-cell columns by dividing the section into three basic components: corner, T-shaped and crisscross element. However, all the central angles between plates in these elements are right angles.

According to the study of Zhang and Huh [10], central angles showed significant influence on the crush resistance of a three-

* 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.ijimpeng.2014.12.004
0734-743X/

panel or four-panel angle element. One hundred percent increase in mean crushing force can be achieved by varying the angles between panels. Consequently, it is necessary to develop theoretical models that can well describe the influence of angle variations. With this in mind, Zhang and Zhang [11,12] proposed theoretical models for corner elements, three-panel elements and X-shaped elements. Numerical and experimental investigations [13–15] were also carried out by them to validate the correctness and accuracy of the proposed models for elements with different angles. However, up to now, there is no theory for crush resistance of four-panel angle elements (that is, the elements with edge connectivity of four) with arbitrary angles. Only one theoretical model has been established for a special type of four-panel angle elements: X-shaped elements [12] which have two pair of equal angles. This is obviously not sufficient to predict the energy absorption of some common multi-cell sections shown in Fig. 1. Therefore, it is necessary to investigate the crush resistance and to establish theoretical models for four-panel angle elements with arbitrary angles.

In the present work, the axial crush resistance of four-panel angle elements with arbitrary angles is analyzed and theoretical models are established to predict the mean crushing force of these elements. The paper is organized as follows: In Section 2, four-panel angle elements are classified into four types and the finite element models employed to simulate the crushing of the elements are described. Numerical and theoretical analyses for four different types of elements are then carried out in Sections 3 and 4, respectively. Experimental test of multi-cell sections is reported in Section 5 where theoretical, numerical and experimental results are compared to each other. Finally, Section 6 summarizes the present study.

2. Element classification and finite element modeling

2.1. Element classification

As we know, square or circular tubes can develop different collapse modes under axial compression, which is primarily determined by geometric parameters of the tubes. Similarly, an angle element under axial loading may deform in different collapse modes when the central angles between the plates are varied. For example, two types of collapse modes (Types I and II) were defined and analyzed for three-panel elements by Zhang and Zhang [11]. The elements tend to deform in type I mode when the central angles are within a certain range and to deform in type II in another range. It can also develop mixed modes when the angles are set to intermediate values.

For four-panel angle elements, the possible collapse modes are more complicated. Even determining the range of geometrical parameters for different modes is not an easy task. As defined in Ref. [7], a four-panel angle element may deform in four possible collapse modes as shown in Fig. 2. The folding direction of each lobe in one folding wavelength is denoted by the dashed lines and all these directions are reversed in the subsequent fold. It should be mentioned that the central angles have no influence on the definition of the deformation modes. Only the folding directions of the lobes are critical. However, the central angles are one of the most important factors to determine which mode will be developed.

Based on the study of the influence of central angles on the collapse modes of angle elements [10–14], four-panel angle elements are classified into four types as shown in Fig. 1. They are corner element, K-shaped, X-shaped and tree-shaped element. To simplify the analysis, all these types of elements are defined to have one or two symmetric planes here. It can be found that the first three types can actually be described by X-shaped element if φ_1 and φ_2 in Fig. 1(c) take arbitrary values (all the angles in the present work are assumed to be positive). However, when φ_1 and φ_2 are varied, the deformation mode that the element tends to develop will also change. When $\varphi_1 < 180^\circ$, $\varphi_2 \geq 180^\circ$, the element is expected to deform in collapse mode I (see Fig. 2) which is similar to the inextensional mode of the two-panel corner element [10] or type I mode of three-panel element [11]; while if $\varphi_1 \leq 90^\circ$, $\varphi_2 \leq 90^\circ$, the element is expected to deform in collapse mode II; if $\varphi_1 \leq 90^\circ$, $90^\circ \leq^\circ \varphi_2 \leq 180^\circ$, the collapse mode of the element is hard to predict and it could be dominated by the initial structural imperfections. Taking this into consideration, three types of elements, i.e. corner, K-shaped and X-shaped elements, will be further defined.

For corner elements, the sum of angles $\alpha + 2\beta$ should be less than 180°. K-shape elements can be deemed as a special type of corner elements with $\alpha + 2\beta = 180^\circ$, but they will be analyzed separately here since they are frequently encountered in multi-cells. The angle φ_1 and φ_2 of X-shaped elements are constrained by $\varphi_1 \leq 90^\circ$ and $\varphi_2 < 180^\circ$, although it will be discussed in two separate ranges: $\varphi_1 \leq 90^\circ$, $\varphi_2 \leq 90^\circ$ and $\varphi_1 \leq 90^\circ$, $90^\circ \leq^\circ \varphi_2 < 180^\circ$. The tree-shaped element is a special type of four-panel angle elements and the central angle γ of it is set to be less than 90°.

2.2. Finite element modeling

For each type of element, parametric analysis is firstly carried out to investigate the influence of geometric parameters: angles, width and thickness, on crush resistance of the structure and to study the possible collapse modes and their relevant geometric

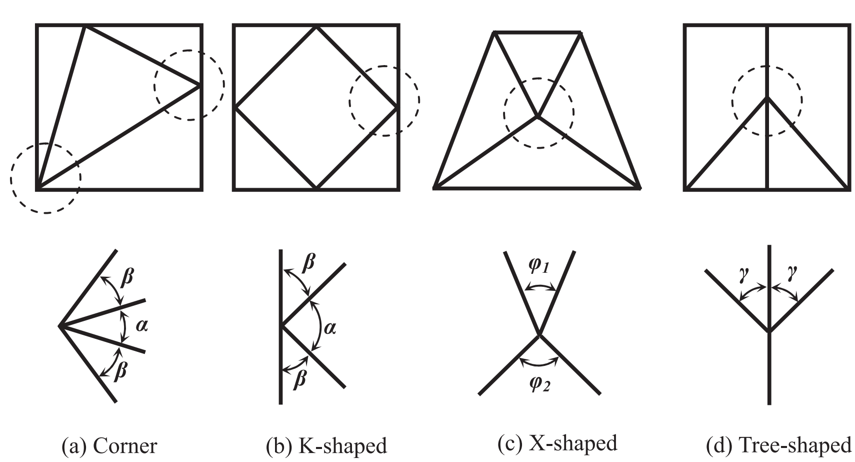

Fig. 1. Multi-cell sections with four-panel angle elements and definition of four types of elements.