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Multi-cornered thin-walled sheet metal members for enhanced crashworthiness and occupant protection

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ABSTRACT

Crash energy management in frontal crumple zone of the automotive body is one of the key elements for the design of automotive structure. Improving energy absorption characteristics reduces the magnitude of forces transferred to the occupant compartments. Here, a new strategy has been proposed to improve energy absorption efficiency of thin-walled columns by introducing extra stable corners in the cross-section. Several profiles of multi-corner thin-walled columns obtained through this strategy were presented and their crashworthiness capacities under axial crush loading were investigated analytically, experimentally, and numerically. First, explicit formulations for predicting the mean crushing force of multi-corner thin-walled columns were derived using the theory of super folding element (SFE). Predicted results of these formulations showed a good agreement with the results of quasi-static experiments and CAE simulations, which were performed by explicit non-linear finite element code through LS-DYNA. Based on this agreement, other significant crashworthiness assessment parameters were then investigated experimentally and numerically. Newly introduced 12-edge section with high energy absorption capacity was developed and its dominance was established through the responses in quasi-static experiments and CAE simulations. Finally, the foundational dominance of the 12-edge section was extended to the dynamic environment through a full vehicle crash test simulation to evaluate overall reduction in crashworthiness parameters which reflected occupant safety. Interestingly, in the case of using 12-edge section as crush absorbers, specific energy absorption (SEA), dash intrusion and maximum occupant's chest deceleration showed significant improvement, compared to the baseline design which used a rectangular section.

1. Introduction

Thin-walled structures are widely used as kinetic energy absorbers, since they are cheap, have high energy absorbing capacity, and are weight efficient [1]. They can dissipate a large amount of kinetic energy through plastic deformation in the case of collisions. Such members must appear as major energy-absorbing components in automotive structures and absorb a substantial amount of crash energy at the time of impact occurrence. Front rail and front cross member in automotive are typical thin-walled energy absorbers [2], which dissipate the kinetic energy by longitudinal and transverse deformations. Energy absorption capabilities of such components are very effective and weight-efficient approach in improving vehicle crashworthiness. Such a quest for lighter and more efficient energy absorbing components in various transportation systems has led to an increased interest in thin-walled sections [3]. Many research articles have studied impact responses and crash performance of thin-walled structures. [2,4–6]. The behavior of structural collapse of the thin-walled structures in axial mode has been the focus and also been extensively studied over the past decades [7]. A thin-walled structure can significantly contribute in minimizing the amount of forces transmitted to vehicle occupants. Many efforts have been made in experimental research [7–10] and in developing safe design criteria using plastic hinge analyses with thin-walled structures [4,11,12]. Collapse of thin-walled sections is an excellent mechanism for energy absorption [4] and has been widely used in engineering structures because of high load carrying capacity and low structural weight. These components in service are commonly subjected to axial compressive loading. It is well known that the energy absorbing ability of structures depends on various crushing characteristics and failure modes [11–13].

Energy absorption efficiency of a thin-walled column is influenced by many factors, such as material property, cross-section configuration, and wall thickness. Some studies have focused on the tubes with various cross-sections including circular [7,14,15], polygonal (e.g. square, rectangle, etc.) [5,10,16], top-hat like [12], and tailor-made tubes [17] while other researchers have tried to

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improve the energy absorption of thin-walled members by filling them with different materials including metallic [18–22] and polymer [23,24] foams or by using high-performance impact absorbing materials [25,26]. Moreover, thin-walled members with multiple cells have shown to have desirable energy absorption and weight efficiency [27,28]. Zhang and Cheng [29] made numerical simulations to demonstrate that the energy absorption efficiency of multi-cell members was higher than that of foam-filled columns. More recently, Tang et al. [30] and Abbasi et al. [31] showed that, by introducing more corners into the structure, energy absorption of thin-walled tubes could be further increased.

An approximate theoretical model was first proposed by Alexander [14] to predict the mean crushing force and energy absorption of cylinder tube under axial crush loading. Wierzbicki and Abramowicz [16] studied the axial crushing of square columns and proposed a theory of super folding element (SFE). Wierzbicki and Abramowicz [4] conducted a research on the collapse of the members with square cross-sections. They observed that severe deformation occurred near the corners of the section, while most of the energy was dissipated by membrane deformation and bending deformation along the bending hinge lines especially in corner zones. The number of corners in a column's cross-section has significant effects on energy absorption [4,14,32]. On the other hand, the number of side flanges enclosing one corner element has to be even for the stable progressive collapse, and also the angle between neighboring flanges should be 90–120 degrees for the highest efficiency of crushing energy absorption [32].

Thin-walled sections designed with greater number of corner elements in a cross-section with the favorable angle between neighboring flanges provide stable progressive collapse for efficient energy absorption [32]. This understanding has been later utilized to develop a new section with twelve corner elements. Based on such a motivation, in this study, different tubular structures were made in order to study the difference in energy absorption characteristics. In this paper, prismatic tubes including square, hexagonal, octagonal, and newly introduced 12-edge cross-sections, which were expected to have higher crashworthiness efficiency, were investigated. Moreover, first, the correlation of CAE simulations and experimental tests with the results of SFE theory was investigated for mean crushing force (P_m) criterion. A wide range of crashworthiness parameters including total absorbed energy (E_{abs}), specific energy absorption (SEA), crush efficiency (S_E), crush force efficiency (A_E), and energy efficiency (E_E) were then calculated numerically and experimentally. Finally, thin-walled members of rectangular, hexagonal, octagonal, and 12-edge sections were tested in a full finite element model of a real automotive as frontal crush absorbers and the crashworthiness parameters including SEA, dash intrusion, and maximum occupant's chest deceleration, were calculated and compared.

2. A review of super folding element (SFE) theory

Progressive folding of box columns was studied under the assumption of purely inextensional deformation modes with stationary or moving hinge lines [33–35]. On the other hand, for axially symmetric cases such as tube inversion [36], crumpling of the cylindrical shells in the crinkling deformation loads [14], and crushing of rotationally symmetric shells [37], a predominantly extensional type of deformation was assumed. Wierzbiki et al. [16] combined these two approaches with kinematic method of plasticity to develop the crushing behavior of a certain class of shells. Therefore, accurate prediction of the crushing strength of thin-walled members with an arbitrary central angle was extracted based on generalized mixed folding mechanism which combined the features of the two simple folding modes: quasi-inextensional mode and extensional mode. It was also concluded that the number of corners in a column's cross-section could largely determine the efficiency of energy absorption [16]. An important inference that can be drawn from their study using super folding element theory is that the number of side flanges enclosing one corner element has to be even with included angles within the range of 90 to 120 degrees for considerable energy absorption potential. Consequently, thin-walled sections which are designed with greater number of corner elements in the cross-section with a favorable angle between the neighboring flanges provide stable progressive collapse for efficient energy absorption.

Consequently, for a given assembly of corner elements, the global energy balance equation can be generalized by summing up the contributions of plastic mechanisms in a single corner element and then adding the energies of individual corner elements. Therefore, by considering a pure quasi-inextensional mode and assuming the clamp boundary conditions on horizontal planes, the energy balance equation can be re-arranged to the following form [16]:

$$\frac{P_m}{M_0} = \left\{ A_1 \frac{b}{h} + A_2 \frac{C}{H} + A_3 \frac{H}{b} \right\} \tag{1}$$

where P_m and M_0 represent mean crushing force and plastic moment per unit length, respectively and parameters A_1 through A_3 are known and can be evaluated using the particular integrals which depend on the type of the problem. Length of each horizontal hinge line is constant and equal to C; while h, b and H represent thickness of shell, radius of the toroidal surface and half-length of local buckling or length of plastic fold wave, respectively. This expression involves two unknown geometrical parameters H and b which can be further determined by setting minimum conditions for the least mean crushing force.

$$\frac{\partial P_m}{\partial H} = 0, \qquad \frac{\partial P_m}{\partial b} = 0 \tag{2}$$

Consequently, the solution is obtained as

$$b = \sqrt[3]{A_1 A_3 / A_1^2}\,\sqrt[3]{Ch^2}$$
$$H = \sqrt[3]{A_2^2 / A_1 A_3}\,\sqrt[3]{C^2 h} \tag{3}$$

Inserting (3) in Eq. (1) results in

$$\frac{P_m}{M_o} = 3\sqrt[3]{A_1 A_2 A_3}\,\sqrt[3]{C/h} \tag{4}$$

where M_0 can be related to energy equivalent flow stress σ_0 as $M_0 = \sigma_0 h^2/4$. Moreover, It has been shown that the energy equivalent flow stress for progressively collapsing prismatic columns made from mild steel approximately equals: $\sigma_0 = 0.92\sigma_u$ [16].

As indicated in the above considerations for the single corner element, the efficiency of the structure in energy absorption majorly dependents on the number of corner elements that are capable of collapsing predominantly in inextensional mode, accommodated into the considered section. Wierzbicki and Abramowicz [4] presented this theoretical basis according to which the above method can be used to predict the crushing resistance of prismatic columns (square, hexagonal, octagonal, etc.) composed of n identical corner elements. The following section provides a treatment for such cross-sectional columns.

3. Crushing resistance of prismatic columns

For square columns, in the particular case of inextensional mode of deformation, the solution to Eq. (4) can be obtained in a