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Multiobjective crashworthiness optimization of multi-cornered thin-walled sheet metal members

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ABSTRACT

Plastic deformation of structures absorbs substantial kinetic energy when impact occurs. Therefore, energy-absorbing components have been extensively used in structural designs to intentionally absorb a large portion of crash energy. On the other hand, high peak crushing force, especially with regard to mean crushing force, may lead to a certain extent and indicate the risk of structural integrity. Thus, maximizing energy absorption and minimizing peak to mean force ratio by seeking for the optimal design of these components are of great significance. Along with this analysis, the collapse behavior of square, hexagonal, and octagonal cross-sections as the baseline for designing a newly introduced 12-edge section for stable collapse with high energy absorption capacity was characterized. Inherent dissipation of the energy from severe deformations at the corners of a section under axial collapse formed the basis of this study, in which multi-cornered thin-walled sections was focused on. Sampling designs of the sections using design of experiments (DOE) based on Taguchi method along with CAE simulations was performed to evaluate the responses over a range of steels grades starting from low end mild steels to high end strength. The optimization process with the target of maximizing both specific energy absorption (SEA) and crush force efficiency (CFE), as the ratio of mean crushing load to peak load, was carried out by nonlinear finite element analysis through LS-DYNA. Based on single-objective and multi-objective optimizations, it was found that octagonal and 12-edge sections had the best crashworthiness performance in terms of maximum SEA and CFE.

1. Introduction

Thin-walled structures are widely used as kinetic energy absorbers, since they are cheap, high energy absorbers, and weight efficient [1]. They can dissipate a large amount of kinetic energy through plastic deformation, slit, and fracture in the case of collision. Such members must appear in automotive structures as major energy-absorbing components and absorb a substantial amount of crash energy at the time of impact occurrence. For instance, 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 important in improving vehicle crashworthiness without increasing body weight. This quest for lighter and more efficient energy absorbing components for various transportation systems has led to an increased interest in thin-walled sections [3]. Therefore, these members have received great research interest and numerous works have demonstrated their responses and performance during crashworthiness analyses [2,4–6]. Thin-walled metal members, particularly the square ones, are commonly used as energy absorbers, since they are relatively cheap and efficient for absorbing energy. Behaviors of structural collapse in their axial crushing have been extensively studied over the past decades [7].

As a result, it is necessary to design a cross-section which minimizes the amount of forces transferred to 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].

An approximate theoretical model was first proposed by Alexander [14] to predict the mean crushing force and energy

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absorption of cylinder tube under axial crush loading. Wierzbicki and Abramowicz [15] studied the axial crushing of square columns and proposed a theory called super folding element (SFE) theory. In this theory, by adopting a rigid-plastic material model and the condition of kinematic continuity on the boundaries between rigid and deformable zones, a model consisting of trapezoidal, toroidal, conical, and cylindrical surfaces with moving hinge lines was developed. It was also found that general characteristics of the force–displacement curves of these thin-walled tubes were similar. The axial force first reached an initial peak, followed by a drop and then fluctuated. However, their collapse modes were very different for different basic shapes [10].

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 tubes with various cross-sections including circular [7,14,16], polygonal (e.g. square, rectangle, etc.) [5,10,15] and top-hat like [12], while other researchers have tried to improve the energy absorption of thin-walled members by filling them with different materials including metallic [17–21] and polymer foams [22,23] or by using high-performance impact absorbing materials [24,25]. Besides, thin-walled members with multiple cells have been shown to have desirable energy absorption and weight efficiency [26,27]. Zhang and Cheng [28] made numerical simulations to demonstrate that the energy absorption efficiency of multi-cell members was higher than that of foam-filled columns.

Among these factors, cross-section configuration is one of the most important issues. Numerous works [4,5,12,14,15] have been conducted theoretically, experimentally, and numerically on metal columns with various cross-sections, which include circular [7,14,16], polygonal (e.g. square, hexagon, etc.) [5,10,15,29], and top-hat like [12] ones. More recently, Tang et al. [30] showed that, by introducing more corners into the structure, energy absorption of thin-walled tubes can be further increased.

Wierzbicki and Abramowicz [4] conducted a research on the collapse of the members with square cross-sections and 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 the corner zones. The number of corners in a column's cross-section largely decides on the efficiency of energy absorption [4,14,31], which turned to a motivational point for this study. On the other hand, the number of side flanges enclosing one corner element has to be even for the stable progressive collapse and the angle between neighboring flanges should be 90–120 for the highest efficiency of crushing energy absorption [31].

Thin-walled sections designed with more number of corner elements in a cross-section with the favorable angle between neighboring flanges provide stable progressive collapse for efficient energy absorption [31]. 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 carried out in order to study 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 studied.

In designing such members, maximizing their crashworthiness performance should always be a major objective. There are two approaches for enhancing the performance of the multi-corner thin-walled structures: either using advanced materials with high mechanical properties or designing optimized wall thickness and cross-sectional configuration to provide the best crash performance.

In this article, to seek for the optimal crashworthiness performance, a set of simulation tests which had different wall thicknesses, material properties, and cross-section configurations was designed using a four-level design of experiments (DOE) based on Taguchi [32] method. Finite element (FE) models were created for those designs and used for computer crashworthiness analyses by explicit finite element code through LS-DYNA to provide crash responses of those design samples. The optimal design for the members was derived following the same design approach. Beside design optimization, parametric studies were performed to investigate the influences of the cross-section configuration, material properties, and wall thickness on the crashworthiness performance.

Design objectives in crashworthiness optimization include specific energy absorption (SEA), which is absorbed energy per unit structural mass, and crush force efficiency (CFE), which is ratio of average crushing load to peak crushing. SEA and CFE should always be maximized to improve crashworthiness performance. To deal with these multiple objectives, multiobjective optimization design method was employed in the crashworthiness design of thin-walled members under axial loading and Pareto-optimal set of designs was extracted.

2. Problem description

The structures considered in this study were thin-walled multi-corner prismatic members. Schematic diagram of the computational models is shown in Fig. 1. The boundary condition and load condition were identical for all four FEM models including rectangular, hexagonal, octagonal, and 12-edged cross-sectional members. Moreover, all the members had the same length equal to 250 mm.

The only difference between all the four members was in their cross-section configuration, which is illustrated in Fig. 2.

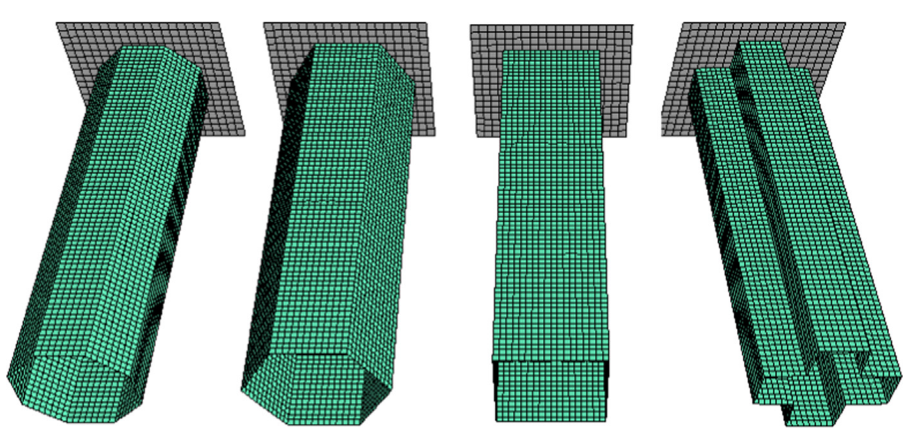

Fig. 1. Schematic of octagonal, hexagonal, rectangle, and 12-edge columns.