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Collapse behavior of thin-walled corrugated tapered tubes

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ABSTRACT

Thin-walled structures have been widely used in energy absorption and safety applications such as automotive, due to their lightweight and progressive folding modes. This work studies the collapse behavior and energy absorption of corrugated tapered tubes (CTT) under axial crushing numerically. The tested tubular structures were impacted axially with a striker's mass that is restricted to translational motion along the structures' axes. The effect of CTT's geometric features on different performance indicators, namely the initial peak force (PF), mean crushing force (MF), energy absorption (EA) and specific energy absorption (SEA) was studied. The results showed that the amplitude of corrugation is the most influential factor on the force-displacement characteristics of CTTs. Moreover, three deformation modes were found for CTTs, and the development of a mode was mainly influenced by the corrugation's amplitude and wavelength. In addition, for the tested range of geometric features, the initial peak force was found to be reduced when corrugation is adopted, especially for longer corrugation's amplitudes and wavelengths. On the other hand, the energy absorption (EA) and specific energy absorption (SEA) were found to be reduced when corrugation is adopted. Finally, it was found that the two most influential geometric factors on the performance indicators of CTT were the corrugation's amplitude and wall thickness.

1. Introduction

Thin-walled engineering structures, such as tubular structures, are widely used in automotive such as automobile vehicles as frontal structures of the chassis, aircraft fuselages, and trains. This is due to their lightweight, low cost, and good energy absorption efficiency. Tubular structures are responsible for dissipating or minimizing the crash energy by undergoing plastic deformation, thus preventing the kinetic energy of the crash from reaching the passenger compartment. Due to their significance in energy absorption and safety applications, there has been a tremendous focus by researchers and scientists on studying and improving thin-walled structures responses under different loading conditions. The efforts of researchers can be categorized into three main categories: (1) studying different geometric modifications and foam fillers, (2) investigating the tapered layout of tubular structures and (3) studying the effect of surface patterns.

A lot of studies have been conducted on tubular structures of different geometrical features and modifications. One example of these studies is investigating the effect of different tubular cross sections on the crashworthiness and energy absorption performance. Some researchers investigated cross-sections such as circular, polygonal, hexagonal and rectangular [1–3], while others studied star-shaped cross sections [4]. Other research work tried to enhance the overall crushing and energy absorption performance by dividing the tubular structure into multi-cells of different configurations. Chen and Wierzbicki [5] studied the effect of dividing square tubes into single, double and triple cell configuration. Their results showed that double and triple cell configuration led to an approximate of 15% increase in specific energy absorption relative to the single cell configuration. In addition, Tang et al. [6] investigated the characteristics of multi-cells cylindrical tubular structures on energy absorption and found that multi-cell configurations enhance the energy absorption. Furthermore, the effect of multicellular configurations for tubular structures of different cross-sections was studied [7]. Other geometric modifications studies have focused on the effect of thickness on the performance of the thin tubular structure. Zhang et al. [8] investigated the effect of functionally graded thickness on the energy absorption performance of square tubes, while Fang et al. [9] explored the effect of functionally graded thickness on tubes of multicellular configurations. The energy absorption of multi-cornered structures has also been investigated [10–12], as well as the energy performance of bi-tubular structures [13] and nested tubular systems [14]. The areas of composite sandwich tubular structures [15,16] and square-cell systems [17] were also explored for their energy absorption capabilities. Adding foam fillers to the tubular structures was another

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significant area of geometric modifications to enhance the performance of tubular structures. Some research work has studied the effect of foam fillers of uniform density distribution [18–21], while other studies focused on foam fillers of functionally graded density [22–24]. These studies found that foam fillers enhance the energy absorption of thin-walled structures because of the foam's low weight and low initial stress, especially functionally graded foam.

Many researchers have proposed and studied a new layout of tubular structures that can withstand both axial and oblique impacts (i.e. when the tube is impacted with an angle rather than axially). When the tubular structure is impacted with large angles, global bending mode is exhibited, the thing that reduces the energy absorption of the tube [25]. Therefore, the research trend shifted toward studying tapered tubes which were found to be very effective under different loading conditions. Nagel and Thambiratnam [26] studied the energy absorption and characteristics of rectangular tapered thin-walled structures. They concluded that such tubes are more beneficial for oblique loading conditions, as they provide a steady decrease in the mean crushing force relative to straight tubes. From there, researchers started studying the effect of different geometric modifications on tapered tubes. For instance, Taştan et al. [27] studied and optimized the crashworthiness of tapered thin-walled tubes with lateral circular cutouts. The results have indicated that the cutouts led to a 26.4% increase in specific energy absorption relative to tapered tubes with no cutouts. In addition, Acar et al. [28] have investigated the crashworthiness of tapered tubes with axisymmetric indentations. The results have shown that a tapered tube with indentations increases the crushing force efficiency and specific energy absorption significantly compared to a tapered tube with no indentations. Some research work tried to study the effect of varying thickness on tapered tubes. For example, Zhang et al. [29] investigated the axial crushing of tapered circular tubes with graded thickness. The results showed that tapered tubes with graded thickness have better performance in terms of specific energy absorption relative to regular circular tubes (30–40% higher). The effect of multicellular configurations on tapered tubes has also been studied. One example is the study done by Qi et al. [30] in which the crashworthiness of tapered square tubes of multi-cellular configurations under axial and oblique loading conditions was investigated. The results indicated that multi-cellular tapered square tubes have higher energy absorption and lower initial peak force than conventional tapered and straight tubes for all the tested loading angles.

Other approaches followed by researchers to reduce the initial crushing force and obtain smooth energy absorption characteristics were to introduce patterns to the tubular structure surface. One example is the latest study carried out by Kai et al. [31] in which tubes with pre-folded origami patterns were tested numerically. The study findings showed that thin-walled tubes of pre-folded origami patterns reduces the initial peak crushing force in a significant manner, and increases or maintain the specific energy absorption of the tube. Similarly, Song et al. [32] studied the effect of window-like wall holes' surface patterns. It was found through experimental tests that the window-like holes reduce the initial peak crushing force and increase the energy absorption relative to a conventional tubular structure (with no patterns). Other researchers have focused on sinusoidal and corrugation surface patterns. For instance, Wu et al. [33] have studied the crashworthiness of straight tubes with sinusoidal corrugation under axial impact. Their results revealed that corrugated tubes reduce the initial peak crushing force and increase the undulation load carrying capacity of the tube significantly. In addition, Liu et al. [34] have investigated the energy absorption characteristics and buckling modes of tubes of sinusoidal patterns under axial loading conditions. They found that corrugated tubes have lower initial peak force and higher specific energy absorption and crushing force efficiency for long corrugation's amplitude relative to regular circular tubes. Moreover, Kılıçaslan [35] have investigated the crushing behavior of aluminum foam filled sinusoidal single and double circular corrugated tubes. His findings showed that corrugation led to higher crushing force efficiency values and lower mean crushing force values. Similarly, Eyvazian et al. [36] have studied the crushing behavior and energy absorption performance of corrugated tubes. The findings show that corrugated tubes reduce the initial crushing peak forces and the fluctuations in the crushing forces.

The previously discussed categories revealed that a lot of geometric modifications could enhance the performance of thin-walled structures. For instance, foam fillers were found to enhance the specific energy absorption if designed correctly, especially functionally graded foam. Also, multicellular configurations of tubular structures were found to increase the energy absorption. In addition, tubular surface patterns were found to reduce the initial peak crushing force and offer a smoother and more controllable energy absorption. Finally, the studies conducted on tapered tubular structures have shown that such tubes are superior to straight tubes under oblique loading conditions and as good under axial conditions. The last two categories offer significant advantages in terms of smooth energy absorption, reduced peak load and withstanding impact under different loading angles. Therefore, integrating these two categories into the tubular structure can be beneficial. To the authors' knowledge, no research has been conducted on tapered thin-walled structures with sinusoidal corrugated patterns. In the present study, the collapse behavior and energy absorption performance of corrugated tapered tubes (CTTs) under axial impact were investigated numerically. The explicit finite element code ABAQUS was used to predict the collapse behavior and energy absorption characteristics of CTT. The effect of geometrical features was analyzed to understand the collapse behavior and energy absorption performance of CTTs.

2. Performance indicators and material properties

2.1. Performance indicators

The thin-walled structure performance is mainly evaluated based on the overall compression response and the following performance indicators (Fig. 1).

2.1.1. Peak load

The peak load (*PF*) is the highest initial force needed to initiate the plastic deformation of the thin-walled structure. A low value of peak force is desirable to prevent occupant's injuries and reduce damage due to high reaction forces [37].

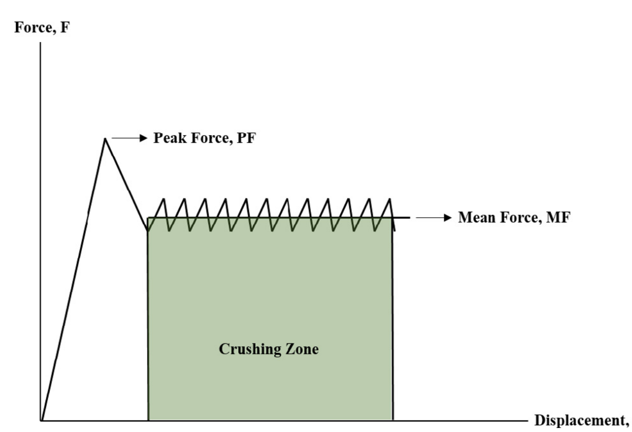

Fig. 1. Typical force-displacement diagram.