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Axial-impact buckling modes and energy absorption properties of thin-walled corrugated tubes with sinusoidal patterns

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ABSTRACT

Corrugated tubes with sinusoidal patterns were studied to improve the energy absorption properties of traditional circular tubes and reduce the initial peak force. The effects of the radius-thickness ratio, wavelength, and amplitude of corrugated tubes under an axial impact were determined using the LS-DYNA. The numerical simulations show that tube deformation can be classified into three crushed modes, namely, dynamic asymptotic buckling, dynamic plastic buckling, and transition buckling. The theoretical equation for dynamic plastic buckling was developed to predict the impact force using certain assumptions. The theoretical prediction results are consistent with the findings of the numerical simulations.

1. Introduction

Thin-walled metal structures are low-cost and exhibit high strength, high rigidity, excellent bearing capacity, and high energy absorption efficiency. These materials have been extensively used in collision kinetic energy dissipation systems [1–4]. Corrugated tubes, which are thin-walled structures with distinct patterns, are extensively used in piping systems for most factories because of its low weight, flexibility, high pressure resistance, and ability to withstand high-temperature environments (Fig. 1) [5].

Plastic deformation of thin-walled metal tubes under axial impacts is the most effective method of energy absorption. Two types of collapse mode, namely, axial and bending collapses, generally occur on thin-walled tubes during crash events. Understanding the behavior of these tubes under crash conditions has been the aim of numerous studies. Therefore, extensive studies have been conducted on the deformation mechanism and energy absorption performance of various materials as well as on the cross-sectional shapes of thin-walled tubes.

Several types of design schemes have been proposed to improve the energy absorption efficiency of thin-wall tubes. Experimental research and theoretical analysis conducted by Yu [6,7] showed that the large progressive deformation of axially crushed circular tubes switches from an axisymmetric or mixed mode to a nonaxisymmetric mode using special buckling initiator. Singace [8] experimentally investigated the energy absorption characteristics of corrugated tubes. The results indicated that corrugated tubes have highly controllable energy absorption properties. Furthermore, the corrugation patterns reduce compressive force fluctuations.

A number of researchers have also proposed the use of traditional circular tubes with grooves to improve the energy absorption efficiency and buckling response of grooved tubes. Rais-Rohani et al. [9] investigated the quasi-static axial collapse response of cylindrical tubes that were externally stiffened by multiple identical rings. The results showed the viability of externally stiffened tubes as efficient energy absorbers. Hosseinipou et al. [10] experimentally investigated the quasi-static axial compressor of thin-wall steel tubes with circumferential grooves. The experimental results showed that grooves can stabilize the deformation. Numerical simulations conducted by Mamalis et al. [11] determined the mechanical response of grooved steel tubes subjected to axial plastic collapse. The mean height of the lobes formed by the crush force appears to be significantly affected by the number of grooves. Niknejad et al. [12] theoretically predicted the mean folding force, total absorbed energy per unit of tube length, and specific absorbed energy per unit of total mass of polyurethane foam-filled grooved tubes under axial compression. Acar et al. [13] investigated the effects of tapering and introducing axisymmetric indentations on the crash performances of thin-walled tubes. Numerical simulations conducted by Chen et al. [14] showed that the deformation modes corresponding to corrugations can be classified into axisymmetric and asymmetric modes. In addition, Chen et al. [15] studied the circumferential strain concentrations in cylindrical and square tubes with corrugated

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Fig. 1. Corrugated tubes: (a) corrugated tubes main applications; (b) corrugated tubes structures.

surfaces under axial compression. They proposed that corrugation is the main factor that determines the deformation mode of corrugated tubes.

A well-designed crash absorber should be lightweight and must be able to absorb a large amount of energy during an accident to minimize damage to the passenger cabin. The crash absorber should also be effective in case the crash is misaligned rather than perfectly axial [16]. To improve the energy absorption properties of beams, the wavelengths of progressive buckle formations must be controlled and denser collapse formations should be obtained. Qureshi et al. [17] proposed a new automotive box-beam crash absorber design with sinusoidal patterns embedded on the beam surfaces. Results showed that the relief patterns can be effectively used to change the buckling modes and reduce the buckle wavelength and increase the amount of total energy absorbed.

The experimental materials during vehicle crashes process contain a pure metal tube and a composite material. The crushing response of composite corrugated tubes subjected to quasi-static axial loading was investigated by Elgalai et al. [18]. The results showed that corrugation using modified corrugation angles and fiber types can significantly enhance the energy absorption capability of composite tubes. Mahdi et al. [19] proposed a cotton fiber composite corrugated tube with the corrugation along a shell generator to enhance the crash absorption performance. The simulation results showed that the energy absorption capability of the tube was significantly affected by the number of corrugations and the radius-thickness ratios. Palanivelu et al. [20] studied the crushing and energy absorption performance of glass/polyester composite tubes under quasi-static loading conditions. The results showed that the crushing characteristics and corresponding energy absorption of the composite tubes with distinct geometric shapes are better than those of tubes with standard geometric shapes.

The previously described studies showed that corrugated tubes are preferable over traditional circular tubes as energy absorbing structures. However, these studies focused only on the axial compression experiments and finite element numerical simulations under quasi-static loading conditions. There are few studies have been published on the mechanical mechanism of corrugated tubes under axial impact loading conditions. In the present study, the energy absorption behaviors of traditional circular tubes with corrugated patterns under an axial impact were investigated. An efficient analytical model was established using the explicit finite element code LS-DYNA to predict the energy absorption characteristics and dynamic impact collapse mode of the structures. The effects of geometry, material properties, and other factors on the corrugated tube were determined to understand the dynamic response and energy absorption properties of corrugated tubes.

2. Analytical method

2.1. Finite element model

The explicit dynamic finite element analysis software LS-DYNA was used to simulate the elastoplastic deformation of corrugated tubes under an axial impact (Fig. 2).