Crashworthiness analysis of corrugated tube under axial and oblique load

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Abstract. Thin-walled tubes have been widely used as energy absorption structure. In this paper, the energy absorption properties of straight circular tube, straight sinusoidal tube and conical sinusoidal tube under oblique load were studied based on simulation analysis. The simulation model was validated by comparing with experiment. According to the simulation results, the straight circular tube is found to have the best crashworthiness performance under axial load. The crashworthiness performance of the conical sinusoidal tube is least influenced by the oblique load angle. The straight sinusoidal tube has the worst crashworthiness performance both under axial and oblique load.

1. Introduction
As an energy absorbing structure, thin-walled tube has the advantages of high strength, light weight, simple structure and low cost, and thus has been widely used in the energy absorbing system of automobile, rail transportation, aerospace. For example, a rectangular tube is applied to a car’s energy absorption box, which can absorb energy by plastic deformation when subjected to an axial impact and protect the safety of the passenger. The research on thin-walled tube began in 1960s. Alexander [1] first proposed a theoretical model for axial collapse of thin-walled metal tubes, which laid the foundation for the research of thin-walled tubes. Later scholars carried out a lot of experiments on thin-walled tubes to study the relationship between the deformation modes of thin-walled tubes and their geometric sizes. For example, Guillow [2] carried out a large number of quasi-static tests to classify the deformation modes of aluminum alloy tubes. Abramowicz and Jones [3] carried out the axial dynamic crushing tests of square steel tubes with different width and thickness ratio. Alavi Nia [4,5] and Tarlochan [6] respectively studied the energy absorption performance of thin-walled tubes and multi cell tubes with different cross sections under quasi-static compression and dynamic impact. The study of energy absorption performance of thin-walled tube under oblique load is also very important as the energy absorbing structures are often subjected to oblique loads rather than pure axial loads [7,8]. Børvik et al.[9] and Reyes et al.,[10] studied the energy absorption performance of circular tube and square tube under oblique load respectively, and found that, the straight tube is prone to occur global bending. The energy absorption performance of the conical tube is almost the same under the oblique and axial loading, found in literature [11].

Generally, there will be a peak load in the load-displacement curve of thin-walled tube’s compression, which is not good for the protected object. The research on corrugated tubes in literatures [12,13,14] show that the deformation of corrugated tubes is stable and controllable, and the peak load rather low, comparing with ordinary thin-walled tube.

At present, there is rather limited research on the energy absorption performance of corrugated tube.
and conical corrugated tube under oblique load. This research aimed to study the energy absorption performance (peak load, average load, energy absorption and specific energy absorption) of straight circular tube, straight sinusoidal tube and conical sinusoidal tube under different oblique loading angles, based on the simulation analysis.

2. Numerical modelling

2.1. Configuration of tubes
Three kinds of thin-walled tubes were studied in this paper, including straight circular tube (SCT), straight sinusoidal tube (SST), and conical sinusoidal tube (CST). Their geometric configuration and parameters were shown in Figure 1. The total length of all tubes is 120mm, the wall thickness is 1.2mm, the diameter of the circular tube and the nominal diameter of the sinusoidal tube are all 36mm, the wavelength of the sinusoidal tube is 10mm, the amplitude is 2mm. The wavelength and the amplitude of the conical sinusoidal tube are the same as those of the sinusoidal tube, and the taper is 15 degrees.

![Figure 1 geometric configuration and parameters of three kinds of tube](image)

2.2 Finite element model
The compression process of thin-walled tube is simulated using the nonlinear explicit dynamic software Ls-dyna. Figure 2 shows the schematic diagram of the finite element model. The load angle $\alpha$, taken as $0^\circ$, $5^\circ$, $10^\circ$, $15^\circ$, indicates the angle between the normal direction of the rigid wall and the vertical direction. The top end of the tube is compressed by a rigid wall in vertical direction in a constant velocity of 5m/s, and the bottom end of the tube is fully constrained. The tube is modelled with Belytchko-Tsay 4-node shell element, with five integration points through the thickness. The element size is 1.5mm. The contact between the rigid wall and the tube is automatic-node-to-surface, and the contact of the tube itself is automatic-single-surface, and all the friction coefficients are set as 0.2. The material of the tube is AA6061 O, its engineering tensile stress-strain curve and properties are shown in Figure 3 and Table 1 respectively [15]. Material model #123 (Modified Piecewise Linear Plasticity) in LS-DYNA is chosen to model the tube.
2.3 Model validation
To validate the finite element model, the numerical results of circular tube under axial load are compared with the experimental data in literature [15], in which the sizes and material of the tube are the same as the circular tube in this paper. Figure 4 and Figure 5 respectively shows comparisons of the force-displacement curves and deformed shapes of simulation and experiment. They show that the force-displacement and the deformed shapes in simulations are very similar to the experimental. The finite element model can successfully simulate the deformation of the tube and will be used for further analyses in this paper.

Table 1 Material properties of AA6060 O

| Property         | Value         |
|------------------|---------------|
| Density          | 2700 kg/m³    |
| Young’s modulus  | 68.0 GPa      |
| Poisson’s ratio  | 0.33          |
| Yield stress     | 71 MPa        |
| Tangent modulus  | 0.68 GPa      |

3. Numerical results and discussion

3.1 Crashworthiness indices
To evaluate the crashworthiness performance of the energy absorbers, it is essential to predefined the crashworthiness indices. There are several indices, including the peak force ($F_p$), the energy absorption ($E_A$), mean crushing force ($F_m$), specific energy absorption ($SEA$). The $F_p$ is the maximum force in the force-displacement curve, which generally refers to the first wave peak, and should be as small as possible. The $E_A$ is the energy absorbed in the whole compression process of the tube, which can be
calculated by integrating the force-displacement curve, like

\[ EA = \int_0^S F(x)dx \]

where \( F(x) \) is the axial crushing force, and \( S \) is the effective crushing displacement. Thus, the \( F_m \) can be calculated as

\[ F_m = \frac{EA}{S} \]

The \( SEA \) denotes the energy absorbed by unit mass of the tube, and can be calculated as

\[ SEA = \frac{E}{M} \]

Where \( M \) is the mass of the tube.

3.2 Numerical results

Figure 6 shows the deformed shapes of tubes at different loading angles. It can be seen that at loading angle \( 0^\circ \), all of the tubes generate progressive folds. At loading angle \( 5^\circ \), the deformations of the tubes are still stable, but deflect to the side of the load inclines to, and the SCT deflects the most seriously. At loading angle \( 10^\circ \), the deformation patterns of the tubes have changed greatly, and the SST occurs global bending. At loading angle \( 15^\circ \), the SCT also occurs global bending, and the CST has a distorted deformation.

![Figure 6 Deformed shapes of three tubes under different loading angles](image-url)
Figure 7 shows the force-displacement curves of three tubes under different loading angles. It can be seen that under all loading conditions, the SCT has the highest peak load, and the SST has the lowest crushing force. At loading angle 0°, 5° and 10°, the crushing force of the SCT is higher than that of the other two tubes. At loading angle 15°, the crushing force of the SCT is greatly reduced, which is lower than that of the CST.

Figure 8 shows the energy absorption performance of three tubes under different loading angles. It can be seen that under all loading conditions, the $F_m$, $EA$, $SEA$ of CST is almost invariable, showing that that the loading angle has minimal impact on CST. The SCT has the best energy absorption performance under all load conditions, but greatly influenced by the load angle. The SST is not only
poor in energy absorption but also easily to be influenced by the load angle.

4. Conclusion
This paper presents and discusses the energy absorption performance of three kinds of thin-walled tubes, including straight circular tube, straight sinusoidal tube and conical sinusoidal tube under axial and oblique load based on numerical simulation. According to the results, the straight circular tube has the best energy absorption performance under axial load or oblique load of small angle, but sensitive to the load angle. The energy absorption performance of the conical sinusoidal tube has the best robustness under different load angle. The SST is not only poor in energy absorption but also easily to be influenced by the load angle.

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