Study on Impact Resistance of Composite Reinforced Thin-Walled Tubes

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Abstract. In order to further improve the impact resistance of composite multi-cell thin-walled structures under axial loading, a new type of composite multi-cell sandwich tubular structure is proposed. Based on the MAT54 material model and the Chang-Chang failure criterion, a composite laminated shell modeling method was developed to simulate the failure behavior of the material under axial compression load and verified by quasi-static compression tests. The effectiveness of the simulation model is verified by comparing the parameters of peak load and specific energy absorption. The impact-resistance sensitivity of cell number and sandwich structure in composite multicellular structure was studied by this model. The results show that number of cells have a significant effect on the specific energy absorption of the composite multi-cell structure.

1. Introduction

Nowadays, crashworthiness is playing a vital role to ensure structural integrity in vehicle design. Carbon fiber reinforced polymer (CFRP) has been used in a wide range of contemporary applications particularly in space and aviation, automotive, maritime and manufacturing of sports equipments. Hong et al. [1] designed and fabricated multicellular tubes with triangular and kagome mesh. Furthermore, through quasi-static axial compression experiments, the gradual collapse mode, folding mechanism and deformation law of the multicellular tubes were revealed. A classical plastic model for predicting the average breaking force of the multicellular tubes was proposed. It was pointed out that the multicellular lattice tubes had higher energy absorption efficiency. Meltem Altin Karatas et al. [2] introduced various studies of non-traditional manufacturing methods (WJM, AWJM, LJM, EDM, etc.) for CFRP and GFRP composite processing. Nia and Parsapour [3] compared simple thin-walled tubes with multicellular thin-walled tubes with triangular, square, hexagonal, and octagonal cross sections. Zhang et al. [4] studied the energy dissipation mechanism of circular multicellular columns and proposed a theoretical model to predict the average breaking force. Shivdayal Patel [5] studied the crashworthiness parameters of materials such as carbon fiber reinforced plastics (CFRP), glass fiber reinforced plastics (GFRP) under axial and oblique loading conditions. The continuum damage
The mechanics (CDM) method was used to observe the dynamic response change and dynamic response of the composites under different configurations. Soutis C [6] reviewed recent advances in the use of composite materials in modern aircraft construction, arguing that fiber-reinforced polymers, especially carbon fiber reinforced plastics (CFRP), will contribute more than 50% of aircraft structural quality in the future. In aerospace manufacturing, both civil and military, affordability is key to survival, because they are closely connected. Zhu [7] studied the crashworthiness characteristics of aluminum/carbon fiber reinforced plastic (CFRP) hybrid tubes. The deformation patterns of the aluminum/carbon fiber reinforced plastic hybrid tubes and several key indicators related to the crashworthiness of these structures were experimentally and numerically investigated by comparison with individual aluminum and cfrp tubes. Sun et al. [8-9] investigated the energy-absorption properties of self-similar triangular lattice structures with a hierarchical structure much higher than the average crush load (MCF) of the unitary tubular structure or even the multicellular tubular structure. Corin Reuter [10] studied collision resistance and numerical simulation of circular mixed aluminum-CFRP tubes. The results show that hybrids provide significant lightweight potential.

In this paper, the energy absorption characteristics of thin-walled tubes are revealed by numerical simulation, theoretical analysis and experimental verification.

2. Experiment

The length, diameter and thickness of the composite tubes are 60mm, 40mm and 2mm, and the maximum load is 300kN through the electronic universal material testing machine. The quasi-static compression test is carried out at room temperature, as shown in figure 1. The composite thin-walled round tube specimens were made of a 12-layer t700/3234 carbon fiber epoxy composite with a paving angle of [0/90]3s, where the 0° direction is the axis direction. the t700/3234 mechanical properties parameters [12] are shown in table 1 below.

![Figure 1. Quasi-static compression on CFRP tubes.](image)

| Property  | Description | value    |
|-----------|-------------|----------|
| $\rho$    | Density     | 1.53g/cm$^3$ |
| $\nu$    | Poisson’s ratio | 0.31      |
The experimental specimens shown in Figure 2 are designed in this paper. The geometric dimensions of the specimens are shown in Table 2. The quasi-static axial crush test was carried out on an electronic universal testing machine with a loading rate of 2 mm/min.

The morphology of thin-walled tubes before and after the crushing of the composite material is shown in Figure 2(a) and (b). Farley [14] and so on, through the experiments, the crushing process of the composite pipe is summarized into three failure modes: transverse shear, lamellar bending and local bending. From figure 2(b), it can be seen that the crushing process of the thin-walled tube of the composite material is a transverse shear failure mode. In the induction stage, there are a large number of short interlayer cracks and cracks in the longitudinal layer germinating and spreading, at the same time, the split lamellar bundle will be subjected to transverse shear action, forming bending moment at the base of the lamellar bundle. When the tensile strength of the material is exceeded, the lamellar bundle breaks and finally absorbs energy through the fracture of the lamellar bundle and the propagation of the intra-lamellar crack.

(a) (b)

Figure 2. Samples of thin-walled tubes: (a) before the experiment, (b) after the experiment.

Table 2. Failure parameters used in MAT54.

| Parameter | Description                        | Value |
|-----------|------------------------------------|-------|
| ALPH      | Nonlinear shear stress parameter   | 0.0   |
Common parameters for evaluating energy absorption performance [11] include: Specific energy absorption (SEA), initial peak load ($F_{\text{max}}$), average collapse load ($F_m$) and load efficiency ($AE$) were adopted as evaluation indexes of the energy absorption characteristics of specimens in this paper:

(1) Specific energy absorption (SEA) refers to the energy absorbed per unit mass ($m$) within the structure effective failure length ($l$) and is the most important parameter to measure the energy absorption capacity of the element. The total energy absorbed during the entire crushing process is obtained by integrating the crushing distance by the crushing force (1)

$$SEA = \frac{\int E_A}{m} = \frac{\int F_{dl}}{m} = \frac{\int F_{dl}}{\rho A l}$$

(1)

In the formula: $\rho$ is the material density, $A$ is the effective cross-sectional area of the thin-walled tube, and $l$ is the crushing length.

(2) the initial peak value ($F_{\text{max}}$) is the threshold value of the broken structure, which is used to evaluate the degree of energy absorption difficulty of the structure under the action of external forces, and is the initial peak value of the load-displacement curve.

(3) the average crush load ($F_m$) is the average of the load of the whole crush process, as shown in formula (2).

$$F_m = \frac{\int F_{ds}}{S}$$

(2)

(4) the ratio of the average load to the peak load of the load efficiency ($AE$) type.

$$AE = \frac{F_m}{F_{\text{max}}}$$

(3)

The load-displacement curve obtained from the experiment is shown in figure 5. It can be seen from the figure that the initial peak load and average crushing load of the composite thin-walled circular tube with the laying-mode of [0/90]$_3$s are 70.39kN and 28.69kN respectively, and the specific absorption energy and load efficiency are 75.95kJ kg$^{-1}$ and 40.76% respectively.

3. Establishment and validation of numerical modeling

3.1. Numerical modeling and material parameters

According to the test size of the composite thin-walled tube, the finite element model under
quasi-static axial compression load of the composite thin-walled tube was established in the lsdyna simulation software using a single-layer shell unit finite element modeling method, as shown in Figure 3. The finite element model uses the MAT54 Mat_Enchance_Complete damage material model, and the mechanical properties parameters and strain failure parameters of the T700/3234 carbon fiber composite are shown in Table 1 and Table 2 and judged by the Chang-Chang criterion. The rigid wall material model is MAT_Rigid and its material parameters are shown in Table 3.

Meanwhile, in order to reduce the calculation time and shorten the whole simulation process, the motion speed of the thin-walled tube is set to a constant crushing speed of 100 mm/s (the actual compression speed is 2 mm/min, but it is not practical to use this speed in the numerical simulation, so the rigid wall is compressed at a speed of 100mm/s) The feasibility of this speed replacement has been validated by other researchers [13-14]) the total compression displacement is set to 40 mm, and the system energy to internal energy ratio is less than 5% during the whole axial loading crushing failure process, which is determined as a quasi-static process. The tube wall itself is defined as Contace_automatic_Single_Surface contact, with multiple contact definitions available in finite element software. The surface contact (CONTAC_AUTOMATIC_SURFACE_TO_SURFACE) is used to simulate the contact between the rigid wall (Rigid plate) and the composite tube. The same ideal result can be obtained by point-to-face contact. One-sided contact is used to avoid penetration of the shell unit itself. The coefficient of friction between all the contacts connected is 0.2.

The deformation diagram of the quasi-static crushing test failure process of the composite thin-walled tube is compared with the deformation diagram of the composite thin-walled tube

| Property | Description       | Value       |
|----------|-------------------|-------------|
| $\rho$   | Density           | 7.9x10$^3$g/mm$^3$ |
| $E$      | Young’s modulus   | 210GPa      |
| $\nu$    | Poisson’s ratio   | 0.3         |
simulated, as shown in figure 4.

![Figure 4(a). Quasi-static compression on CFRE tubes.](image)

From the comparison of the results of the specimen and the simulation, it can be seen that both of them are failure deformation. During the whole crushing process of the composite thin-walled pipe, the thin-walled pipe cracks along the circumferential direction, and the "flowering type" failure mode appears, which produces a large number of fragments in the crushing process.

Due to the limitation of pore size of thin-walled tube, the inner thin-walled tube is continuously bent and broken under the action of axial quasi-static compression force, and the inner tube is gradually compacted as the thin-walled tube wall is continuously crushed, which forms a filling effect for the uncompressed thin-walled tube. From the test and simulation results, it can be shown that the failure mode of the numerical simulation of the composite thin-walled tube is similar to that of the test, and the trend is the same, and the failure form is the same. However, there will be some uncertain factors in the crushing test, and the finite element software will ignore some of the actual factors in the numerical simulation, which will lead to some errors in the simulation and test. But in general, the simulation results of the composite thin-walled tube can predict the failure mode of the composite thin-walled tube test to some extent.

3.2. Numerical modeling validation
The progressive failure mode diagram of the composite thin-walled tube is shown in figure 4 (comparison diagram of the axial quasi-static test and simulated collapse failure of the thin-walled tube). It can be seen that the failure behavior of the circular tube shows that the stable unit gradually disappears, which is a gradual failure process, but the single-layer shell unit model cannot simulate the micro interlayer crack and the bundle fracture etc. As can be seen from the load-displacement curve comparison diagram of the crush simulation and experiment in figure 5 and the results of the crush simulation and test in table 4, compared with the test results, the peak load deviation of the simulation
results is 14.4%, the average load deviation is 1.32%, the specific energy absorption deviation is 15.28%, and the load efficiency deviation is 11.55%. The simulation results show that the load-displacement curve fits well, and the modeling method and the simulation model of composite thin-walled tube are validated.

Figure 5. Force-displacement curve of quasi-static crushing test and simulation of carbon fiber thin-wall tube.

Table 4. Comparison between experimental and numerical results.

|                | $F_{\text{max}}$/kN | $F_m$/kN | AE/%   | SEA/(kJ·kg$^{-1}$) |
|----------------|---------------------|----------|--------|---------------------|
| Experiment     | 70.39               | 28.69    | 40.76% | 75.95               |
| Simulation     | 60.25               | 28.31    | 46.99% | 67.18               |
| Error/%        | 14.40               | 1.32     | 15.28  | 11.55               |

4. Study on impact resistance of composite materials by cell number

Based on the above effective numerical models, the impact resistance of composite thin-walled tubes with different section shapes was studied, and the numerical models of single-cell (C), 2-cell (C_MC2) 4-cell (C_MC4) 6-cell (C_MC6) 8-cell (C_MC8) cross-stiffened cell (C_MC) were established respectively.

Figure 6 Schematic of cross-sectional shapes of thin-walled tubes and relevant size
Table 5. Simulation results of axial crushing composite stiffened tubes.

| Tube  | Cell number | M/g  | SEA/kJ kg⁻¹ | $F_{\text{max}}$/kN | $F_n$/kN | $F_n$/ $F_{\text{max}}$ |
|-------|-------------|------|--------------|---------------------|---------|-----------------------|
| C     | 0           | 15.11| 75.95        | 70.39               | 28.69   | 40.76%                |
| C_MC2 | 2           | 24.89| 78.54        | 79.48               | 48.87   | 61.49%                |
| C_MC4 | 4           | 26.67| 90.60        | 91.38               | 60.40   | 66.10%                |
| C_MC6 | 6           | 27.56| 68.50        | 90.62               | 47.20   | 52.09%                |
| C_MC8 | 8           | 29.33| 82.32        | 110.40              | 60.36   | 54.67%                |
| C_MC  | 4           | 24   | 47.18        | 60.25               | 28.31   | 46.99%                |

Figure 7 Crush force versus displacement for all columns with constraints.

From the comparison of data in Table 5 and Figure 7, the following conclusions can be drawn: the efficiency of energy absorption and compression force of each multicellular cell was significantly better than that of the same type of unicellular cell. It can be seen from the evaluation level that quad cells are superior to other multicellular cells in terms of specific energy absorption and load efficiency, and octet cells have the maximum initial peak load ($F_{\text{max}}$).

The thickness of the interlayer wall and the number of cells have significant influence on the specific energy absorption and load efficiency of the composite multi-cell structure, and there is an optimal value. Among the two types of multicellular tubes studied, the energy absorption characteristics of multicellular tubes with internal ribs and inner tubes are better than those of the cross-shaped multicellular tubes. As the number of cells increases, the specific energy absorption and compression force efficiency of thin-walled tubes also increase.
5. Conclusions
Quad is superior to other cellular structures, octet has the highest initial peak load, cell number has a significant influence on specific energy absorption and load efficiency of complex multicellular structure, and there is an optimal value. In the two kinds of multicellular tubes studied, the energy absorption characteristics of the inner rib and inner tube were better than that of the cross-shaped multicellular tubes. With the increase of cell number, the specific energy absorption and compression force efficiency of thin-walled tubes also increase.

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