Research on energy-absorption and failure of carbon fiber reinforced epoxy resins double cone structure

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Abstract. One of the research hotspot in strategic missile is to develop a multifunctional and lightweight composite launcher, which has a certain bearing capacity and anti-fragment penetration capability. On this basis, this paper designs the launcher’s wall by using carbon fiber reinforced epoxy resin composite double cone structure (CFREPDCS) as sandwich core layer. Due to obtain the high-speed impact energy-absorption and failure characteristic of the CFREPDCS, the quasi-static collapse experiment and the LS-DYNA finite element simulation were used. The experimental results and the scanning electron microscope show that the failure mode of the carbon fiber reinforced epoxy resin composite (CFREP) circular tube is progressive failure, which includes matrix fragmentation and fiber fracture. The CFREP circular tube with larger wall thickness has higher specific energy-absorption (SEa), approximately 58.6 J/g. The coupled relationship between SEA and mid-diameter height shows that the maximum SEA occurs while mid-diameter height reaches 8 mm. On the other hand, the change of the mid-diameter height also reflects the influence of loading direction on SEA. This study provides the significant guide to design and manufacture of sandwich carbon fiber composite launcher.

1. Introduction

An important use of carbon fiber reinforced polymer composites (CFRP) is to act as a buffer element. The biggest advantage of CFRP is that it can absorb more energy with lighter mass, i.e., it has a good SEA. In addition, there are many excellent mechanical properties, such as high modulus, high strength and high tensile strength. At present, more and more countries make the missile launcher by using CFRP to meet the battlefield mobility requirements. As a result, it’s worth noting that the mechanical properties, anti-fragment penetration properties, high temperature gas impact-ablation properties, storage properties and creep properties of CFRP launcher.

The failure process of CFRP is very complex due to the anisotropy and uneven stress distribution, and the failure mode of CFRP has a great relationship with the external load and its own structure [1]. Ma’s research showed that there might be two modes of collapse failure, which was named as abrupt...
failure and progressive failure, and the energy-absorption of progressive failure was greater than abrupt failure [2]. Farley proved that the energy-absorption capacity of composite was 5-10 times of metal by static collapse test [3]. Joosten carried out an experimental study on the quasi-static energy-absorption characteristics of CFREP ladder wavy beams. The modeling method of weak links was put forward, which could predict the collapse energy-absorption characteristics of CFREP [4]. The cross-sectional shape of the tubular element of the composite material was studied by Kinderver, they found that the energy-absorption of the circular tube was higher than the square tube [5]. The numerical simulation of sandwich beam composed of composite/foam/composite was investigated out by Vladislav La, and the stress-strain relationship of the composite was expressed as linear and nonlinear by using VUMAT subroutine [6]. Carla McGregor and David verified the feasibility and accuracy of the simulation by comparing the experimental and simulation results of axial compression of composite circular tubes [7-8].

For obtaining the lightweight multifunctional composite launcher, this paper designs a sandwich wall to make launcher, and the core layer of the sandwich wall is carbon fiber reinforced epoxy resin composite double cone structure (CFREPDCS). To study the compression energy-absorption and failure characteristics of CFREPDCS, the compression failure mode and failure morphology of CFREP circular tube are analyzed by quasi-static collapse experiment and scanning electron microscope diagram. We also used LS-DYNA finite element software to simulate the impact process of CFREPDCS with different medium-diameter height. The energy-absorption index and failure mode of CFREPDCS are analyzed, and obtained the relation between the medium-diameter height and SEA.

2. Evaluation index of energy-absorption

From many researches, SEA, Load Peak (LP), Average Collapse Load (ACL) and Load Efficiency (LE) are used as evaluation indexes of energy-absorption. Similarly, these parameters are used as the impact energy-absorption index of CFREPDCS to evaluate the energy-absorption characteristics.

SEA: Energy-absorption of per unit mass. The calculation formula is

\[
SEA = \frac{E}{m} = \frac{1}{m} \int_0^T E(t) dt
\]  

Where, \(E(t)\) is energy-absorption about time, \(m\) is the mass of CFREPDCS, \(t\) is time, \(E\) is the total energy-absorption.

LP: The maximum load peak value, which can evaluate the failure condition of the CFREPDCS under the external force. Generally, it can be written as

\[
LP = \max(F_i, i = 1, \cdots, n)
\]

Where, \(F_i\) is the external force.

ACL: The average load of the whole collapse process. Defined as

\[
F_{\text{average}} = \frac{1}{L} \int_0^L F dl
\]

Where, \(F\) is load in the collapse stroke \(L\).

LE: The ratio of the ACL to the LP, which is as follows
3. Quasi-static experiment

3.1. Materials and experiments

The composite tube used in this experiment is T700/3K CFREP, which is wound with T700 carbon fiber orthogonal [0°/90°], and is adhered by epoxy resin matrix. The number of monofilament in each beam of carbon fiber is 3000, and the density is 1.476 g/cm³. The wall thickness of CFREP thin-wall circular pipe is 1 mm (laying 7 layers) and 2 mm (laying 14 layers). The height is 30 mm, and the outer diameter is 15 mm. The sample is shown in figure 1. The quasi-static experiment is the most common method currently used to explore the buffer energy-absorption and the collapse failure of the CFRP. The MTS universal electronic testing machine and the experimental process are shown in figure 2. In order to ensure the loading process is quasi-static, the ratio of kinetic energy to internal energy of the system must be less than 5%. Based on this requirement, the loading speed is set as 1.8 mm/min, the maximum collapse stroke is 25 mm, and the precompression force is 0.1 kN. When the thin-wall circular tube with wall thickness 0.2 mm is tested, the failure mode is observed by the results of compression stroke 3 mm-7 mm.

Figure 1. Experimental specimen.  Figure 2. Quasi-static experimental process.

3.2. Experimental results

According to the experimental results, Farley divided the collapse process of the composite tube into three types of failure modes, which were layer beam bending, transverse shearing and local buckling [9]. Hull divided the macroscopic failure modes of composite thin-wall cylindrical shells into splaying (delamination propagation caused by interlaminar cracks) and fragmentation [10]. Mamalis proposed four different failure modes: type I (delamination failure), type II and type III (brittle fracture failure) and type IV (progressive buckling failure). Among them, there’re a large number of cracks parallel to the fiber direction and interlaminar cracks on the pipe wall [11].

Based on the above scholars’ viewpoint, combining with the failure situation of figure 3 (progressive failure mode), the compression failure of CFREP thin-wall circular tubes can be attributed to: the transverse fiber bundles with 90° (circumferential direction) are destroyed by shear force, and the failure forms are matrix fragmentation and fiber fracture. This process is brittle, and the
residual amount of the damaged part on the thin-wall circular pipe is pretty small. The longitudinal fiber bundles with a layer of 0° (axial direction) produce initial cracks and expand rapidly in the longitudinal direction under pressure, which leads to the failure of the matrix and delamination failure. The failure forms include opening, internal folding, bending and even shedding. However, the toughness and modulus of the axial fiber bundle are higher than other direction, which lead to the damaged portion is still connected to the portion that is not damaged. The failure mode of the “blooming” is formed, which is very helpful for energy-absorption. In addition, by comparing the results of two kinds of collapse with different wall thickness, it can be found that the “petals” with wall thickness of 0.2 mm are larger than those with wall thickness of 0.1 mm, which is due to the large amount of fiber contained in the wall, and the fiber layer bundles are not easy to curl when the wall thickness is large. In this paper, the compression failure mode is roughly named FMH (Farley-Mamalis-Hull) comprehensive failure mode, in which Farley and Mamalis failure mode is the mechanical mechanism of failure, Hull failure mode is the physical phenomenon of failure.

Figure 3. Experimental results of quasi-static compression of CFREP thin-wall circular pipe.

Combining with the scanning electron microscope diagram of figure 4, it can be found that the broken microstructure is the fracture of fiber and the fragmentation of matrix. The fractured fibers in the working distance WD=9.9 mm are wrapped in the matrix, and the protruding of fracture can be seen in the red ring. Broken particles (in light blue circles) and cracks can be clearly found on the matrix. From the point of view of working distance WD=10.2 mm, the fiber bundles with uniform
arrangement and distribution have been broken, the broken matrix are partly bonded to the fiber. The undamaged fibers are still well fixed to the matrix, but cracks are likely to occur between the fibers.

![Fibre breakage and matrix fragmentation](image)

**Figure 4.** Scanning electron microscopic diagram of failure fragments of CFREP.

![Force-displacement curve](image)

**Figure 5.** Force-displacement curve of quasi-static compression.

According to figure 5 (a), the CFREP circular pipe with wall thickness 0.2 mm is subjected to greater force when it collapses, so the area surrounded by force and displacement is larger and the energy-absorption is more. In the whole collapse stage, the development trend of force-displacement of the two kinds of CFREP pipes with different wall thickness are the same. There is a downward trend at the end of the collapse, which is the result of the crack spreading to the pipe’s bottom and the decreasing of the pipe’s resistance. Through further calculation, the SEA of 0.1 mm CFREP tube is 44.775 J/g, the LP is 3.895 kN, the ACL is 3.423 kN, and the LE is 0.879. The SEA of 0.2 mm CFREP tube is 58.599 J/g, the LP is 10.018 kN, the ACL is 8.359 kN, and the LE is 0.834. The compression stress of the force divided by the cross-section area of the specimens is shown in figure 5 (b). The compression stress of the circular pipe with wall thickness 0.2 mm is larger, and the difference between the compression stress is much less than the difference between the compression force. The experimental results can provide a reference for the relationship between wall thickness and energy absorption, and as a guide for the CFREP failure mode in the next simulation.
4. Simulation Design

The element type of composite is SHELL and material model is *MAT 54 in the simulation, which uses Chang-Chang failure criterion. The *CONTACT_AUTOMATIC_SINGLE_SURFACE is adopted for the purpose of avoiding erosion, whose dynamic and static friction coefficient are 0.2. The height $H$ of CFREPDCS is 10 mm, the wall thickness $\delta$ is 2 mm, the end face diameter $D$ is 20 mm, the middle diameter $d$ is 4 mm, and the structure is convergent-expansion type. The middle-diameter height is $h$, the loading speed is constant at $v = 100$ m/ s, and the value of $h$ is 1-9 mm. The finite element grid model and size relationship of $d=4$ mm and $h=5$ mm are shown in figure 6. The mechanical properties of CFREP used in the simulation are shown in table 1.

![Figure 6. CFREPDCS.](image)

Table 1. Mechanical parameters of CFREP.

| $E_A$ (GPa) | $E_B$ (GPa) | $E_C$ (GPa) | $PR_{BA}$ (GPa) | $PR_{CA}$ (GPa) | $PR_{CB}$ (GPa) | $G_{AB}$ (GPa) |
|-------------|-------------|-------------|-----------------|-----------------|-----------------|---------------|
| 135         | 9.12        | 9.12        | 0.021           | 0.021           | 0.032           | 5.67          |
| $G_{BC}$ (GPa) | $G_{CA}$ (GPa) | $X_T$ (GPa) | $Y_T$ (GPa) | $Y_C$ (GPa) | $S_C$ (GPa) | $\rho$ (kg·cm$^{-3}$) |
| 3.80        | 5.67        | 2.326       | 0.51           | 0.209           | 0.0879         | 1.53          |

5. Results and discussions

![Images of results and discussions](image)

$h=1$ mm

$h=2$ mm
$h = 3$ mm

$h = 4$ mm

$h = 5$ mm

$h = 6$ mm

$h = 7$ mm

$h = 8$ mm

$h = 9$ mm
Figure 7. Impact failure results at different $h$.

From the typical collapse process in figure 7, with the increase of the middle-diameter height $h$, the failure mode of CFREPDCS has no change, all of which are longitudinal cracks, shear failure, and then breakage. The results are consistent with the failure mode of FMH in the experiment. The structure of $h=1$ mm, 2 mm, 3 mm and 5 mm belongs to progressive failure, which upper cone structure fails first and the lower cone structure fails again. The other structures occur shear failure at the same time as upper and lower cones. Comparing the results of $h=1$ mm and $h=9$ mm, it can be understood that $h=1$ mm is the result of $h=9$ mm reverse loading, $h=2$ mm and $h=8$ mm, $h=3$ mm and $h=7$ mm, $h=4$ mm and $h=6$ mm are the same theory. The results show that when the loading direction is different, the failure form is also different.

The sum of energy in 70 $\mu$s is analyzed by using the energy-absorption index of formula (1)-(4), which is shown in figure 8. Generally, the transition position of convergence-expansion structure is called larynx, which is the interface of the upper and lower cones in CFREPDCS. If the upper and lower cones fail successively, there will be two resistance stages, which is called quadratic effect in this paper. In figure 8 (a), $h=1$ mm, 2 mm and 3 mm are divided into class A; $h=5$ mm, 6 mm and 7 mm are divided into class B; $h=4$ mm, 8 mm and 9 mm are divided into class C. The development trend of energy curve of class A is similar, and it has obvious quadratic effect. The energy-absorption of class B is less and the quadratic effect is not obvious. Class C absorbs more energy, but has no quadratic effect. In figure 8 (b), SEA is fluctuated with the $h$, but it can be known that the SEA is the largest at $h=8$ mm. For figure 8 (c) and (d), the most LP of CFREPDCS is the first peak, but the LP appears at the second peak when $h=2$ mm. The LP has an upward trend with the increase of $h$, but the LP of $h=4$ mm has a mutation, which corresponds to the mutation of energy in figure 8 (a) and (b).
6. Conclusions
The experimental results show that the failure mode of CFREP thin-wall circular tube is progressive
failure, and the physical phenomenon of failure is fiber fracture and matrix breakage, that is, FMH failure mode. The SEA of CFREP thin-wall circular tube with wall thickness 2 mm is more, but its LE is less. The simulation results of CFREPDCS show that the influence of medium-diameter height \( h \) is not regular for SEA, LP, ACL, LE, but it can be found that the optimum \( h \) value of SEA is 8 mm, and the loading direction has an effect on energy-absorption and failure. These results will provide a guidance for the fabrication of sandwich core layer to design a composite launcher with better energy-absorption characteristics.

**Acknowledgments**

This work was financially supported by the National Natural Science Foundation of China (51303081), Natural Science Foundation of Jiangsu Province of China (BK20170837) and Postgraduate Research & Practice Innovation Program of Jiangsu Province of China (KYCX19_0327).

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