1. Introduction

T-shaped composite is a kind of common engineering structural material with higher specific strength and specific modulus than T-shaped metal or cement. Therefore, it is used widely in aerospace, sailing, construction, bridge, etc [1–2]. But at present, the T-shaped composite is fabricated by fibers laminating. And, the laminated T-shaped composite show some phenomenons in the long using process, such as lamination, stripping, destroying and so on. So the laminated T-shaped composite has the poor overall performance, and the limited resistance for impacting [3]. The laminated T-shaped composite could not satisfy some special needs, and need further optimize the works. Numerous experts and researchers have been betaked this issue about saving the defect of the laminated T-shaped composite to gain the better performances and firm structure. So they keep their eyes in the 3-D textile structural composites.

In weaving of 3-D textile fabrics, Yang et al. [4] introduced the organization structure design of T-shaped and I-shaped fabrics, but the operation was too complicated for the loom with 3 beams and 2 shuttles. Chen et al. [5] studied that the organization structure and weft layers affected the mechanical property of three kinds differently fabrics. Wang et al. [6] introduced the feasibility of weaving I-shaped and T-shaped fabrics with dobby. Liu et al. [7] described the weaving processing of several special fabrics, but the manipulation was too complex on the loom with 2 beam and 2 shuttles. Gu et al. [8] analyzed the structure and characteristics to get the equation of smallest structural unit of T-shaped fabric, but they didn’t describe the feasibility of the actual weaving about T-shaped fabric. Chen et al. [9] tried to design T-shaped and I-shaped fabrics by angle of chain structure. But, now, the studies do not picture the process of weaving in ordinary loom. Lv et al. [10] introduced the weaving method of T-shaped 3-D integrated woven fabric on common loom by
reasonable design with low cost processing which laid a foundation for the paper.

In mechanical properties of T-shaped composites, Lopez et al. [11] studied the mechanical properties of T-shaped fiber-reinforced composites. Chen et al. [12] presented an approach to predict the delamination of braided carbon fiber composite T-piece specimen using cohesive models. Shahaway et al. [13] studied the bending properties of T-shaped carbon fiber composite materials. Kotynia et al. [14] evaluated the performance of a novel strengthening system using T-shaped carbon fiber reinforced polymer profiles. Zhang et al. [15] compared the quasi-static bending performance and dynamic impact performance of the 3-D Biaxial spacer weft-knitted composite T-beam. Lu et al. [16] researched and simulated the bending properties of 3-D knitted T-shaped composite. Zhang et al. [17] fabricated the 3-D crocheted T-shape composite materials by Four-step braiding and VARTM(Vacuum-Assisted Resin Transfer Molding), tested the bending properties and the broken fiber in high beam was the major failure mode.

But the research literatures about the bending property of T-shaped 3-D integrated woven composites were less, its mechanical properties, failure damage mechanism and mode needed further exploration. The author et al. [18] studied the mechanical properties and applied the reasonable FEM models to forecast the tensile and bending properties of 3-D woven basalt fiber composite materials. The FEM model adopted the unit-cell model, the geometrical and meshing model was divided according to the number of actual unit-cell. Then, the geometrical model was set with trial parameters of the composite property, and the simulated curves were obtained. It was applied to forecast the tensile and bending properties of 3-D woven basalt fiber composite materials. This laid a certain foundation for this paper.

Based on the above studies, three kinds differently high beam T-shaped 3-D integrated woven fabrics with the glass fiber filaments tows 600 tex as warp yarns and the basalt fiber filaments tows 2000 tex as weft yarns were fabricated on common loom by reasonable design with low cost processing. The T-shaped 3-D integrated woven composites were manufactured by VARTM molding process. Then, the bending properties of T-shaped 3-D integrated woven composite with differently high beam were tested. Finally, the load-displacement curves, energy absorption-displacement curves and failure modes were gained by FEM simulation with ABAQUS software. The FEM results were verified with experimental results to show the validity of the FEM models.

2. Experiment

2.1 Experimental materials and equipment

The 2000 tex basalt fiber filaments tows were non-twist and poor wear resistant, so they were not used as warp yarns. We used 600 tex E-glass fiber filaments tows as warp yarns and 2000 tex basalt fiber filaments tows as weft yarns. Vinylester resin was used as matrix. Methyl ethyl ketone peroxide was used as solidification reagent. And cobalt was used as promoter.

Loom for weaving small sample in the lab (Y100S) was applied, VARTM molding system was adopted for molding, universal system prototype (NYH-W) was put up use for cutting samples, and microcomputer control electronic universal testing machine (RGT-5) was employed for testing.

2.2 Design and weaving of T-shaped 3-D integrated woven fabrics

The weft section diagram of T-shaped 3-D integrated woven fabric was showed in Figure. 1. The sizes in Figure. 1 were \( A_1 = A_3 \neq A_2, H_1 \neq H_2 \). When it was weaving, the loom width affected the size of \( A \) and the numbers of heald frame limited the thickness \( (H_1, H_2) \).

2.2.1 Design of T-shaped 3-D integrated woven fabrics

In Figure. 1, the T-shaped 3-D integrated woven fabrics were designed through the \( A_1/A_3 \) area with three layers and the \( A_2 \) area with fourteen layers, seven layers and zero layer. The warp structural diagram and chain draft were designed about the \( A_2 \) area with fourteen layers.

(1) The warp structural diagram of \( A_2 \) area with

![Fig. 1 Weft section diagram of T-shaped 3-D integrated woven fabric](image-url)
fourteen layers was showed in Figure 2.

(2) The chain draft of T-shaped 3-D integrated woven fabric about A₂ area with fourteen layers was showed in Figure 3.

2.2.2 Weaving of T-shaped 3-D integrated woven fabrics

The weaving parameters of T-shaped 3-D integrated woven fabrics were showed in Table 1.

2.3 Fabrication of T-shaped 3-D integrated woven composites

VARTM was applied to fabricate T-shaped 3-D integrated woven composite. The role of its principle and structure of each part could be seen in literature [19]. The photograph of T-shaped 3-D integrated woven composite with 12 mm high beam was showed in Figure 4.

2.4 Testing of T-shaped 3-D integrated woven composites

The three-point testing of bending properties was according to GB/T1449‒2005 (the sample was 110 mm long and 15 mm wide, the high beam was 0, 6, 12 mm respectively, and the span was 60 mm), and the universal system prototype (NHY-W) was used to prepare testing samples. Then the samples were tested on the microcomputer control universal testing machine (RGT-5). The test speed was 2 mm/min.

Table 1  Weaving parameters of T-shaped 3-D integrated woven fabrics

| Kinds (A₂ area) | Recurring number of A₁/A₃ area | Recurring number of A₂ area | Total number of warp yarns |
|----------------|-------------------------------|-----------------------------|---------------------------|
| 14 layers      | 23                            | 14                          | 394                       |
| 7 layers       | 21                            | 7                           | 224                       |
| 0 layer        |                               | 60                          | 240                       |
3. Results and discussion

3.1 Geometrical model

This FEM model adopted the unit-cell model, the geometrical and meshing model was divided according to the number of actual unit-cell. The geometrical model of three kinds differently high beam T-shaped 3-D integrated woven composites were set up according to actual specimen in ABAQUS/ Explicit dynamic finite element analysis module with the left hand spiral rules. The geometrical model of sample with 12 mm high beam was showed in Figure 5.

![Fig. 5 Geometrical model of sample with 12 mm high beam](image)

3.2 Material property

The material properties of T-shaped 3-D integrated woven composites were showed in Table 2. The material properties that was gained with iterative simulation and the material properties in Table 2 of simulation were the closest the experimental results.

3.3 Mesh model

The C3D8R solid elements were employed for meshing the geometrical model. Total number of elements of mesh model with 0 mm high beam was 928. Total number of elements of mesh model with 6 mm high beam was 1272. And total number of elements of mesh model with 12 mm high beam was 1632. Then, the mesh model with 12 mm high beam was showed in Figure 6.

![Fig. 6 Mesh model with 12 mm high beam](image)

3.4 Load-displacement curve

The load-displacement curves of T-shaped 3-D integrated woven composites: Experiment and FEM simulation were showed in Figure 7.

From Figure 7, the load-displacement curves could be divided into three phases. At the beginning, the load-displacement curves were almost linear. This indicated that bonding situation was also good between resin and fiber. That was to say the resin and fiber was good enough to combine into a whole, so the materials exhibited linear elastic performance. The second phase was that the curves no longer presented straight lines and the slope of curves was reduced. The reason was that the contact surface area was growth between the sample and cone with the increase of displacement. And, the resin began to be destroyed, at this time the fiber bundles born the main load as the reinforced materials. So, the modulus of materials decreased gradually, and the internal damage (crazing, lamination, etc) of resin was acquired. The third phase was the descending branch. When the load reached the maximum, the fiber bundles and resin began to be damaged and the curves showed tiny wave. This was mainly due to T-shaped 3-D integrated woven fabrics as reinforced material with loose positive angle chained structure and it had good elastic deformation and delayed the destruction. From Figure 7, the 12 mm high beam of T-shaped 3-D integrated woven composite had the a maximum load and the 0 mm high beam of T-shaped 3-D integrated woven composite had the a minimum load.

![Fig. 7 Load-displacement curves of T-shaped 3-D integrated woven composites: Experiment and FEM simulation](image)

| Table 2 Material properties of T-shaped 3-D integrated woven composites |
|--------------------------|----------|----------|-----------|-----------|-----------|----------|----------|----------|
| E1(GPa)                  | E2(GPa)  | E3(GPa)  | G12(GPa)  | G13(GPa)  | G23(GPa)  | V12      | V23      | V13      |
| 89                       | 7.8      | 7.8      | 1.35      | 1.35      | 1.33      | 0.25     | 0.25     | 0.21     |

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integrated woven composite. The good agreements of the comparisons proved the validity of the FEM models. But, there was a certain difference between Experiment and FEM simulation for assuming homogeneous materials and good interface between fiber and matrix in FEM simulation. So, the simulation curves were more smooth, continuous and bigger slope at the beginning than the experiment curves.

3.5 Energy absorption-displacement curve

The energy absorption-displacement curves which were obtained by the integral calculation of the load-displacement of T-shaped 3-D integrated woven composites: Experiment and FEM simulation were showed in Figure.8.

![Fig. 8](image)

Fig. 8 Energy absorption-displacement curves of T-shaped 3-D integrated woven composites: Experiment and FEM simulation

From Figure.8, at the beginning, the curve showed growth slowly, because little energy were absorbed and composites were as a whole shared the load. With the increase of the displacement, fiber parted gradually, the resin was broken and composite was broken increasingly. So, the energy absorption of materials were grown. And, the higher beam was, the more absorb energy of composite was. The 12 mm high beam of T-shaped 3-D integrated woven composite had the a maximum absorb energy. There was a good agreement of energy absorption-displacement curves of T-shaped 3-D integrated woven composite: Experiment and FEM Simulation, which proved the veracity of the finite element model.

3.6 Failure mode and failure mechanism

(1) Experiment results

Local amplification photograph and failure modes of three kinds differently high beam T-shaped 3-D integrated woven composite were seen in Figure. 9.

From Figure. 9, the bending failure modes indicated that the 0 mm high beam of T-shaped 3-D integrated woven composite was a typical bending failure mode with the compression failure in the front and tensile failure in the back. It could be observed that the sample was not broken entirely, the matrix of both surfaces crazed merely, on the front side, the fiber was intact. But on the back side, the crazed matrix was obvious and some fiber had been damaged, while the bending failure modes of 6 mm and 12 mm high beam of T-shaped 3-D integrated woven composite were compression failure in the front and shear failure in the back. And, the failure location of samples with 6 mm and 12 mm high beam of T-shaped 3-D integrated woven composite were junction place between A2 and A1/A3 zone for the organization structure. On the front surface, the matrix was crazed, but no fiber was destructed. On the back surface, the fiber tows and the matrix had been striped in a little scale, attributed to the shear force of the layer’s matrix beyond the limited value which sample can be born during the increasing load. So when the load between layers was bigger than the matrix value of the binding course stress between fiber and resin, this was contributed to the phenomenon of unsticking and stripping of composite. Furthermore, the T-shaped 3-D integrated woven composites had high delamination resistance because no delamination was found.

(2) Comparison of experiment and FEM results

Figure. 10 was the comparison of experiment and FEM results of three kinds differently high beam T-shaped 3-D integrated woven composites.

From Figure. 10, we can see a good agreement of bending deformation and damage of the three kinds differently high beam T-shaped 3-D integrated woven composites between the experiment and FEM results, which proved the veracity of the finite element model.
4. Conclusions

Three kinds differently high beam T-shaped 3-D integrated woven fabrics were fabricated on common loom by reasonable design with low cost processing. The T-shaped 3-D integrated woven composite was manufactured by VARTM molding process. Then, the bending properties of T-shaped 3-D integrated woven composite with differently high beam were tested throughout the universal testing machine with
the velocity of 2 mm/min. And, the load-displacement curves, absorb energy-displacement curves and bending failure mode were obtained. Finally, the load-displacement curves, energy absorption-displacement curves and failure modes were obtained by FEM simulation with ABAQUS software. The good agreements of comparisons proved the validity of the FEM models.

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