Mechanical Properties of Three-Dimensional Fabric Sandwich Composites

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ABSTRACT
Three-dimensional fabric sandwich composites (3D fabric composites) were prepared by impregnating epoxy resin in a hand lay-up procedure. Two types of the 3D fabric composites with the core height of 10mm and 20mm were selected to study the mechanical properties of 3D fabric composites, including flat compression, shear, and flexure properties. The results show that the flexure properties of the 3D fabric composites increased with the increase of core height, while the flat compression and shear properties decreased. Compared with the 3D fiber composites, the 3D fabric composites have much better flat compression and shear properties, although the flexure properties were similar. This work could provide a reference for the optimization of design and mechanical properties of the 3D fabric sandwich composites.

Keywords: 3D fabric sandwich composites; 3D fiber sandwich composites; flat compression properties; shear properties; flexure properties

INTRODUCTION
Three-dimensional (3D) sandwich composites, a new type of three-dimensional structural ones, have been used in various fields including aerospace, automobile, marine, locomotive, and building; because of their excellent properties, such as high strength, high modulus, low weight, fire retardance and thermal insulation [1-5].

The traditional 3D sandwich composites, such as honeycomb and foam sandwich composites, have been commonly used in many fields [6, 7]. However, the traditional 3D sandwich composites were only used in structural parts of non-load-bearing, but not in structural parts of load-bearing. This was because the face-sheet and core of the 3D sandwich composites were bonded by glue, which consequently caused delaminating and damaging under mechanical loads and/or impacts in humid and hot environments [8-10].

Stitched sandwich composite structures are also getting popular for a range of structural applications. Some stitch-bonded sandwich structures have been developed using commercial close-cellular core and woven broadcloth. While the traditional sewing machines are not suitable for relatively hard and thick core materials, also some new processing solutions for the production of 3D stitch-bonded fabrics should be developed [11-12].

In recent years, a new structural sandwich composite, three-dimensional fiber sandwich composites (3D fiber composites), as shown in *Figure 1*, have been developed and widely used in various fields for their excellent properties, especially complete molding and good designing [13,14]. Recent studies found that the 3D fiber composites were sensitive to low-velocity impact loads because the core parts were mainly composed of fibers. Therefore, it's necessary to do much more work to design the 3D fiber composites, especially in designing the core [15-1].

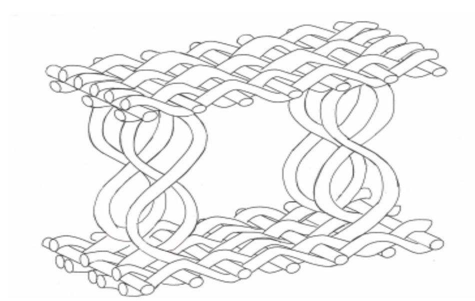

FIGURE 1. Schematic diagram of 3D fiber composites.

In this work, a new type of 3D sandwich composite, three-dimensional fabric sandwich composites (3D fabric composite), was designed and fabricated. A 3D fabric composed of two face-sheet woven fabrics interconnected by core woven fabrics was designed, as shown in *Figure 2*. Then the 3D fabric composites were integrally manufactured by impregnating epoxy resin, and the flat compression, shear, and flexure properties of the 3D fabric composites were studied.

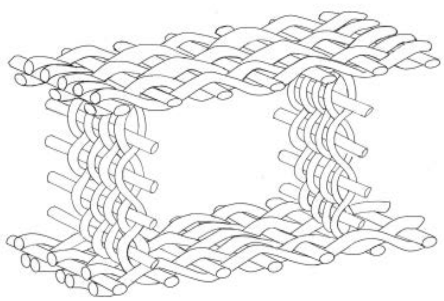

FIGURE 2. Schematic diagram of 3D fabric composites.

MATERIALS AND EXPERIMENTS

Specimen Preparation

The steps for testing specimens of the 3D fabric sandwich composites were as follows. Firstly, the weave structure of the 3D sandwich fabric was designed. The warp structure of 3D fabric composites is shown in *Figure 3*. Glass fibers with a linear density of 2200 Tex were used as the original materials, and plain weave was selected to weave the 3D sandwich fabric. When the core height was 10mm, there were 6 warp yarns and 26 weft yarns in a weave repeat unit as shown by the lifting plan in *Figure 4*. When the core height was 20mm, the weave repeat unit had 6 warp yarns and 30 weft yarns.

Secondly, the 3D sandwich fabrics were woven on the automatic rapier loom (SGA598) according to the lifting plan. In order to support the fabrics during the composites manufacturing process, the ordinary foam which was used as the cushion in the packing-case was cut into the same size and embedded into the interspace of the 3D sandwich fabrics.

Finally, the 3D fabric sandwich composites were prepared by a standard hand lay-up technique with a mixture of epoxy resin (WSR6101), hardener (WSR9055), and diluents (propylene oxide tert-butyl ether 660). The mass ratio of the mixture was 100 of epoxy resin, 40 of hardener, and 10 of diluents [19, 20]. After keeping in an oven (101A-4S) at 70 °C for 8 hours, the 3D fabric sandwich composites were obtained, as shown in *Figure 5*.

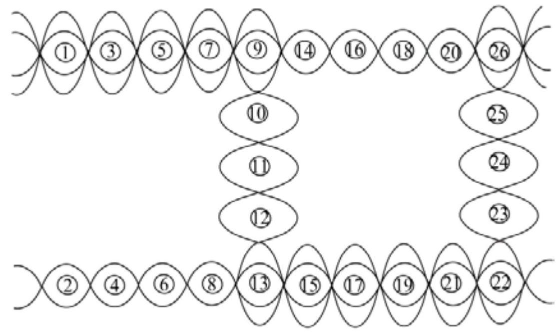

FIGURE 3. Warp structure diagram of 3D fabric composites.

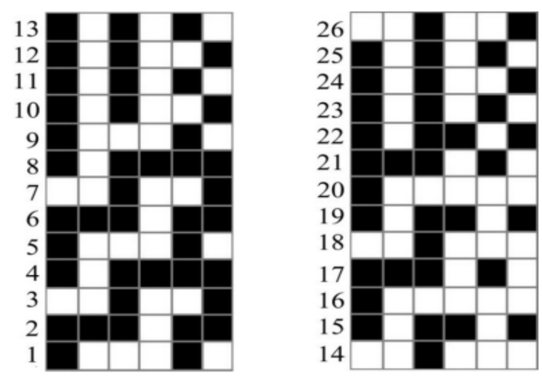

FIGURE 4. Lifting plan of 3D fabric composites.

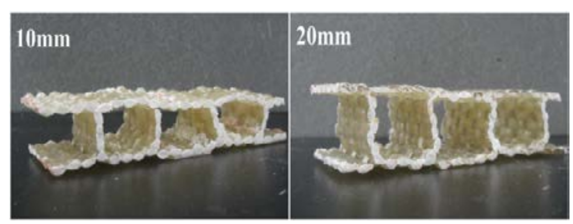

FIGURE 5. 3D fabric sandwich composites with core height of 10mm and 20mm.

Mechanical Tests

All the mechanical tests were performed on a universal testing machine (Instron 3385H) with the maximum load of 250KN. Five specimens were tested in each test and the final results were obtained from the average value. The environment conditions of the lab were controlled at 23±2°C and 50±10% relative humidity.

Flat compression tests were carried out according to GB/T 1453-2005 standard of People's Republic of China [21]. For flat compression tests, the size of specimens was 60mm×60mm and the loading speed was set at 2 mm/min. The flat compression strength was calculated according to the following equation:

$$\sigma = \frac{P}{F} \quad (1)$$

where P and F were the fracture load (N), cross section area of the specimen (mm^2), respectively.

Shear tests were carried out according to GB/T 1455-2005 standard of People's Republic of China [22]. For shear tests, the size of specimens was 100mm×30mm and the loading speed was set at 1mm/min and the span between the upper and lower indenter was 10mm. The shear strength was calculated according to the following equation:

$$\tau_c = \frac{P}{l \times b} \quad (2)$$

Where P, l and b were the fracture load (N), length (mm), width (mm), respectively.

Flexure tests were carried out according to GB/T 1456-2005 standard of People's Republic of China [23]. For flexure tests, the size of specimens was 100mm×30mm and the loading speed was set at 2 mm/min and the span of the indenter was 60mm. The flexural strength was calculated according to the following equation:

$$\sigma_f = \frac{P \times l}{4b \times t_f \times (h - t_f)} \quad (3)$$

where P and t_f presented the maximum load (N) which exerted on the specimen prior to fracture and the face sheet thickness (mm), respectively; l, b and h were the length (mm), width (mm), thickness of the specimen (mm), respectively.

Breakage Photography

The breakage photographs of the face-sheet and core of the 3D fabric composites were taken by a digital camera (Sony DSC-TX1). The locations and degree of the breakage were observed on the face-sheet and core of the testing specimens. The photographs were also taken for comparison after flat compression, shear and flexure tests.

RESULTS AND DISCUSSION

The flexural properties of the 3D fabric composites increased with the increase of core height, while the flat compression and shear properties decreased. The flat compression strength and shear strength of 3D fabric composites were better than that of 3D fiber composites, while their flexure strength were similar.

Flat Compression Properties

The properties of flat compression were shown in *Figure 6* and *Table I.*

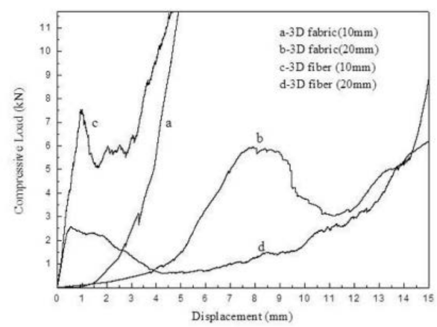

FIGURE 6. Load-displacement curves of flat compression tests on 3D fabric and 3D fiber composites.

TABLE I. Flat compression properties of 3D fabric and 3D fiber composites.

Sample	Core Height (mm)	Maximum Compressive Load (kN)	Elasticity Modulus (MPa)	CD_{max} (mm)
3D fabric	10	11.74	39	4.69
3D fabric	20	5.97	11	7.94
3D fiber	10	7.55	60	1.00
3D fiber	20	2.58	38	0.58

CD is: compressive displacement when compressive load reached the maximum.

(1) It can be seen from curve b of *Figure 6* that the compressive load increased with the increase of displacement initially. When the compressive load reached the maximum, the resin matrix and fibers on the face-sheet were partly fractured. The color of the connection of face-sheet and core changed to white, as shown in *Figure 7a* and *Figure 7b*, and the sound of crack could also be heard. Then the fabrics of core began to collapse, at the same time the compressive load began to decrease. Finally the fabrics of core completely collapsed and the 3D fabric composites were damaged completely, when the compressive load went up again.

It can also be seen that the breakage of the 3D fabric composites with core height of 10mm and 20mm were different, the composites with core height of 20mm were damaged more badly, as shown in *Figure 7c* and *Figure 7d*.

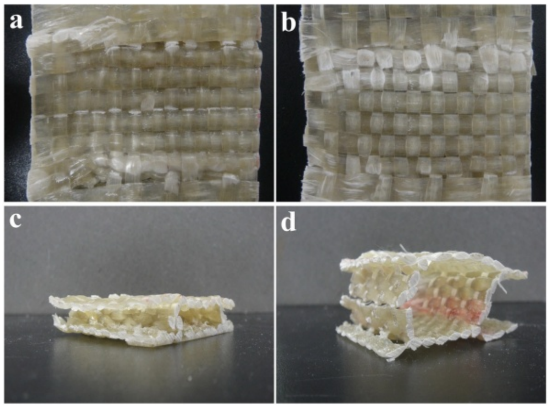

FIGURE 7 Breakage photographs of 3D fabric composites suffering flat compressive loads for face-sheet with core height of (a) 10mm and (b) 20mm and for core with core height of (c) 10mm and (d) 20mm.

(2) The flat compression strength decreased with the increase of core height, as shown in *Figure 6* and *Table I*. The maximum compressive load of 3D fabric composites with core height of 10mm was 11.74kN, while the value was 5.97kN for 20mm. It can be explained that the 3D sandwich composites with low core height were more stable than that with high core height, and were not easily collapsed.

(3) It can be seen from *Figure 6* and *Table I* that flat compression properties of 3D fabric composites were better than that of 3D fiber composites at the same core height. The main reason is that the core parts of 3D fiber composites were composed of fibers, which were fractured brittlely under load, while the core parts of 3D fabric composites were composed of fabrics, which could bear larger loads.

It can also be seen from *Figure 6* and *Table I* that 3D fiber composites were broken in a short displacement, while the damaging process of 3D fabric composites were lengthy. This means that the 3D fabric composites could absorb much more energy than 3D fiber ones when they suffered the flat compressive load. Obviously, the ability of suffering the flat compressive load of 3D fabric composites were better than that of 3D fiber ones.

Shear Properties

The properties of shear were shown in *Figure 8* and *Table II*.

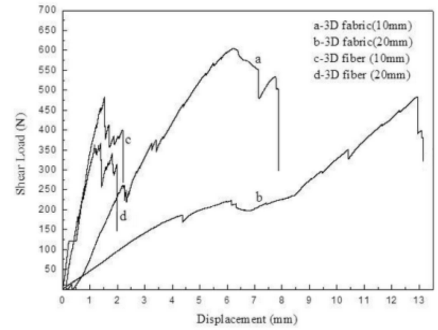

FIGURE 8. Load-displacement curves of shear tests on 3D fabric and 3D fiber composites.

TABLE II. Shear properties of 3D fabric and 3D fiber composites.

Sample	Core Height (mm)	Maximum Shear Load (N)	Elasticity Modulus (MPa)	SD_{max} (mm)
3D fabric	10	605.83	2.21	6.26
3D fabric	20	483.84	0.61	12.93
3D fiber	10	482.79	5.88	1.53
3D fiber	20	366.30	4.09	1.40

SD is: shear displacement when shear load reached the maximum.

(1)The properties of shear decreased with the increase of core height, as shown in *Figure 8* and *Table II*. The maximum shear load of 3D fabric composites with core height of 10mm was 605.83N, while the value was 483.84N for 20mm. It can be explained that when the core density was the same, the shear properties of 3D fabric composites mainly depended on the torque of the core. The higher the core height, the bigger the torque of the core.. Thus the 3D fabric composites with high core height were easily broken [24, 25].

(2) It can also be seen from *Figure 8* and *Table II* that shear strength of 3D fabric composites was better than that of 3D fiber composites at the same core height. It could be because the core parts of 3D fiber composites were immediately stretched to fracture under loads, while the core parts of 3D fabric composites were first stretched to bend then collapse.

It can also be seen from *Table II* that the ability of 3D fabric composites to support shear load was better than that of 3D fiber ones. When shear load reached the maximum, the displacement of 3D fabric composites with core height of 10mm was 6.26mm, while the value was only 1.53mm for 3D fiber ones.

Flexure Properties

The properties of flexure were shown in *Figure 9* and *Table III*.

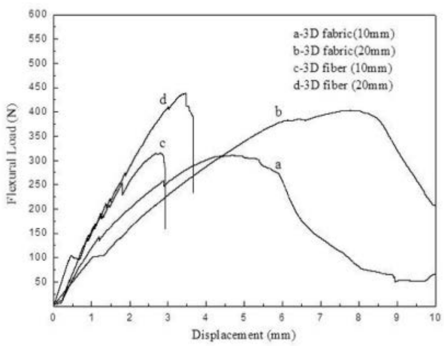

FIGURE 9 Load-displacement curves of flexure tests on 3D fabric and 3D fiber composites.

TABLE III. Flexure properties of 3D fabric and 3D fiber composites.

Sample	Core Height (mm)	Maximum Flexural Load (N)	Elasticity Modulus (Mpa)	FD_{max} (mm)
3D fabric	10	311.24	24.99	4.69
3D fabric	20	403.09	19.03	7.78
3D fiber	10	315.59	39.96	2.80
3D fiber	20	438.80	46.73	3.45

F is: flexural displacement when flexural load reached the maximum.

(1) The properties of flexure increased with the increase of core height, as shown in *Figure 9* and *Table III*. The maximum flexural load of 3D fabric composites with core height of 10mm was 311.24N, while the value was 403.09N for 20mm. It could be because the flexure properties of 3D fabric composites mainly depended on the moment of inertia, and the moment of inertia was closely related to the core height. The higher the core height, the greater the moment of inertia of the composite. Thus the flexure properties of the 3D fabric composites with high core height were better [24, 25].

(2) It can also be seen from *Figure 9* and *Table III* that the flexure properties of 3D fabric composites were similar to that of 3D fiber composites. It could be because the main factor affecting flexure properties was the core height, while the performance and weave of the core itself had less effect on the flexure properties [24, 25].

(3) It can also be found from *Figure 9* that when the flexural load reached maximum, curve a and curve b decreased slowly, while curve c and curve d dropped instantaneously. It could be because the core parts of 3D fiber composites were fractured rapidly under loads, while the core parts of 3D fabric composites were collapsed very slowly over a period of time.

It can be seen that the breakage of the 3D fabric composites with core height of 10mm and 20mm were different. The crack of the face-sheet appeared obviously and the color of the fibers changed to white, as shown in *Figure 10a* and *Figure 10b*, while the fabrics of core of the composites with core height of 10mm were damaged more badly, as shown in *Figure 10c* and *Figure 10d*.

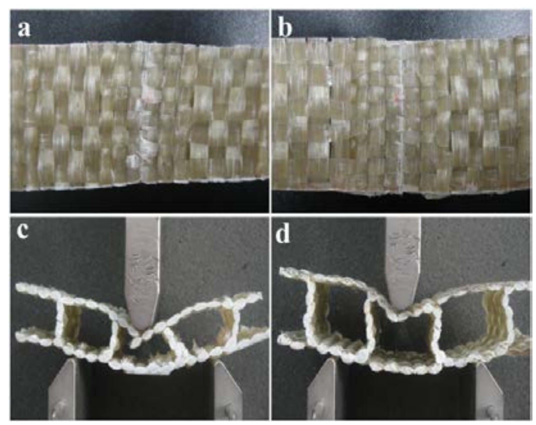

FIGURE 10. Breakage photographs of 3D fabric composites suffering flexural loads for face-sheet with core height of (a) 10mm and (b) 20mm and for core with core height of (c) 10mm and (d) 20mm.

CONCLUSIONS

Three-dimensional fabric sandwich composites were manufactured in this work. The flat compression, shear, and flexure properties of the 3D fabric composites with core height of 10mm and 20mm were also studied. The results show that the flexure properties of the 3D fabric composites increased with the increase of core height, while the flat compression and shear properties decreased. The flat compression and shear properties of 3D fabric composites were better than that of 3D fiber composites, while their flexure properties were very similar. Further work is needed to evaluate the mechanical performance of the 3D fabric composites, in particular, the low-velocity impact performance and peel resistance, but now these initial results clearly show the advantages of the 3D fabric sandwich composites and the application prospects of these composites.

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