NOVEL SEMI-RIGID NET STRUCTURE COMPOSITE: PART III. MECHANICAL PERFORMANCE UNDER UNIAIXAL AND BIAXIAL LOADS

Xiao-ming Liu*, Nan-liang Chen*, Xun-wei Feng*
*** College of Textiles, Dong Hua University, Shanghai 200051, P.R.China**

Keywords: *Composite; Net structure; Mechanical test, Theoretical analysis*

Abstract

Since its birth in 1960s, composites make up a very broad and important class of engineering material for its good strength/weight property. However, most of the products, using in field such as aerospace, military, recreation devices, are made into the shape of bar, plate, shell or block, which is usually rigid and stiff, providing ultra high modulus and strength as metal does. In this paper, a new kind of semi-rigid net structure composite was designed by combining the flexible feature of textile with the rigidity of composite. The manufacturing process is introduced and relative properties including knot strength, uni-and bi-axial tensile tests were tested. The results show that the novel semi-rigid composite can keep the figuration of the basic mesh grid while minimizing product's weight and providing enough strength to its end use.

1 Introduction

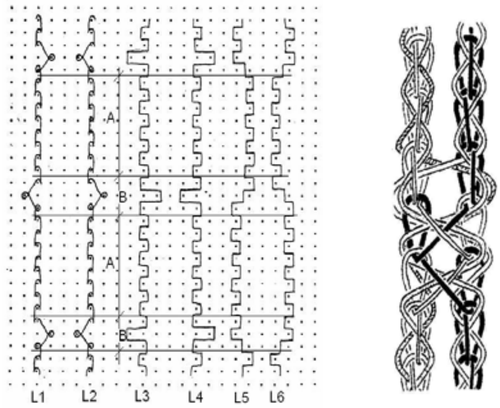
Since its birth in 1960s, composites make up a very broad and important class of engineering material for its good strength/weight property. Lots of researches have been done on the tensile, compressing, bending and impact properties of unidirection, multidirection and 3D composites made by high performance yarn and polymer matrix [1]. But most of the products, using in field such as aerospace, military, recreation devices, are made into the shape of bar, plate, shell or block, which is usually rigid and stiff, providing ultra high modulus and strength as metal does [2-10].

In this paper, we introduced a new kind of semi-rigid net structure composite by combining the flexible feature of textile with the rigidity of composite. The manufacturing process is introduced and relative properties are tested. The results show that the novel semi-rigid composite can keep the figuration of the basic mesh grid while minimizing product's weight and providing enough strength to its end use.

2 Structure Selection and Fabric Manufacturing

2.1 Structure Selection

Our objective is to design a new kind of net structure composite which can be fixed on the rigid frame to work as a sustentation of small pieces. The mesh grid should be of good strength/weight ratio and can satisfy the end users' requirement.



(a) (b)

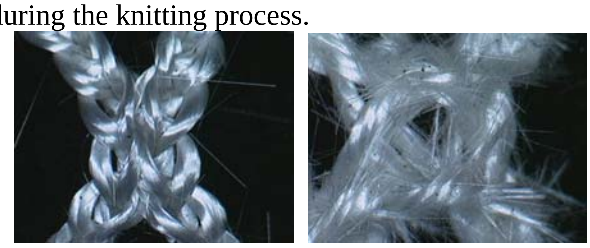
Fig. 1. Six-guide-bar net structure with 4 inlay yarns strengthen the connection (a) Lapping movement and threading diagram (b) Loop structure

In terms of mesh grid structure, four kinds of net making systems should be mentioned, that is, twisting (bobbinet type), braiding, knotting and warp knitting (Raschel). The bobbinet machines have not been used for the purpose of industry net manufacture since they are essentially fine gauge and of delicate construction designed for handling very fine yarns. Braided nets have found to be strong, durable and easy to handle. However, they have a tendency to slip and distort the holes. Manual fabrication of knotted nets has been practiced since the dawn of civilization. Comparing with Raschel products, however, the knotted nets have lost a great deal of their traditional market, particularly in the small and medium sizes, due to their low productivity, limited amount of yarn accommodation, higher yarn cost, slippage of knots and lower strength/weight ratio. So, our concerns concentrate on the Raschel net structure. Fig. 1 shows the lapping movement and threading diagram of the six-bar Raschel structure. Four inlay yarns were inserted to reinforce the strength of the knot connection.

The first two bars, threaded one in one out, knit the pillar sections A forming the sides or "leg" of the mesh as well as the junctions B creating the equivalent of knots. Four inlay yarns (bars L3-L6), which also threaded one in, one out and move over one needle in the "leg" portion and two needles in the junctions, were inserted to reinforce to reinforce the "leg" and increase the strength of the connection.,.

2.2 Net Structure Composite Manufacture

The mesh grid preform of six bar Raschel net structure was fabricated with S-glass yarn on a special warp knitting machine. During the process, we found that the glass yarns were very easy to get damage [11], which greatly affected the final mechanical property. Fig. 2 shows the damage caused with different yarn tension. So the knitting machine is equipped with compound needle and contains electrical yarn let-in and take-down mechanic and the procession conditions were restrictedly controlled to minus the damage caused during the knitting process.



a) Lower yarn tension b) Higher yarn tension

Fig. 2. Microphotograph of the yarn damage knitted with different yarn tension

Then the fabric was stretched and immerged into silicon resin. The resin suspenders were removed by a blower and the resin net was cured in the oven with temperature of 200℃ for 7 hour. The final composite are showed in Figure 3.

3 Test Methods

The mechanical properties of the preform and the composite are tested.

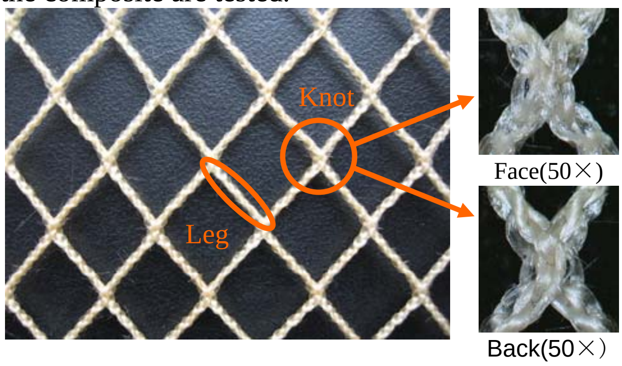
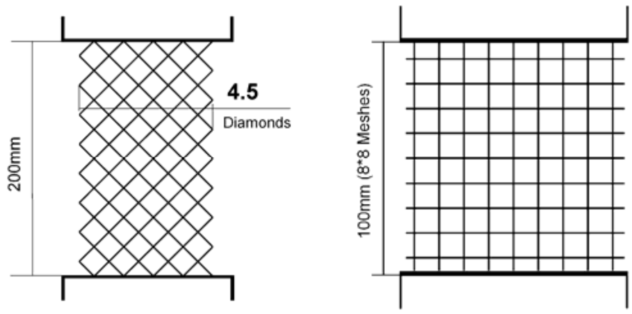


Fig. 3. Photograph of the mesh grid composite

3.1 Knot Strength

3.1 Uniaxial Tensile Test

The uniaxial tensile property of the mesh grid fabric is tested according to GB4925-85[12] for both warp direction and weft direction. The mesh grid fabric was relaxed on a plan desk with 45 degree angle between all the mesh edges. Each spaceman was cut into a box shape with 200mm long and 4.5 diamond width, i.e., there are totally nine columns in the width direction (Fig. 4). The tests were carried on HUALONG WDW-20 Strength Tester with a crosshead speed of 50mm/min.



In warp/weft direction In 45 degree direction

Fig. 4 Sketch of uniaxial tensile test

3.2 Biaxial Tensile Test

To fully understand the mechanical property of the mesh grid composite in the status of its actual usage, the biaxial tensile property of the net structure composite was tested on Zwick/Roell Z010 bixial tensile machine. The size of the specimen was 135*135mm. The test window size was 80*80mm with nine columns in each direction, i.e. 8*8 mesh grids. Tests with 3 different axial load ratios (ALR) were carried out. The inner sides of the clamps were coved with rubber in order to avoid sample slippage or breakage at the clamp positions. Five tests were preformed for each testing case, and the mean value of the breaking forces was calculated. Fig. 5 shows the biaxial testing machine and the clamped sample.

Fig. 5. Biaxial testing machine and clamped sample

4 Results and Discussion

4.1 Performance Summary

According to the above test method, the knot strength and the uniaxial tensile properties were tested and the results are listed in Table 1.

Table 1. Fabric and composite basic properties

		Fabric	Composite	Increase
Weight per Unit (g/m2)		141.79	190.14	+ 34.10%
Uniaxial	Warp	404.33	421.73	+ 4.30%
tensile	Weft	237.38	349.18	+47.10%
strength (N)	45 degree	363.49	668.42	+83.89%

From the result, we can see that the weight of the fabric is only 141.79g/m2 and that of the composite is only 190.14g/m2, which is even lighter than common garment fabrics.

The breaking strengths of the uniaxial tension in different direction are different due to less connecting yarns in the weft direction.

The mechanical properties of the preform are relatively weak ranging between 237 and 405 with the strength of weft direction the least and that of warp direction the largest. After compound with the resin, the mechanical properties of the mesh grid increased greatly with an increase of 47.10% in the weft direction and 83.89% in the 45 direction. Only the breaking load of warp direction gets a slim increase of 4.30 %. The mechanical differences between two directions decrease greatly from 166.95 to 72.55 with only a resin content (weight) of about 25%.

The load-strain curves (Fig.6 and Fig.7) further show the mechanical property change with resin immerging.

Fig. 6 shows the load-strain curves of preform extended in the three directions. During the test, large shrinkage in the transverse direction was found because of the rotation of the “leg” orientation, looped yarn straightening and inter-yarn slippage. As deformation increases, the yarns begin to lock at the crossover points and the force and the stiffness of the fabric goes up rather rapidly as deformation increases. In the breaking stage, a number smaller peaks and troughs ensued on the tensile curve corresponding to the yarn breakage gradually. This repeated decrease and increase in strength continued with the peak value increasing up to a maximum stress and then decreasing gradually up to the point of final fracture. This was believed to be attributed to the premature yarn breakage caused by the stress concentration before final rupture preform. Although the warp strength is higher than that of 45 direction, its first breakage strength is relatively low, showing that the tensile strength in the direction of 45 degree exhibits the best.

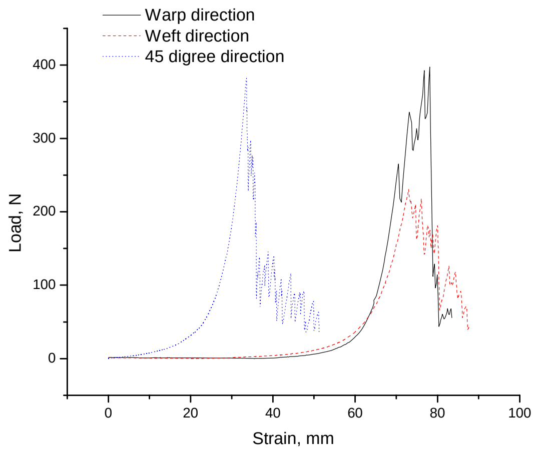


Fig. 6. Uniaxial tensile curve of the preform

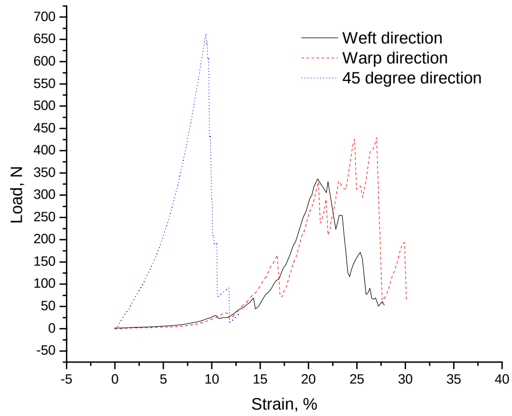


Fig. 7. Performance of the composite under load in different directions

After compound with the resin, the present of resin increases the stress transfer and protects the yarn from contact forces both of which decrease the stress concentration and hence improve the mechanical performance of the composite. This is shown clearly in Fig. 7 with higher curve slop, less peaks and higher fail strength.

The composite performs best in the 45 degree direction with the highest breaking strength, initial modulus and peak breaking value before rupture.

4.2 Biaxial Tensile Performance

As the mesh grid composite is stretched and fixed on the rigid frame when used, it is more important to investigate the performance of the net structure composite under biaxial stress. So, the biaxial tensile test was carried out and the results are listed in Table 2.

Table2 Results of the biaxial tensile test

Tensile ratio of axis1/axis2	Axis 1		Axis 2	
	Breaking strength /N	Elongation /mm	Breaking strength /N	Elongation /mm
1:1	143.36	2.15	139.84	2.83
1:0.8	172.05	4.14	128.03	1.98
1:0.5	197.84	5.49	99.53	0.59

From Table 2, we can find the breaking strength and the elongation of axis 1 go up with the in crease of the axial load ratio, while, at the same time, that of axis 2 goes down. However, the summation of both failure strength and breaking strain are around a constant, as 300N and as 5.39 to 6.12 respectively. This can be explained by strain transforming between two axes and the change of angle will redistribute the stress inner the mesh grid and result in the best failure stress.

Fig. 8 presents the membrane force-strain curve under different ALR during biaxial tensile process. We can find that the shape of the curves differ with each other. When ALR=1/0.5, a negative strain was found with axes 2, accompanied with the highest failure strength and elongation at axes 1. When ALR increased into 1/0.8, positive strain in axes 2， very small (2mm), and great reduction at failure strength in axes 1 were observed, attributed to the biaxial load changes the failure mode of the knot connection from the shear failure dominant to matrix cracking failure dominant. Under the biaxial load with ALR=1/1, the transverse strain in axes 2 is similar with that of axes 1, due to the symmetric structure of the mesh grid, which presents similar performances under balance tensile load in two direction. However, this further reduced the failure strength of the mesh grid.

It is notable that the slopes at the initial parts of all the three curves for axes 1 are similar under different ALR, which means the same initial modulus and deformation status. However, with the increasing of the ALR from 1/0.5 to 1/1, quicker strength increases are found after a certain deformation. This is due to the deform process under different load. When transverse load goes up, the deformability of the mesh grid, especially deformability of the angle, decreases and the chains and knots begin to be stretched earlier than before, which results in the above slope change with the curve superposition at the ALR of 1/1. However, the initial slop did not change which showing that the initial deformation comes from the yarn reinforced matrix of the chain and knot, with no resin break and debonding between fibers and matrix. After that, large deformation comes from the grid angle and the loop structure with chain and fiber orientation into the load direction, which is ended by a fast increasing in tensile strength before mesh grid failure. Fig. 9 shows the photos of the composite fracture under different ALR. To sum up, biaxial load with different ALR affect the mechanical behavior of the mesh grid composite and should be considered by the end users.

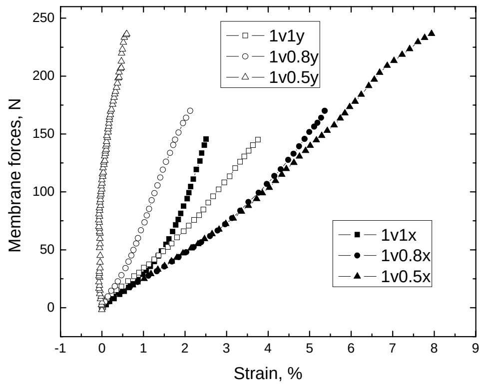


Fig. 8. Membrane force-strain curve for the mesh grid composite under biaxial tensile load

ALR =1v1 ALR =1v0.8 ALR =1v0.5

Fig. 9. Fracture of the composite under different ALR

5 Conclusion

A new kind of semi-rigid mesh grid structure composite is described in this paper. After selection, Raschel net structure, of which the knot is much stronger and mesh size can be adjusted, was selected to work as the preform of the mesh grid composite. The preform was manufactured on a special warp knitting machine which is modified to minimize yarn damage during processing. The property test results showed that the mesh grid structure is light and of enough strength, though the mechanical properties of warp and weft direction are different. After resin immerging, the knot breaking strength and the weft breaking strength increased greatly contributed to the improvement of the stress transfer unity, which allows us to make a light weight product with enough strength. Biaxial tests of the net composite were carried on to evaluate the compound stress it can sustain. The failure strength and the strength-stress curve showed that the mechanical behavior of the mesh grid structure is greatly related to the axial load ratio, which should be considered by the end users.

References

[1] Hull D. and Clyne T. W., "An introduction to composite materials". Second edition. London: Cambridge University Press, 1996.

[2] Aymerich F., Pani C. and Priolo P. "Effect of stitching on the low-velocity impact response of [03/903]s graphite/epoxy laminates". *Composites Part A: Applied Science and Manufacturing*, Vol. 38, No. 4, pp 1174-1182, 2007.

[3] Long A. C., "Design and manufacture of textile composites". Cambridge, England: Woodhead publishing limited, 2005.

[4] Duhovic M., "Deformation characteristics of knitted fabric composites," in *Department of Mechanical Engineering* vol. PhD Thesis Auckland, New Zealand: The University of Auckland, 2004.

[5] Avci A., Sahin O. S. and Tarakcioglu N. "Fatigue behavior of surface cracked filament wound pipes with high tangential strength in corrosive environment". *Composites Part A: Applied Science and Manufacturing*, Vol. 38, No. 4, pp 1192-1199, 2007.

[6] Aydogdu M. "Comparison of Various Shear Deformation Theories for Bending, Buckling, and Vibration of Rectangular Symmetric Cross-ply Plate with Simply Supported Edges". *Journal of Composite Materials*, Vol. 0021998306062313v1, 2006.

[7] Belingardi G., Martella P. and Peroni L. "Fatigue analysis of honeycomb-composite sandwich beams". *Composites Part A: Applied Science and Manufacturing*, Vol. 38, No. 4, pp 1183-1191, 2007.

[8] Butler R., Almond D. P., et al. "Compressive fatigue limit of impact damaged composite laminates". *Composites Part A: Applied Science and Manufacturing*, Vol. 38, No. 4, pp 1211-1215, 2007.

[9] Cesari F., Dal Re V., et al. "Damage and residual strength of laminated carbon-epoxy composite circular plates loaded at the centre". *Composites Part A: Applied Science and Manufacturing*, Vol. 38, No. 4, pp 1163-1173, 2007.

[10] Mouritz A. P., Bannister M. K., et al. "Review of applications for advanced three-dimensional fibre textile composites". *Composites Part A: Applied Science and Manufacturing*, Vol. 30, No. 12, pp 1445-1461, 1999.

[11] Liu X. M., Chen N. L. and Feng X. W., "A study of the knittability of the glass filament yarns. Part I: Yarn/metal abrasion damage," in *2006 Autex World Conference* Raleigh, North Carolina, USA, 2006.

[12] GB/T 4925-1985 Testing method for breaking load and elongation of netting of synthetic fibre. Chinese Standard.