



Tensile Behaviour of Multilayer Knitted Fabric Composites with Different Stacking Configuration

YANZHONG ZHANG, ZHENG-MING HUANG and S. RAMAKRISHNA

Polymer and Textile Composites Laboratory, Department of Mechanical & Production Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260

(Received 21 January 2000; accepted 10 May 2000)

Abstract. In this paper, multilayer plain weft knitted glass fabric reinforced epoxy composite laminates with different stacking configurations, i.e., $[0^\circ]_4$, $[0^\circ/\pm 45^\circ/0^\circ]$, $[0^\circ/90^\circ/90^\circ/0^\circ]$ and $[90^\circ]_4$, were investigated experimentally. The laminates were uniaxially tensile loaded until final fractures occurred. The experimental results show that with the change in layer stacking structure, a corresponding variation in composite strength and stiffness was achieved. The tensile strength and modulus rank as follows: $[0^\circ]_4 > [0^\circ/\pm 45^\circ/0^\circ] > [0^\circ/90^\circ/90^\circ/0^\circ] > [90^\circ]_4$, which implicates a potential desiguability of Knitted Fabric Composites (KFC) for engineering applications. Failure behaviours of the fractured laminate specimens were examined using a 'matrix digestion and layer peeling' method, based on which the behaviour of each lamina in the laminate can be clearly shown. It was found that an angle-plyed lamina in the laminate when subjected to a uniaxial tensile load has a different fracture mode from that of a single ply composite under an off-axial tensile load. This means that the lamina in the laminate is subjected to a more complicated load combination. By comparing the fractured mode of the latter lamina with that of the single ply composite, the load direction sustained by the lamina in the laminate can be identified, which provides a qualitative benchmark for verifying a theoretical simulation.

Key words: knitted fabric composites, multilayer laminate, stacking configuration, mechanical properties, fracture mode, internal load direction, experimentation.

1. Introduction

Knitting techniques are traditionally employed in clothing and apparel industry. By interlocking of loops of fibre bundles, various knitted fabrics can be produced. As one kind of textile materials, knitted fabrics possess some unique characteristics over other kinds of textile fabrics such as woven and braided fabrics, particularly in conformability and drapability which make them irreplaceable in conforming complicated contours or desired shapes. Due to these attractive features and also due to the feasibility of knitting high performance engineering fibres such as carbon/graphite, glass and aramid in current technology, there is an increasing interest in the research and development of knitted fabrics for use in composite industry [1–5]. Compared with some other kinds of fiber reinforced composites, knitted fabric composites generally have inferior in-plane stiffness and strength, as indicated in Figures 1 and 2. Hence, they are not likely to be used as primary structural

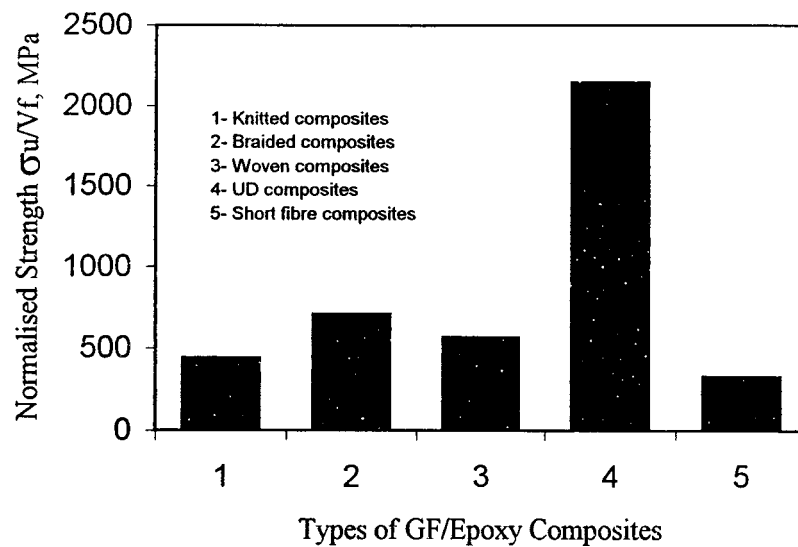


Figure 1. Normalized strength (with respect to the fibre volume fraction) of different fibrous composites in their main directions.

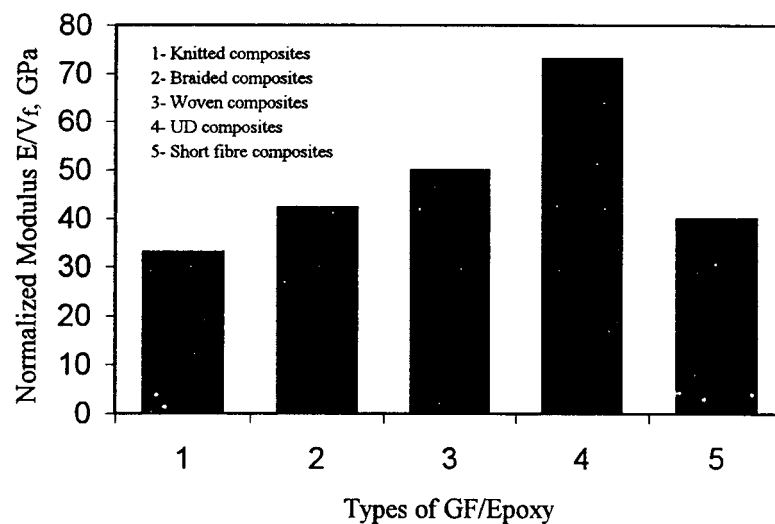


Figure 2. Normalized modulus (with respect to the fibre volume fraction) of different fibrous composites in their main directions.

materials in high performance structure components. However, it is possible to make them secondary load-sharing structures, due to their feasibility of net or near to net shape contours [6] and some other superior mechanical performances such as high resistance to impact [7, 8]. A “flexible composite” with a much larger useable range of deformation than conventional laminated composites could be achieved by combining tougher resins with knitted fabrics [9].

The mechanical properties of knitted fabric composites (KFC) varied with variables such as knit architecture, stitch density, pre-stretching percentage on fabrics, inlay fiber bundles, tow size of fibers etc. have been experimentally investigated by previous researchers [10–18]. The anisotropy feature of KFC has already been recognized. These investigations were mainly carried out based on single layer or equivalent single layer knitted fabric reinforced composites. On the other hand, limited work has been done so far on the mechanical behaviour of knitted fabric composites with varied stacking structures. The present paper focuses on investigation of the tensile behaviours of multilayer plain weft knitted glass fabric reinforced epoxy composites with different stacking configurations. Following laminates have been considered: $[0^\circ]_4$, $[0^\circ/\pm 45^\circ/0^\circ]$, $[0^\circ/90^\circ/90^\circ/0^\circ]$ and $[90^\circ]_4$, where 0° refers to the fabric wale direction and 90° to the fabric course direction. With the variation in the stacking arrangements, different tensile moduli and ultimate strengths have been found. The tensile strength and modulus rank as follows: $[0^\circ]_4 > [0^\circ/\pm 45^\circ/0^\circ] > [0^\circ/90^\circ/90^\circ/0^\circ] > [90^\circ]_4$.

A special attention has been focused on the fracture mode of each lamina layer in the laminate. This was achieved in the present paper by using a special technique, called “matrix digestion and layer peeling” method. The resin matrix in the fractured laminate specimen was digested and each fabric layer was peeled off. The fracture surface of each layer was thus clearly shown. A comparative study was also carried out using a single layer fabric reinforced composite under an off-axial tensile load. It was found that the fracture mode of an angle-ply lamina in the multilayer laminate is different from that of single layer composite subjected to the off-axial tensile load. Hence, the angle-ply lamina in the laminate is subjected to a more complicated load combination. By comparing the two fracture modes, the load direction sustained by the angle-ply lamina can be determined. These experimental evidences are useful for verifying a theoretical simulation on the multilayer knitted fabric reinforced composites.

2. Experimental

2.1. PLAIN WEFT-KNIT FABRIC

Plain weft-knit fabrics were produced on a Flying Tiger knitting machine manually, using CPR407 glass fiber yarns made by ACI Fibreglass, Australia. The linear density of the yarn is 600 Tex (grams per 1000 m in length). Schematic diagram of a plain weft knitted fabric is shown in Figure 3.

The row of loops in the longitudinal direction of the fabric is called “wale”, whereas the row of knit loops in the width direction is named as “course”. In this study, the wale direction is taken as the reference (0°) direction. Thus, 90° direction is along the course direction. The fabric stitch density was characterized as 3.4 loops/cm in the wale and 3.8 loops/cm in the course directions, respectively.

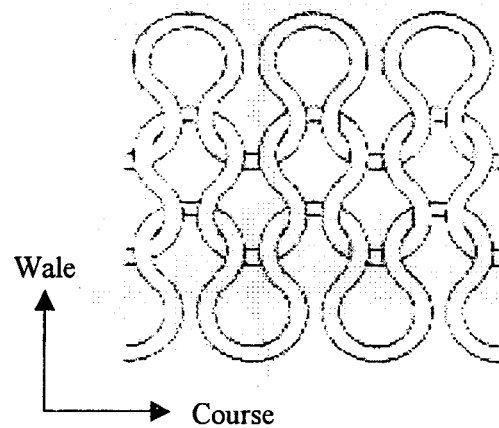


Figure 3. Schematic diagram of a plain weft-knit glass fabric.

2.2. SPECIMENS

Composite laminates were fabricated by a hand lay-up method. The matrix material used was a mixture of epoxy resin R-50 and hardener H-64 (Chemicrete Enterprises Pte. Ltd, Singapore) in a ratio of 100 : 48 by weight. Prior to commencing composite fabrication, the knitted fabrics were dried in an oven at 100°C for 2 h to remove moisture that may influence adhesion between the epoxy matrix and the glass fibers. The epoxy resin and the hardener were separately preheated at 45°C for 30 min to reduce viscosity. Then, the resin and the hardener were thoroughly mixed together, followed by a vacuum treatment for 3 ~ 5 minutes to remove entrapped air bubbles. The composite fabrication was begun by attaching the fabrics with pushpins onto a wooden plank that was covered with a PP (Polypropylene) sheet. The PP sheet was used as a release agent to ensure the surface quality of the final composite laminate. Straight aluminum rods of 2 mm diameter were inserted into the fabric edges to make the curling fabrics flat during the fabrication. The resin mixture was then poured into the fabrics and another PP sheet was placed on the fabric surface. A delicate brush was used to push any air cavities to sides, before applying another wooden plank and heavy weights. The resin-impregnated fabrics were cured at room temperature for 24 hrs. Multilayer laminates of four stacking configurations, i.e., $[0^\circ]_4$, $[0^\circ/\pm 45^\circ/0^\circ]$, $[0^\circ/90^\circ/90^\circ/0^\circ]$ and $[90^\circ]_4$, were prepared. To facilitate comparison, single layer knitted fabric composite panels were also fabricated. The fiber volume fractions, V_f , were 22.2% for the multilayer laminates and 17.1% for the single layer composites, which were determined with a combustion method. Tensile specimens were cut carefully using a water-cooled diamond saw in parallel to the wale or course direction. All specimens have the same width of 25 mm. Aluminum end tabs of 45 mm in length were glued to the both ends of the specimens, leaving a testing gauge length of 120 mm.

2.3. TESTS

Tensile tests were carried out on an Instron testing machine (Type 8516) at a cross-head speed of 1.5 mm/min. Tensile strains were calculated based on the cross-head displacements. Macrostructure of failed specimens was observed using optical microscopy, whereas microstructure of the specimens was examined under a Jeol Scanning Electron Microscope (JSM-5800LV). To identify the fracture mode of an internal layer in the fractured laminate specimen, a resin digestion process was employed. Details will be described in the following section.

3. Results and Discussions

3.1. MECHANICAL PROPERTIES

Figure 4 plots the stress–strain curves of single layer knitted fabric composites subjected to a uniaxial tensile load at loading directions of 0°, 45° and 90° off-axis (with respect to the wale direction). Averaged properties of the single layered composites are summarized in Table I. The composite anisotropy in strength and

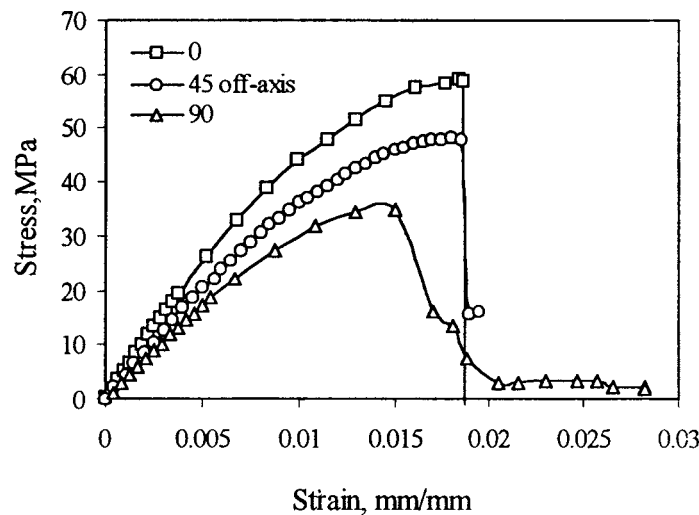


Figure 4. Typical stress-strain curves of single layer GF/Epoxy KFCs.

Table I. Tensile properties of single layer GF/Epoxy KFC.

	0° direction	45° direction	90° direction
Ultimate strength, MPa	59.1	41.3	34.9
Young's modulus, GPa	4.85	4.44	3.63
Failure strain, %	2.2	1.9	1.6

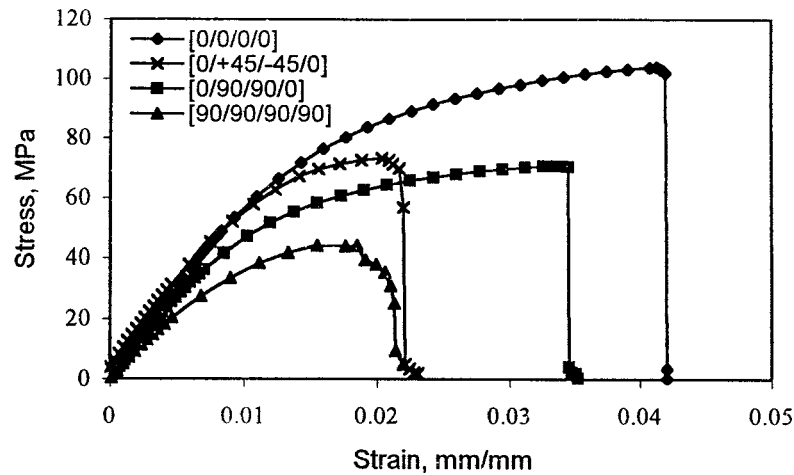


Figure 5. Typical stress-strain curves of multilayer KFC laminates with different stacking configurations.

stiffness with respect to a particular loading direction is quite obvious. Figure 5 shows typical tensile stress versus tensile strain curves of the multilayer KFCs with different stacking sequences. Both the stress-strain curves of single layer and multilayer KFCs exhibit a linear behaviour at the initial stage of load and then go to nonlinear. Grossly, the nonlinear region of the single layer KFC is relatively limited. However, the multilayer KFC exhibits a trend of more ductile characteristic. For the stacking structures of $[0^\circ]_4$ and $[0^\circ/90^\circ/90^\circ/0^\circ]$, the ductile features are quite apparent, as shown in Figure 5. These results indicate that a progressive failure process might have occurred in the laminates. Comparing the tensile stress-strain curve of the $[0^\circ]_4$ composite with that of the single layer composite loaded in the wale direction, it might be concluded that a damage evolution is more serious in a multilayer than in a single layer knitted fabric composite. The ultimate strains of the laminates with different stacking arrangements are graphed in Figure 6.

Figure 7 shows the changes in ultimate tensile strength of the four multilayer KFC laminates, giving a similar variation trend as that of the single layer KFC materials. The strength of the $[0^\circ]_4$ structure is higher than those of all the other stacking structures. For the structures of $[0^\circ]_4$, $[0^\circ/+45^\circ/-45^\circ/0^\circ]$ and $[0^\circ/90^\circ/90^\circ/0^\circ]$, their tensile strengths decrease gradually with the increase of inclined angles of the inside layers. However, the change is not apparent between the $[0^\circ/+45^\circ/-45^\circ/0^\circ]$ and $[0^\circ/90^\circ/90^\circ/0^\circ]$ laminates. In general, the strength of a KFC is proportional to the portion of fibers oriented in the loading direction; the wale (0°) direction specimen exhibits the highest strength when loaded in the wale direction. It is inferred that a variation in the loop architecture of knitted fabrics can also influence the sensitivity of the laminate tensile strength on stacking angles.

Figure 8 shows the stiffness of the multilayer KFC versus different stacking configurations. It was found that an approximately linear relationship exists between

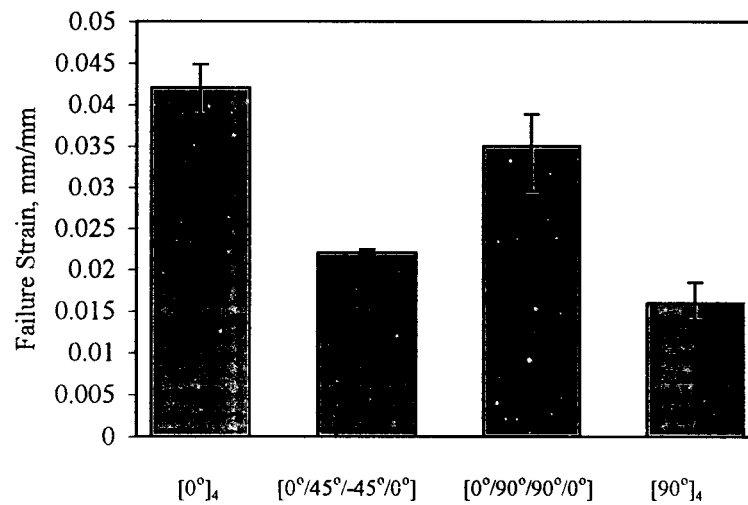


Figure 6. Comparison on failure strain of multilayer KFC laminates.

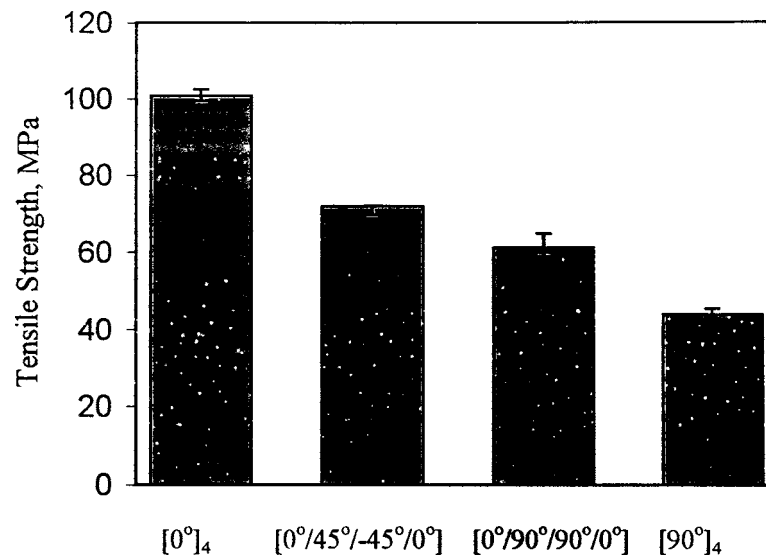


Figure 7. Comparison on the ultimate tensile strengths of KFC laminates with different stacking configurations.

the tensile modulus and the stacking configuration. Based on these experimental evidences, it is possible to choose a stacking sequence so that an optimal strength and stiffness behavior can be achieved for the resulting multilayer knitted fabric composite when subjected to differently combined load conditions.

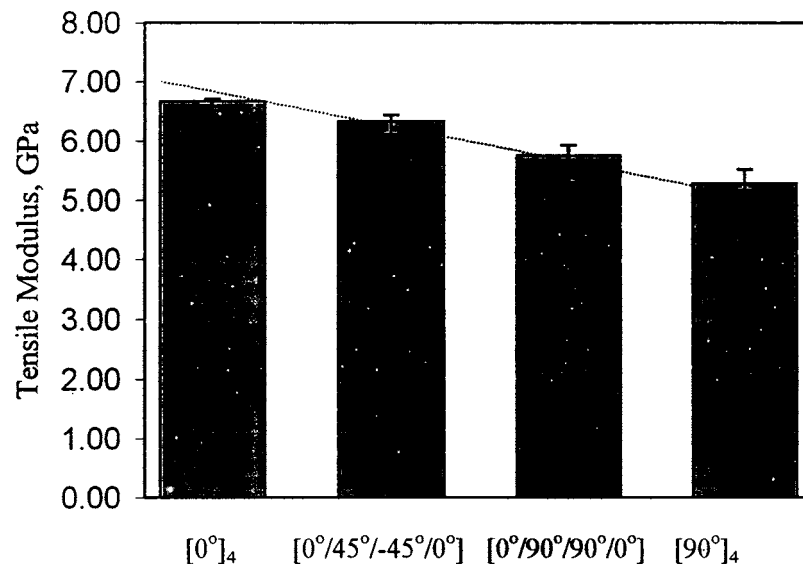


Figure 8. Comparison on the tensile modulus of KFC laminates with different stacking configurations.

3.2. POST-FAILURE ANALYSIS

3.2.1. Overall Failure Behavior

Ramakrishna investigated the failure mechanism of single layer knitted glass fiber fabric reinforced epoxy composites in a previous work [18]. Matrix cracking, interface debonding, and fiber breaking were the main forms of a composite failure. These failure forms also occurred in the present multilayer knitted fabric reinforced laminates. Figure 9 shows the SEM photographs of the surface of a failed multilayer knitted fabric laminate. The fiber breaking is distinct in Figure 9(a), whereas the interface debonding between fiber yarns and surrounding matrix is indicated in Figure 9(b). Furthermore, the smooth surface surrounding the fibre yarns in Figure 9(b) suggests that the matrix cracking already happened there.

3.2.2. Fracture Mode of Inside Layers

For single ply composites, with the change in the load direction with respect to the fabric wale direction, the fractured surfaces occurred in different parts of the fabric, as shown in Figure 10. When the load direction is parallel to the wale direction, the fracture usually takes place over the head of loops or along the fabric side loops (referring to Figures 11(a) and 11(b)). When the load direction is perpendicular to the wale direction (i.e., in the course direction), the fracture occurs near the points where yarns cross over each other (Figure 10(c)). A similar fracture mode as that of a course direction loaded specimen has also been found for the 45° off-axial loaded specimen (Figure 10(b)). Under the off-axial load, it was found that

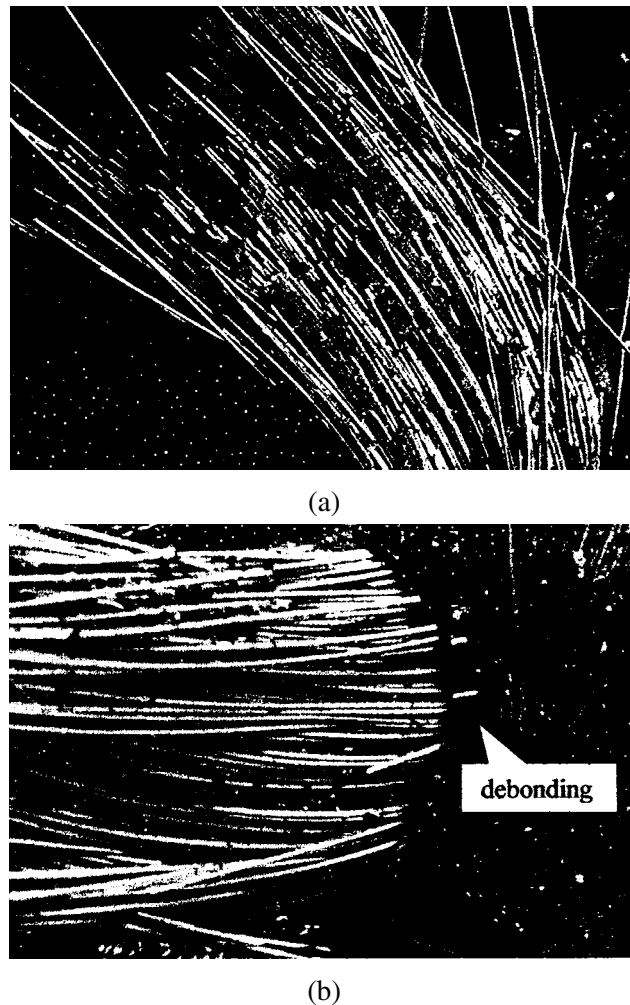


Figure 9. SEM photographs of a failed multilayer KFC.

the angle between the fractured surface and the load direction was the same as the off-axis angle, i.e., 45° . Thus, both the course directional loaded specimen and the 45° off-axial loaded specimen fractured along the needle loops of the fabric (Figure 11(c)). These results are consistent with previous investigations [3, 19–21].

On the other hand, only the fracture modes of the outside layers of a broken multilayer laminate specimen can be observed. It is generally difficult to know detail of the fracture behaviors of those lamina layers inside the laminate. Figure 12 shows the photograph of a fractured multilayer knitted fabric laminate under uni-axial tensile load. Although the matrix used was somewhat transparent, it is still difficult to depict the failure mode of a fabric layer inside the laminate. However, information of the fracture details of all the laminae in the laminate is important for

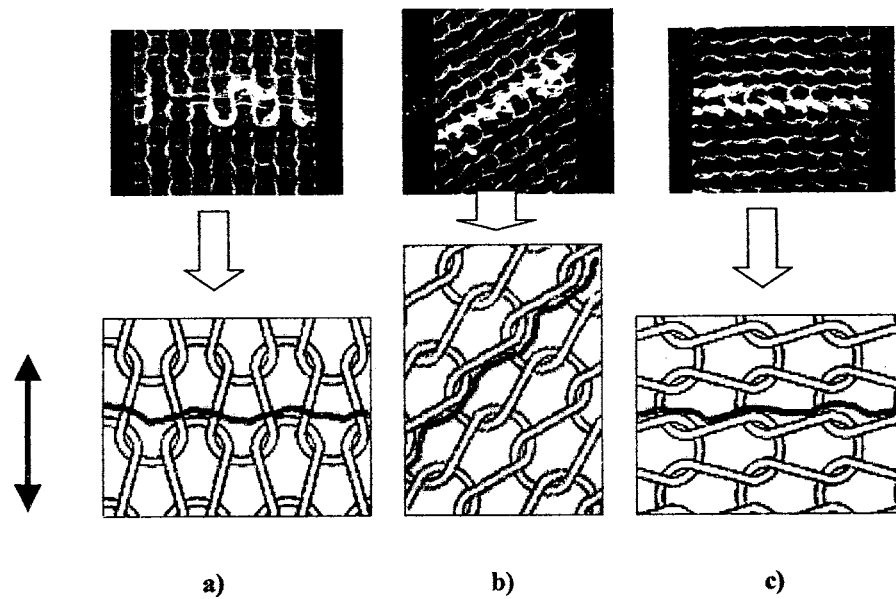


Figure 10. Characteristic Fracture Status of single layer KFC: (a) 0° loading; (b) 45° loading; (c) 90° loading.

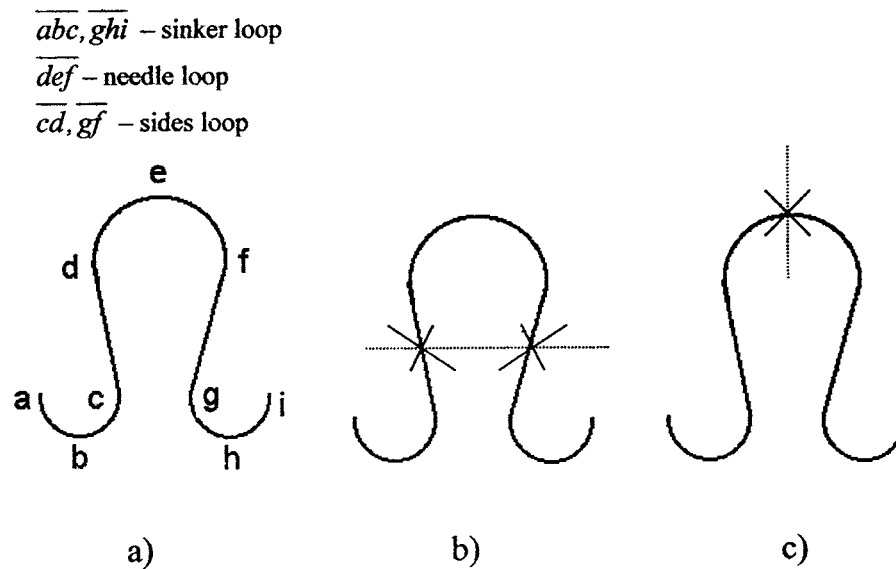


Figure 11. Schematic diagram of basic loop components and fracture types: (a) Loop components; (b) Fracture mode for 0° loading; (c) Fracture mode for 90° and 45° off-axis loading.

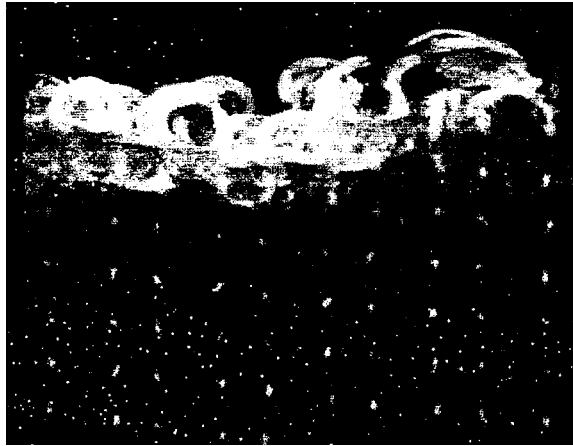


Figure 12. A photograph of a fractured multiplayer KFC.

the whole laminate failure analysis. It was recognized in this study that the matrix digestion by means of a combustion method is very efficient to achieve the desired purpose. It was found that after burning the broken specimen in a furnace using a specially designed procedure, the fracture detail of each layer in the laminate could be clearly shown. For the present GF/Epoxy material, the procedure began by putting the specimen in a 300°C furnace for 1 h, followed by 500°C holding for another 1 h. After cooling down at an ambient condition to room temperature, the multilayer laminate specimen was safely separated into distinct single layer fabrics. All the single layer fabrics could be peeled off and their fracture characteristics could be observed.

Figure 13 through Figure 15 show the photographs of all the fabric layers decomposed from the fractured laminates with different stacking sequence. It is seen that the fracture form of each fabric layer decomposed from $[0^\circ]_4$, $[0^\circ/90^\circ/90^\circ/0^\circ]$ or $[90^\circ]_4$ laminate specimens is the same as that of a corresponding single layer KFC under uniaxial tensile load. However, after digestion for the $[0^\circ/+45^\circ/-45^\circ/0^\circ]$ specimen, it was found that the fractured surfaces of the $+45^\circ$ and -45° plied fabric laminae did not have a 45° inclined angle with the loading direction. Instead, the fractured surfaces are nearly perpendicular to the loading direction. This is different from the fracture form of the single layer knitted fabric composite subjected to the 45° off axial tensile load. Therefore, an angle-plyed lamina in the laminate is generally subjected to a more complicated load combination even though the whole laminate is under a uniaxial load condition.

3.2.3. Load share of Angle-Plyed Lamina

The matrix digestion and layer peeling method can be further used to determine the load direction sustained by an angle-plyed lamina in the laminate. This is achieved

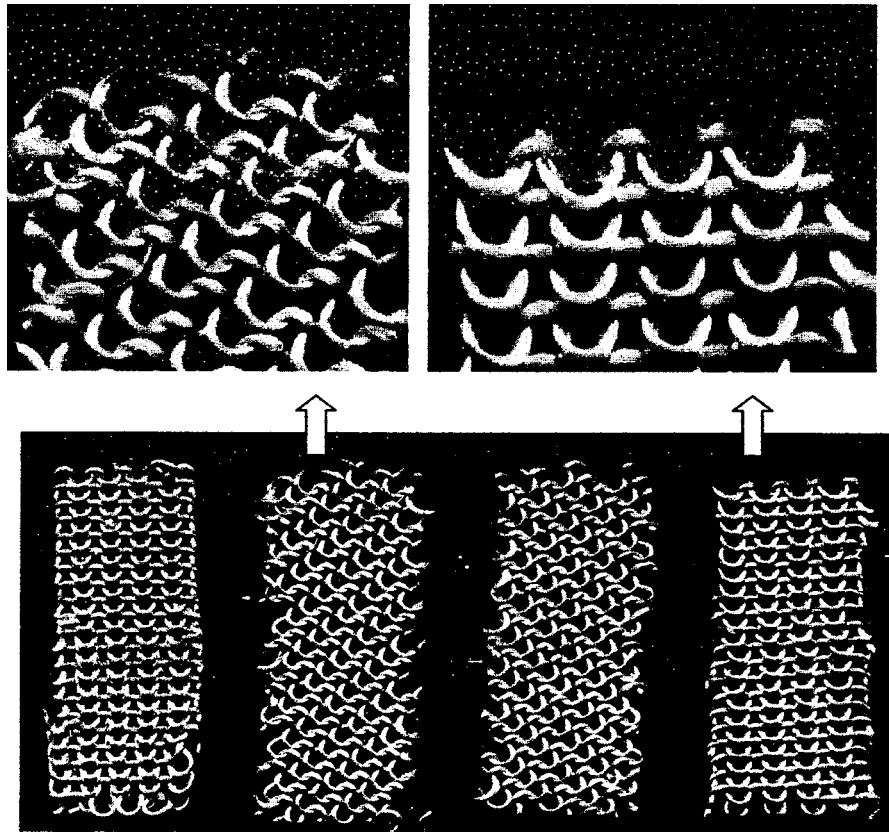


Figure 13. Fracture modes of fabric layers in $[0^\circ/\pm 45^\circ/0^\circ]$ laminate.

again by comparing the fracture mode of the angle-ply lamina with that of the single layer composite. Details are described as follows.

When a single layer composite is subjected to an off-axial tensile load (Figure 16(a)), the resultant stress on an angle inclined surface is equal to the overall applied stress, as indicated in Figure 17(a). The two stress components on the surface, i.e., the stresses in perpendicular and parallel to the surface, are given respectively by

$$\sigma_\alpha = \sigma \cos^2 \alpha, \quad (1)$$

$$\tau_\alpha = \frac{\sigma}{2} \sin 2\alpha, \quad (2)$$

where α is the angle of the inclined surface and σ is the applied external stress. On the other hand, the angle-ply lamina in the laminate is generally subjected to combined normal and in-plane shear stresses, as shown in Figure 16(b) and Figure 16(c). If the overall applied stress on the laminate is a tensile load, then the normal stress sustained by the lamina should be tensile. However, the shear load direction is undetermined. Suppose that the shear stress sustained by the lamina

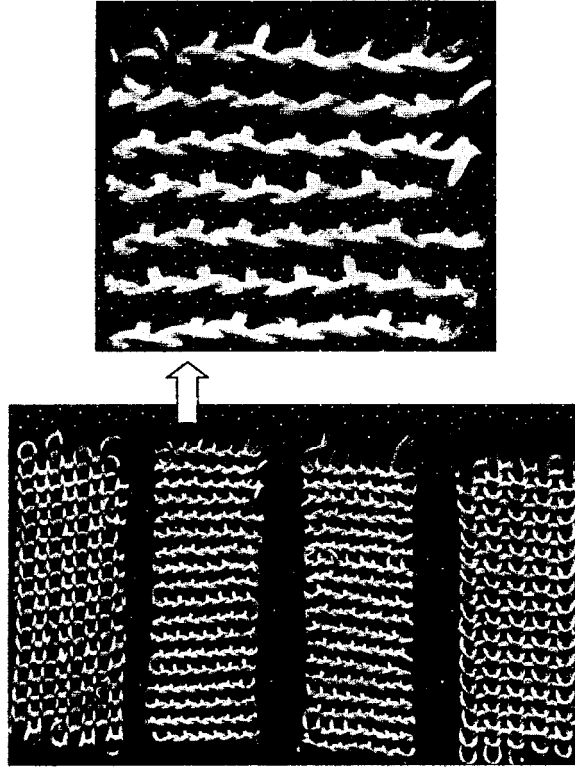


Figure 14. Fracture modes of fabric layers in $[0^\circ/90^\circ/90^\circ/0^\circ]$ laminate.

has an assumed direction as shown in Figure 16(c). Then, the normal and the shear stress components on a similar inclined surface are derived as

$$\sigma'_\alpha = \sigma \cos^2 \alpha + \tau (\sin \alpha + \cos \alpha), \quad (3)$$

$$\tau'_\alpha = \frac{\sigma}{2} \sin 2\alpha + \tau (\sin \alpha - \cos \alpha). \quad (4)$$

In the case of $\alpha = 45^\circ$, the single layer composite fractured along the inclined surface. As the shear strength of a composite is generally higher than its tensile strength, Equations (1) and (2) imply that the failure of the single layer composite subjected to the uniaxial tensile load is mainly caused by the normal (tensile) stress component on the inclined surface. On the other hand, the experiment has shown that the fracture of the $\pm 45^\circ$ plied laminae in the $[0^\circ/+45^\circ/-45^\circ/0^\circ]$ laminate did not occur along a similar inclined surface. Therefore, the resulting normal (tensile) stress component, given by Equation (3), must be smaller than the shear stress component that is given by Equation (4). Thus, the actual shear stress direction should be opposite to the assumed direction as indicated in Figure 16(c) and 17(b).

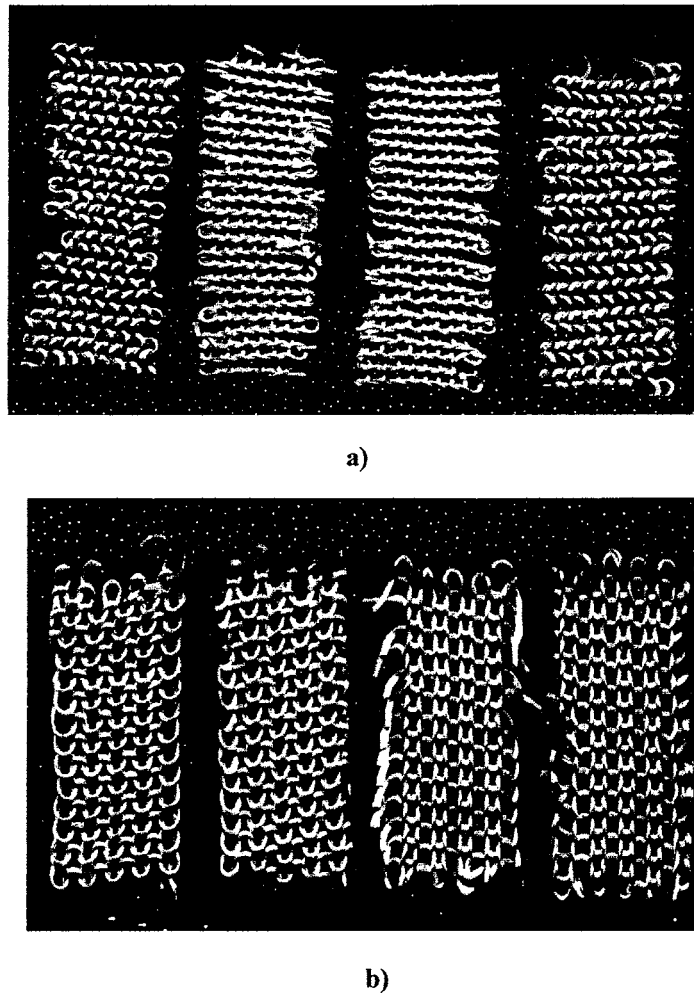


Figure 15. Fracture modes of fabric layers in $[90^\circ]_4$ (a) and $[0^\circ]_4$ (b) laminates.

4. Conclusions

An experimental program has been carried out in this paper to characterize the tensile behaviors of multilayer knitted fabric reinforced epoxy laminates under uniaxial tensile load. The tensile moduli and ultimate strengths of the laminates vary with different lay-up configurations. Due to stacking constraint, a progressive failure process generally occurs in the laminate, which makes the multilayer laminate more ductile than a corresponding single layer composite. The fracture mode of each lamina layer in the laminate can be clearly identified based on a “matrix digestion and layer peeling” method. It is found that an angle-plyed lamina in the laminate subjected to uniaxial tensile load has a different fracture mode than that of a single layer composite under an off-axial tensile load. A more complicated load

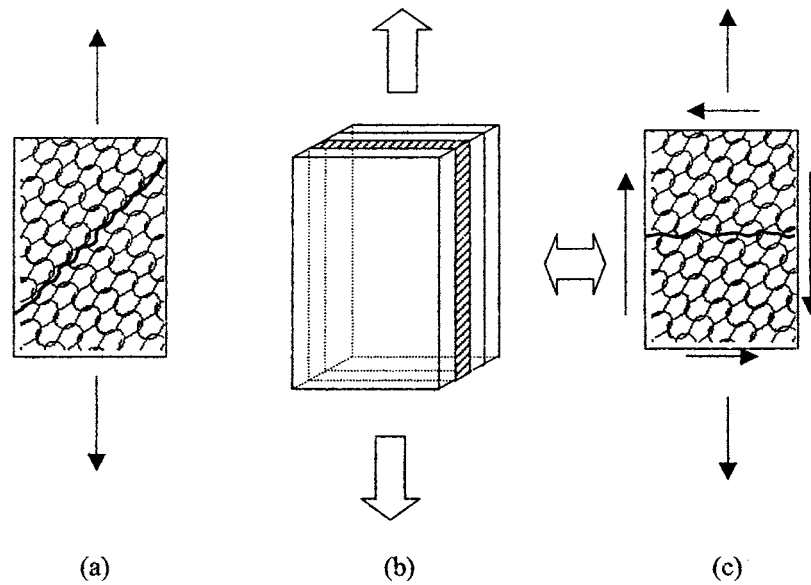


Figure 16. A schematic diagram of (a) single layer KFC under 45° off-axis tensile load; (b) multilayer $[0^\circ/\pm 45^\circ/0^\circ]$ laminate under uniaxial tensile load; and (c) load sharing of 45° angle-ply lamina in the $[0^\circ/\pm 45^\circ/0^\circ]$ laminate.

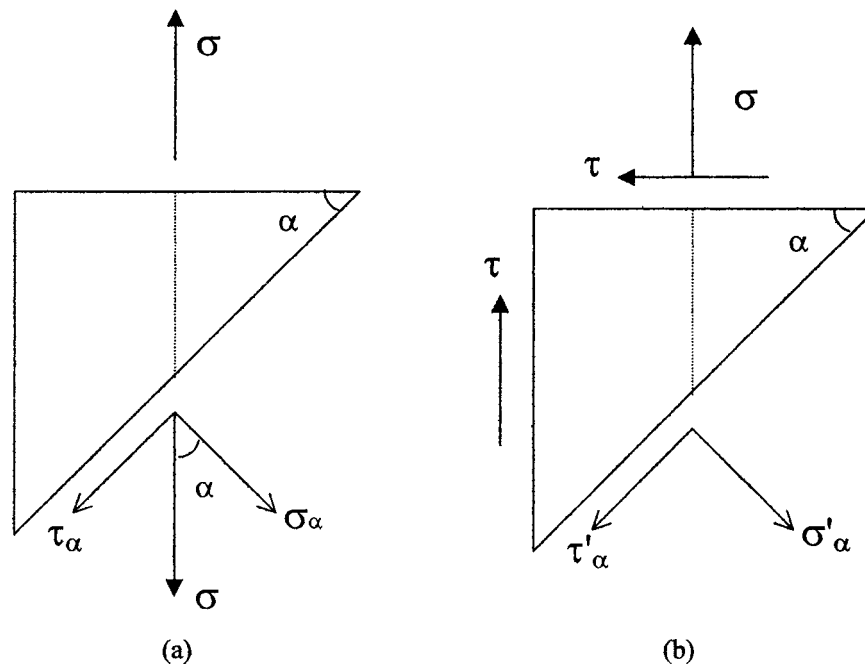


Figure 17. Stress analysis of an isolated element from (a) single layer KFC under 45° off-axis load; (b) 45° angle-ply lamina in $[0^\circ/\pm 45^\circ/0^\circ]$ laminate under uniaxial load.

combination must have been applied to the angle-ply lamina, and the determination of the resulting load direction is described in the paper. Such information may be useful for laminate failure analysis. It is expected that the “matrix digestion and layer peeling” method can be equally well applied to other kinds of fibrous composite laminates.

References

1. Chou, T. W., *Textile Structure Composites (Composite Materials Series, Vol. 3)*, Elsevier, Amsterdam, 1989.
2. Ko, F. K., Van Vuure, A. W., and Balonis, R. J., ‘Textile Preforming for Complex Shape Structural Composites’, *SAMPE Journal* **35**(3), 1999.
3. Ramakrishna, S., ‘Characterization and Modeling of the Tensile Properties of Plain Weft-knit Fabric-reinforced Composites’, *Composite Science and Technology* **57**, 1997, 1–22.
4. Leong, K. H., Ramakrishna, S., Bibo G. A., and Huang, Z. M., ‘The Potential of Knitting for Engineering Composites – a Review’, *Composites A* **31**(3), 2000, pp. 197–220.
5. Gommers, B., Verpoest I., and Van Houtte, P., ‘Modeling the Elastic Properties of Knitted-fabric-reinforced Composites’, *Composite Science and Technology* **56**, 1996, 685–694.
6. Epstein, M. and Nunni, S., ‘Near Net Shape Knitting of Fibre Glass and Carbon for Composites’, in *36th International SAMPE Symposium*, 1991, p. 102.
7. Ramakrishna S. and Hull, D., ‘Energy Absorption Capacity of Epoxy Composite Tubes with Knitted Carbon Fiber Fabric Reinforcement’, *Composite Science and Technology* **49**, 1993, 349–356.
8. Ramakrishna, S., Hamada, H., Rydin, R., and Chou, T. W., ‘Impact Damage Resistance of Knitted Glass Fiber Fabric Reinforced Polypropylene Composite Laminates’, *Science and Engineering of Composite Materials* **4**(2), 1995, 61–72.
9. Huang, Z.-M., Ramakrishna, S., et al., ‘Characterization of a Knitted Fabric Reinforced Elastomer Composites’, *Journal of Reinforced Plastics and Composites* **18**(2), 1999, 118–137.
10. Khondker, O. A., Leong K. H., and Herszberg, I., ‘An Investigation of the Structure-property Relationship of Knitted Composites’, *Journal of Composite Materials* **35**(6), 2001, p. 489.
11. Ramakrishna S. and Hull, D., ‘Tensile Behaviour of Knitted Carbon-fibre-fabric/Epoxy Laminates – Part I: Experimental’, *Composite Science and Technology* **50**, 1994, 237–247.
12. Kelay, M. S., Bader, D. L., and Reed, P. E., ‘Mechanical Deformation Mechanisms in Knitted Fabric Composites’, *Journal of Thermoplastic Composite Materials* **10**(1), 1997, 76–84.
13. Rudd, C. D., Owen, M. J., and Middleton, V., ‘Mechanical Properties of Weft Knit Glass Fiber/Polyester Laminates’, *Composite Science and Technology* **39**, 1990, 261–277.
14. De Haan, J. and Peijs, T., ‘Mechanical Properties of Flexible Knitted Composites’, *Advanced Composites Letters* **5**(1), 1996, 9–13.
15. Chou, S. and Wu, C. J., ‘A Study of the Physical Properties of Epoxy Resin Composites Reinforced with Knitted Glass Fiber Fabrics’, *Journal of Reinforced Plastics and Composites* **2**, 1992, 1239–1250.
16. Verpoest, I. and Dendauw, J., ‘Mechanical Properties of Knitted Glass Fibre/Epoxy Resin Laminates’, in *Proceedings of ECCM-5, Bordeaux*, 1992, pp. 927–932.
17. Gommers, B., Wang, T. K., and Verpoest, I., ‘Mechanical Properties of Warp Knitted Fabric Reinforced Composites’, in *Proceedings of the 40th International SAMPE Symposium*, Anaheim, California, 1995, pp. 966–976.
18. Ramakrishna, S., ‘Tensile Failure Mechanisms of Knitted Glass Fibre Fabric Reinforced Epoxy Composites’, in *Proceedings of the 4th International SAMPE Sym.*, 1995, pp. 661–666.
19. Xiaoping Ruan and Tsu-Wei Chou, ‘Failure Behavior of Knitted Fabric Composites’, *Journal of Composite Materials* **32**(3), 1998, 198–222.

20. Lim, C. T., Ong, L. B., Huang, Z. M., and Ramakrishna, S., 'Effects of Anisotropy on the Mechanical Performance of Knitted Fabric Reinforced Thermoplastic (KFRT) Composites', in *6th International Conference on Composites Engineering*, Orlando, Florida, 1999, pp. 491–492.
21. Bini, T. B., Ramakrishna, S., Huang, Z. M., and Lim, C. T., 'Further Studies on the Tensile Behaviour of Knitted Fabric Composites', in *Proceedings of the 6th Japan International SAMPE Symposium*, Tokyo, 1999, pp. 513–516.