Effect of PEK Content on Fracture Toughness of Glass Woven Fabric / Phenolic Resin Composites

Y.Q. Sun[1,2], J.H. Li,[2] J.B. Wang, [2] S.R. Zheng[3] and M.L. Sun[3]

[1]Laboratory for Nonlinear Mechanics of Continuous Media, Institute of Mechanics, Chinese Academy of Sciences, Beijing, 100080, China
[2]Northwest Institute of textile Science & Technology, Xi'an, 710048, China
[3]Northwestern Polytechnical University, Xi'an, 710072, China

SUMMARY: Mode I interlaminar fracture toughness tests were performed with glass satin woven fabric phenolic resin composite materials. The composite panels were fabricated with the phenolic resin containing different amount of polyetherketone (PEK) to investigate the influence of PEK content on the fracture toughness. The results show: the fracture toughness has remarkably improved by increasing the content of PEK while the tensile properties have not considerably changed. For the panel whose matrix contained 40% PEK, its G_{IC} value measured here is 1.209 KJ / m^2, which is more than 4 times of that of the panel without PEK. The scanning electron microscope (SEM) observation of fracture surfaces indicated that increasing the content of PEK to 40% not only evidently improved the fiber / matrix interfacial quality, but also toughened the matrix and changed the failure mechanism of the matrix from the brittle into the ductile.

KEYWORDS: woven fabric composites, interlaminar fracture, mode I fracture toughness, PEK, toughening mechanism, fractographic observation

INTRODUCTION

Textile composite materials have many advantages over their prepreg tap counterparts, such as favourable mechanical properties [1,2], ease of handling, low fabrication cost [3,4], etc. Therefore, they become more popular, and are being widely used in advanced structures in aerospace, automobile and marine industries [1], and have attracted more and more attentions of investigators [3-8]. It is well known that the interlaminar fracture behavior is one of the important characteristics related to the overall performance of composite system. A lot of efforts have been made to improve the fracture toughness of woven fabric composites [8-12]. Some of them directed at weave structure, and the others concentrated on material systems. Among the later, one way to improve the fracture toughness is focused on improve the fracture toughness of the matrix by using toughened thermoset resin system or thermoplastics matrix. However, an increase in resin toughness tends to decrease the tensile properties and thermal properties.

In this work, the blend resin containing both thermoset and the thermoplastics was used as matrix. The objective is to study the influence of the content of the thermoplastics PEK on the mode I interlaminar fracture toughness of the woven fabric composites and the toughening mechanism involved.

EXPERIMENTAL DETAILS

Materials

The materials used in this study were glass woven fabric reinforced phenolic resin composites. Four-harness E-glass satin woven fabric was used as the reinforcement, as shown in Fig.1. The matrix material was phenolic resin modified with a cashew nutshell liquid.

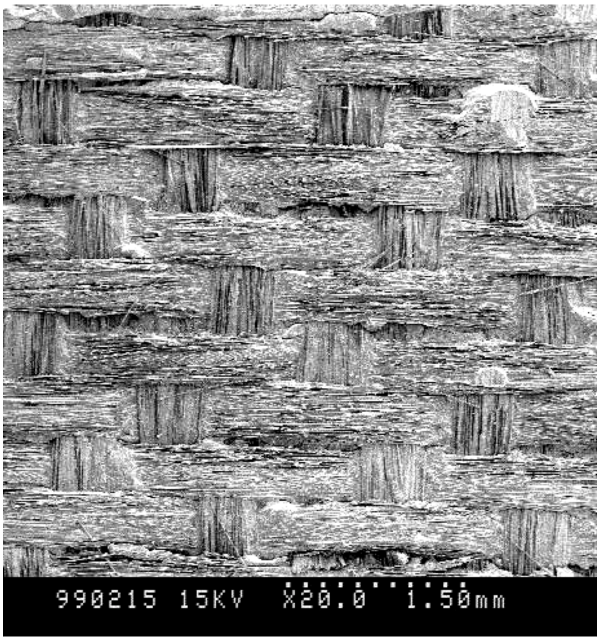


Fig.1 SEM micrograph showing the weave structure of four harness glass fabric

In order to improve the fracture toughness of phenolic matrix composite, a thermoplastic resin polyetherstone (PEK) was added into the modified phenolic (PF) resin. The weight ratios of PEK and PF are 0.15:0.85 and 0.40:0.60 respectively for the two composite panels.

Two glass fabric reinforced PF and PEK blend resin panels were prepared with a $[0^o / 90^o]_{10}$ lag-up. A 25 mm thick Tefl film was inserted at the mid-plane during the laying-up to serve as the crack starter. The panels were mold using a hot press.

Fracture specimens

The double cantilever beam (DCB) specimens were used to measure the Mode I interlaminar fracture toughness G_{IC}. The DCB specimens (150 mm long, 25 mm wide and 2mm thick) were cut from the panels using a sand wheel cutter with water cooling. Then, they were left in an oven overnight and dried. The edges of the specimens were polished and coated with correction fluid and the crack tips were marked along the edges of specimens.

Fracture Toughness Tests

Mode I interlaminar fracture toughness tests were performed in a Instron universal testing machine with a displacement rate 0.5 mm/mm^{-1}. Crack length increment was marked on the load-displacement curve for every 0.5mm of crack growth. The Mode I interlaminar fracture toughness – the critical energy release rate for the DCB tests can be calculated through

$$G_{IC}= \frac{3P_c d_c}{2\,B\ a} \qquad (1)$$

where P_c is the critical load, d_c the corresponding critical displacement, B is the specimen width and a the crack length.

SEM Fractographic Observation

Fractographic Observation and analysis of the Mode I fracture surface of the satin woven fabric composites were conducted by SEM. The fracture surfaces of tested specimens were sputter coated with gold, then observed in a HITACHI S-570 scanning electron microscope with image acquisition and processing system at a accelerating voltage of 10 KV and the morphology recorded as micrographs.

RESULTS AND DISCUSSION

Fracture Toughness

In order to explore the influence of PEK content on the fracture toughness of thermosetting matrix composite the critical strain energy release rates G_{IC} were measured with the glass fabric phenolic resin composites containing different content of PEK. The results calculated from the data of the Mode I tests are listed in the Table 1. To make comparison with tensile properties, Table 1 also presents their tensile strength values measured in this work. The results show: the interlaminar fracture toughness had been remarkably improved by adding the thermoplastic PEK resin into the thermosetting phenolic matrix, while their tensile strength did not deteriote. Moreover, with increasing the PEK content from 15% to 40%, the G_{Ic} value increased to 1.209 KJ/m^2, which is more than twice of the G_{Ic} of the panel containing 15% PEK, and more than four times of that of the panel without PEK, whereas the tensile strength of panel 2 still maintained in the high level.

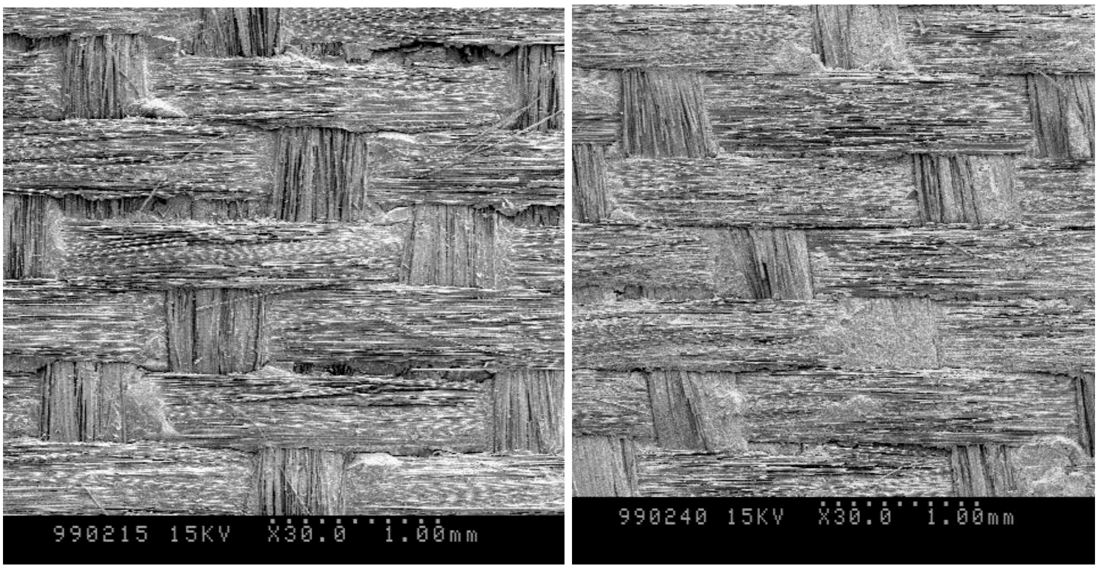
Table 1 The mechanical properties values of the panels with different content of PEK

Panel code	Content of PEK In matrix %	Mode I fracture toughness G_{IC} KJ/m^2	Tensile strength σ_b Mpa
	0	0.267	284
1	15	0.476	286
2	40	1.209	297

It is very encouraging to have remarkably increased the fracture toughness of a material without sacrificing its tensile properties. The toughening method used here has a great potential in the practical applications. The toughening mechanisms involved need to be investigated.

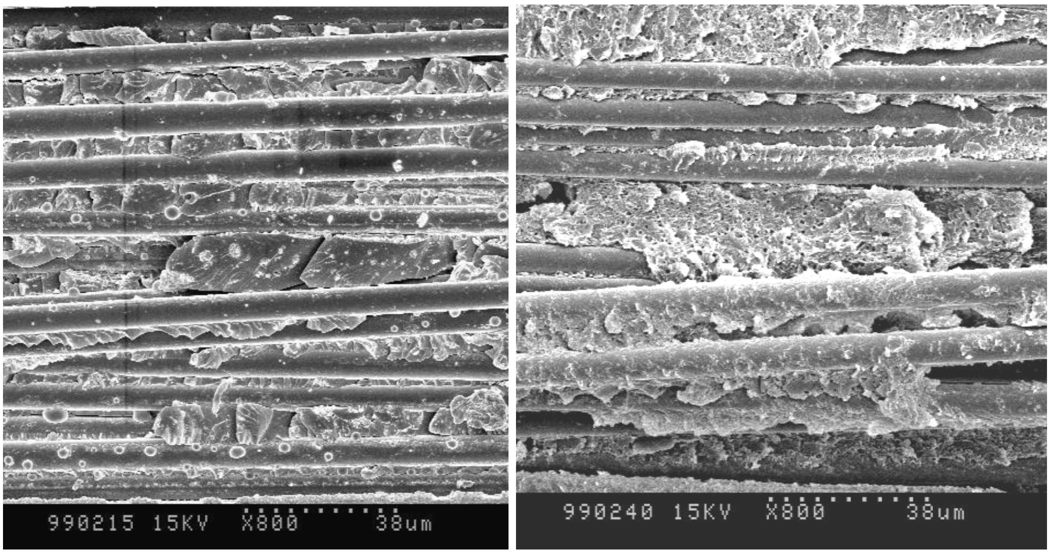
Fractographic Observation

The fracture surfaces of the Mode I specimens were investigated by using SEM. The SEM micrographs in Fig. 2 through Fig. 8 illustrate the meso- or microstructural details of the fracture surfaces of two different materials. The low magnification photos in Fig.2 show the overall mesoappearance of fracture surface.



(a) (b)

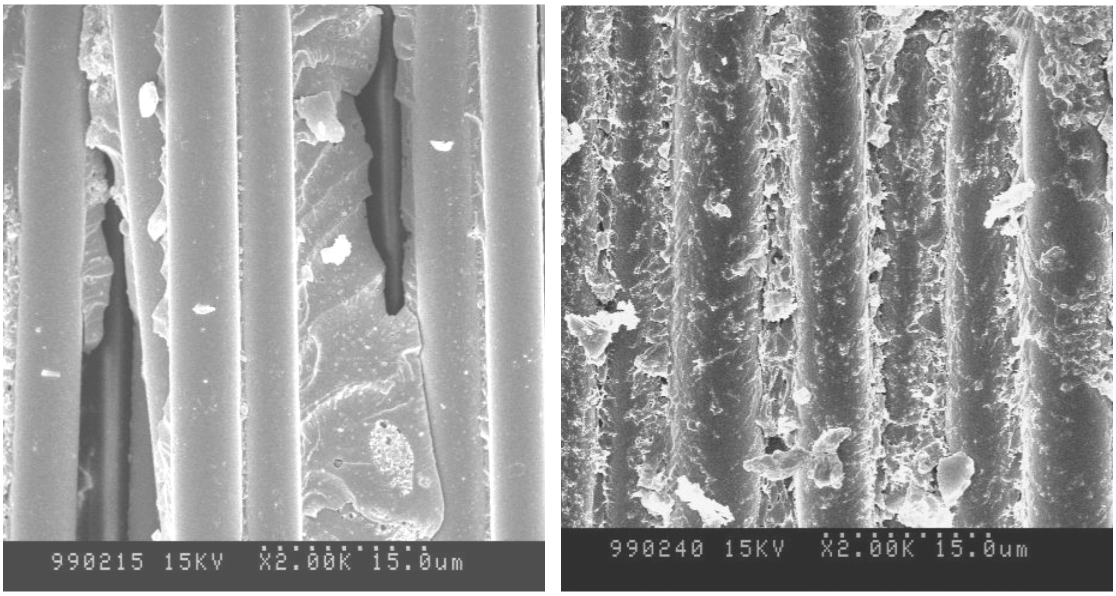
Fig.2 SEM micrographs showing the overall mesoappearance of fracture surfaces.
(a) panel 1, (b) panel 2



(a) (b)

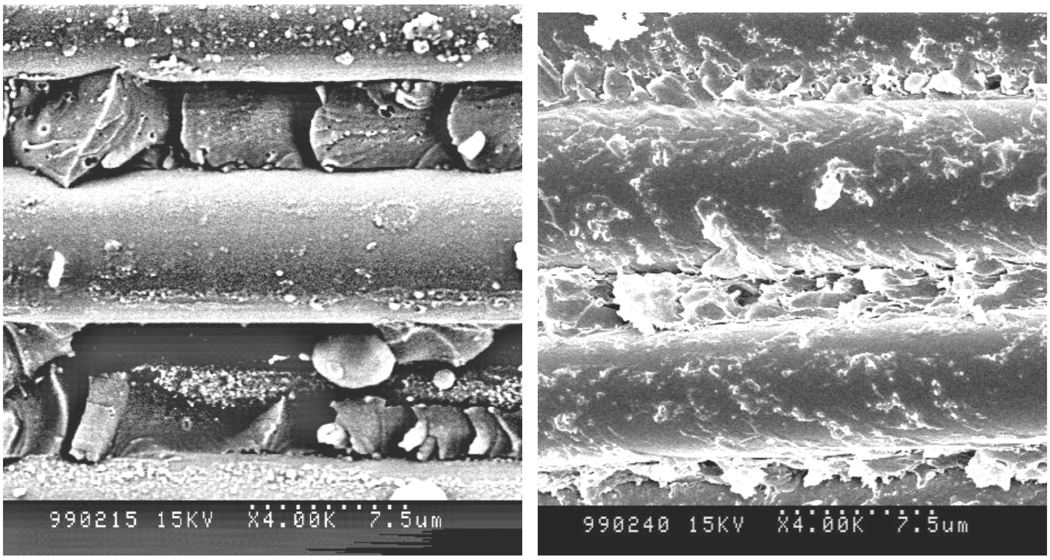
Fig.3 SEM micrographs showing the microstructure of fracture surface.
(a) panel 1, (b) panel 2

The photo (b) corresponding to the panel 2 containing 40% PEK in matrix appears brighter color than photo (a) corresponding the panel 1 containing 15% PEK, which indicates that there is more resin remained on the fracture surface of specimen cut from panel 2.



(a) (b)

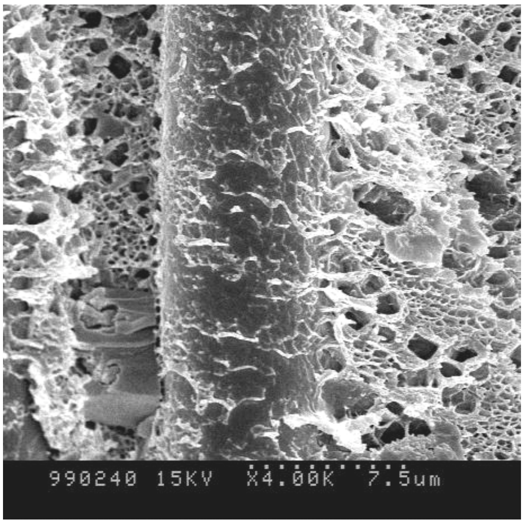
Fig.4 SEM micrographs showing the microstructure of fracture surface.
(a) panel 1, (b) panel 2



(a) (b)

Fig.5 SEM micrographs showing the adhesion quality of interface between the fiber and matrix. (a) panel 1, (b) panel 2

From the SEM micrographs with higher magnification in Fig. 3, Fig. 4 and Fig. 5, it can be easily seen that there exist evident differences in microstructural details between the fracture surfaces of the two materials. For the panel 1, the clean fiber – bare fiber or the fiber with less matrix on it, was observed on most fiber concentrated area, indicating a poor adhesion between glass fiber and matrix. This poor interfacial property might have contributed to the lower G_{IC}. The pure matrix block in resin rich zones between fibers and in matrix pockets where the warp and weft yarn meet failed in a brittle manner without significant matrix deformation. On the contrary, SEM micrographs in Fig. 3 (b), Fig. 4 (b) and Fig. 5 (b) which correspond to the specimen of panel 2 exhibit that the most fibers on fracture surface are covered by matrix resin, and the adhesion between fiber and matrix is much better, and the matrix between fibers failed in a ductile mode.



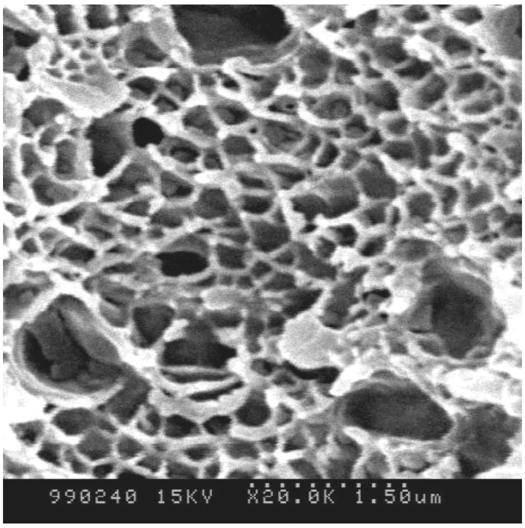


Fig. 6 SEM micrography showing net structure on the fiber surface of fracture surface of panel 2

Fig.7 SEM micrography showing cubic net structure on a resin rich zone between fibers

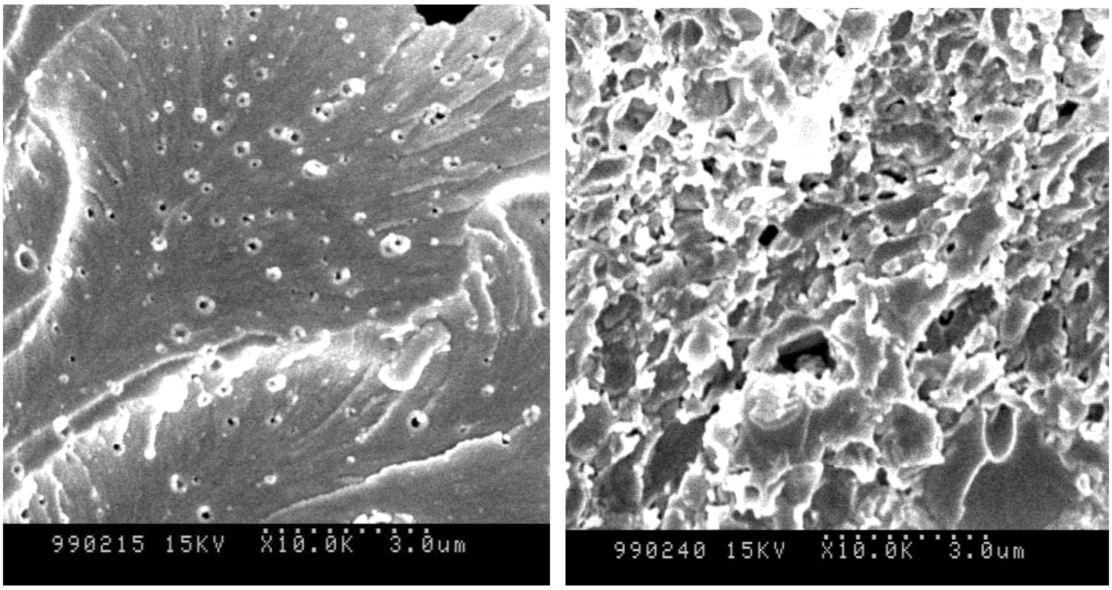
Furthermore, a cubic netlike microstructure was observed extending continually cross a resin rich zone and fiber in the fracture surface of specimen having a higher G_{IC} as show in Fig. 6 and Fig. 7.

Toughening Effect of PEK

Woven fabric composite is made up of three basic components: the resin impregnated fill strand and warp strand and pure matrix block [8]. The interlaminar fracture occurs in the material through debonding of fiber and resin in the fill strand and warp strand area, and matrix in the pure matrix blocks which include the matrix pocket and the resin rich zone between the compact fiber bundles. Therefore, the factors contributing to increasing the resistance to a crack propagation through interfacial debonding or matrix failure are considered to have toughening effect. The total fracture toughness was related quantitatively to the failure mechanisms observed on the fracture surface [10]. SEM observation conducted in current investigation found that the interfacial debonding and matrix cracking are major failure mechanisms.

Mode I interlaminar fracture toughness for the satin woven fabric composites greatly depended on both the interfacial properties and weave structures [10]. Increasing the PEK content to 40% in this study greatly improved the adhesion strength between fiber and matrix, and increased the amount of energy consumed to separate the glass fiber and resin, which result in the higher G_{IC} value.

Increasing the content of PEK not only improved the interface properties, but also toughened the phenolic resin and changed its failure mechanism. The fracture mechanism of matrix in resin rich zone had changed from the brittle manner as shown in Fig. 3 (a), Fig. 4 (a) and Fig. 8 (a) into the ductile mode as shown in Fig. 3 (b), Fig. 4 (b) and Fig. 8 (b).



(a) (b)

Fig. 8 SEM micrographs showing the microapprearance of fracture surface of matrix in a resin rich zone. (a) panel 1, (b) panel 2

The ductile failure involving considerable plastic deformation and consumed much more energy.

CONCLUSION

Mode I interlaminar fracture experiments have been carried out with glass satin woven fabric reinforced PEK toughened phenolic resin composites. The microstructure of the fracture surfaces of specimens with different PEK content was examined by using a SEM. The toughening effects of PEK were analyzed. Test results show that increasing the content of PEK has remarkably improved the fracture toughness G_{IC}, whereas the tensile strength of the material not deterioted. SEM observation found that increasing the content of PEK to 40% not only greatly improved the interfacial quality and increased the adhesion strength between fiber and matrix, but also toughened matrix and changed the failure mechanism of the matrix from the brittle into the ductile.

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REFERENCES

1. Tan, P., Tong, L, and Steven, G. P., "Modeling for Predicting the Mechanical Properties of Textile Composites – A Review", *Composites Part A* 28A, 1997, PP. 903-922.

2. Vandeurzen, P., Ivens, J. And Verpoest, I., "Structure Performance Analysis of Two–dementional Woven Fabric Composites", *Proceedings of the Tenth International Conference on Composite Materials,* Whistler, British Columbia, Canada, August 14-18, 1995, Vol. IV, Poursartip, A. And Street, K. N. Eds, PP. 261-268.

3. Vandeurzen, P., Ivens, J. And Verpoest, I. "Micro-stress Analysis of Woven Fabric Composites by Multilevel Decomposition", *Journal of Composite Materials*, Vol. 32 No. 7, 1998, PP. 623-651.

4. Kuhn, J. L. And Charalambides, P.G. "Elastic Response of Porous Matrix Plain Weave Fabric Composites". *Journal of Composite Materials,* Vol. 32, No.16, 1998, PP. 1426-1471.

5. Naik, N.K. and Ganesh, V.K., "Failure Behavior of Woven Composite Laminates", *Journal of Composite Technology Research*, Vol. 16, 1994, PP. 3-20

6. Ito, M. And Chou, T,W., "An Analytical and Experimental Study of Strength and Failure Behavior of Plain Weave Composites" *Journal of Composite Materials*, Vol. 32, No. 1, 1998, PP. 2-30.

7. Sankar, B.V. and Marrey, R.V., "Analytical Method for Micromechanics of Textile Composites", *Composite Science and Technology*, 57, 1997, PP. 703-713.

8. Ganesh, V.K. and Naik, N.K., " Failure Behavior of Plain Weave Fabric Laminates under On-Axis Uniaxial Tensile Loading", *Journal of Composite Materials*, Vol. 30, No. 16, 1996, PP. 17-1856.

9. Svensson, N., Shishoo, R. And Gilchrist, M., "Interlaminar Fracture of Commingled GF / PET Composite Laminates", *Journal of Composite Materials*, Vol. 32, No. 20, 1998, PP. 1808-1835.

10. Kotaki, M. And Hamada, H., "Effect of Interfacial Properties and Weave Structure on Mode I Interlaminar Fracture Behavior of Glass Satin Woven Fabric Composites", *Composites Part A*, 28A, 1997, PP. 257-266.

11. Wang, J.B., Sun, Y.Q., Zheng, S.R. and Jing X.T., "Effect of Fabric Orientation on Fracture Toughness of Glass Fabric / PC Composite", *Proceedings of the Eleventh International Conference on Composite Materials*, Gold Coast, Australia, July 14-18, 1997, Vol. II, PP. 447-452.

12. Lin, Y. And Andrew, B., "Mesostructural Aspects of Interlaminar Fracture in Thermoplastic Composites: Is Crystallinity a Key?", *Composites Science and Technology*, 53, 1995, PP. 167-173.