Influence of maleic-anhydride polypropylene on transverse cracking in glass fibre-reinforced polypropylene cross-ply laminates

Influence of Maleic-Anhydride Polypropylene on Transverse Cracking in Glass Fibre-Reinforced Polypropylene Cross-Ply Laminates

M.J.A. van den Oever and T. Peijs
Centre for Polymers and Composites, Eindhoven University of Technology
5600 MB Eindhoven, The Netherlands

This study investigates the influence of improved adhesion, resulting from maleic-anhydride modification of the polypropylene matrix, on transverse cracking in $0/90_6/0$ glass fibre-reinforced polypropylene laminates. It was shown that the characteristic damage state in cross-ply polypropylene/glass laminates, i.e. the saturation level of transverse cracks, is independent of fibre-matrix adhesion and corresponds very well with a predicted value using a shear-lag analysis.

Introduction

Generally, transverse cracking is the first damage mechanisms to occur in continuous fibre reinforced laminates under both static and fatigue loading conditions. This damage mechanism has received detailed analysis because of its significance for the prediction of mechanical performance of composite structures. For example, it has been shown that transverse (or matrix) cracks change the stress state in the composite and thus, initiate other, more severe types of damage mechanisms such as delaminations and fibre fracture leading to total failure of the structure. Furthermore, transverse cracking can lead to a significant reduction in laminate stiffness.

According to Reifsnider [1] (fatigue) damage in cross-ply laminates develops in two stages. The first stage consists of homogeneous, non-interactive transverse cracking restricted to individual plies. After reaching the saturation level for transverse cracking the second stage is characterized by the tendency of crack interaction and the development of strong interlaminar stresses resulting in delamination. The saturation level for transverse cracks, i.e the so-called characteristic damage state (CDS) occurs at the transition from first to second stage.

The objective of this study was to investigate the effect of improved adhesion on multiple transverse microcracking in glass fibre-reinforced polypropylene cross-ply laminates. The influence of fibre-matrix adhesion on cross-ply cracking has already been studied extensively by Ivens et al. [2,3] for the system carbon/epoxy. In these studies surface treatment of the carbon fibre resulted in a reduction in damage for both monotonic tensile and fatigue loading. In our case, improved adhesion was realized via the addition of maleic-anhydride modified polypropylene (m-PP) to the polypropylene (PP) matrix material [4]. The effect of this matrix modification on cross-ply cracking was evaluated under both monotonic and fatigue loading.

Analysis of Multiple Transverse Cracking

Since the early work of Bailey and coworkers [5] a number of theories have been developed which describe transverse microcracking in cross-ply laminates [6]. In this investigation we will use a shear-lag analysis similar to the one used by Peters [7]. After an initial transverse crack has formed a subsequent crack might be expected in the 90° ply at a location where the stress has reached the undisturbed stress $\sigma_{90,\infty}$. Stress is reintroduced in the failed ply by shear stresses acting on a resin layer at the interface between the cracked ply and the neighbouring 0° plies. According to this analysis the stress distribution, $\sigma_{90,x}$, in the 90° ply is given by:

$$\sigma_{90,x} = \sigma_{90,\infty} \left(1 - e^{-\gamma x} \right) \tag{1}$$

where:

$$\gamma = \sqrt{\frac{G_m}{b} \left(\frac{1}{E_0 \, a_0} + \frac{2}{E_{90} \, a_{90}} \right)} \tag{2}$$

where E_0, E_{90}, G_m and b represent the tensile moduli of the 0° and 90° layers, the matrix shear modulus and the thickness of the resin shear transfer layer, respectively. The parameters a_0 and a_{90} represent the thickness of the 0° ply and 90° ply, respectively. Crack formation proceeds until the spacing between two cracks is insufficient to reach the failure stress of the transverse ply. This spacing is arbitrarily chosen as two times the distance needed to build up 90% of the undisturbed stress. It should be noted that based on such a shear-lag analysis for multiple cracking the saturation level for transverse cracks, i.e. the characteristic damage state, depends on elastic properties only and not on fibre-matrix adhesion, provided that no delamination occurs.

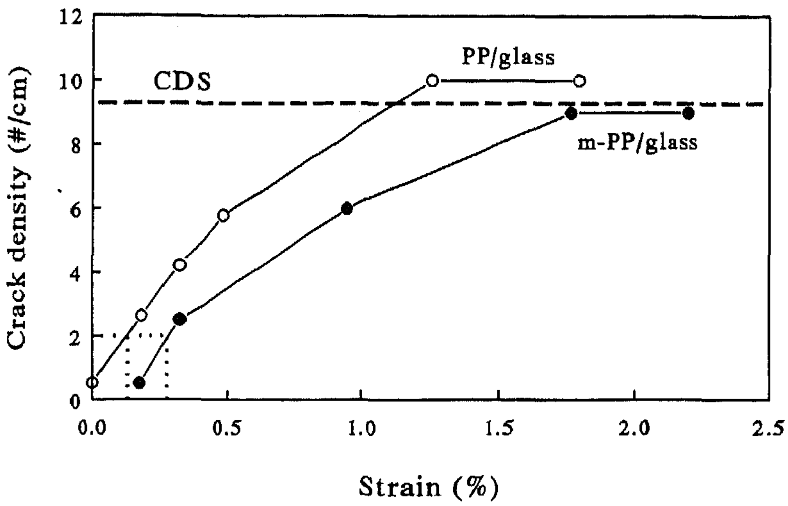
Materials

In this study a continuous E-glass fibre of PPG Industries Fibre Glass BV with a polypropylene compatible sizing (PPG 854-6-S28-1200) and a polypropylene matrix of Shell Chemicals (PP homopolymer VM6100) were used. In order to study the effect of improved fibre-matrix adhesion on cross-ply cracking in PP/glass laminates, 10 wt.% of maleic-anhydride-modified polypropylene (Polybond 3002, BP Chemicals Ltd.) was added to the homopolymer. This blend composition was based on previous research which showed an optimum in mechanical properties for composites based on a blend of 90 wt%. PP-homopolymer (PP) and 10 wt.% maleic-anhydride-modified PP (m-PP) [4]. Cross-ply laminates with a fibre volume fraction of 0.50 were moulded in a two-step process from 0.25 mm thick unidirectional prepregs. These prepregs were manufactured by winding fibres on a rectangular mandrel with alternating layers of polymer film and subsequent hot-pressing at 200°C for 45 min and 25 bar. After hot-pressing the composite plate was slowly cooled. Specimens were cut using a diamond cutting wheel and specimen edges were polished. Aluminium end-tabs were adhesively bonded to the tensile specimens. Test specimens with a free test length of 150 mm had a width of 20 mm and a thickness of 2 mm.

Results and Discussion

Cross-Ply Cracking during Monotonic Tensile Loading

Specimens were loaded monotonically to failure at a strain rate of 5.10^{-4} s^{-1} on a Frank 81565 universal testing machine. An extensometer was used to measure the strain in load direction. Both type of composites, modified as well as unmodified, possessed similar values for ultimate strength (240 MPa) and Young's modulus (13 GPa). Light microscopy directly on the polished specimen edge was used to scan at fixed strain levels the specimen surface over the length of the sample. The number of extended transverse cracks in the specimens as a function of applied strain is plotted in Figure 1. The onset of damage is in fairly good agreement with the first ply failure concept, i.e. the first transverse crack in a composite laminate occurs at the transverse failure strain of a unidirectional laminate. In the case of for example the maleic-anhydride modified system the first transverse crack ccurs at a strain of 0.13%, which is close to the transverse failure strain of 0.14% of a unidirectional glass/m-PP laminate [4]. These observation are in rather good agreement with those of Parvizi et. al. [5] who showed that for relatively thick 90° plies (> 0.5 mm for glass/epoxy) the first ply failure corresponds to the transverse failure strain of a unidirectional laminate.



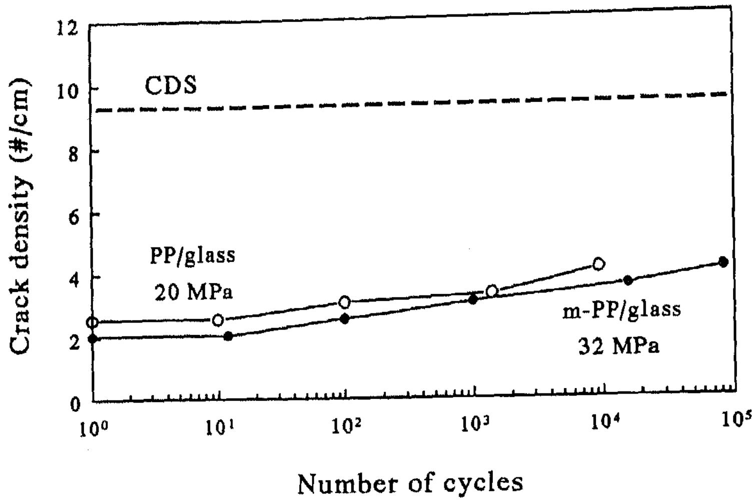
1. Transverse crack density in $[0/90_3]_s$ specimens based on PP (○) and m-PP (•). Drawn line gives CDS as calculated using shear-lag analysis (Equation 1).

Based on the shear-lag analysis the CDS should be similar for composites based on polypropylene (PP) and maleic-anhydride modified polypropylene (m-PP). Experiments show for both composite systems a maximum in crack density of about 9 cracks per cm, indicating that indeed there is no effect of interfacial adhesion on the CDS. However, the CDS is reached earlier for the unmodified system as a result of its lower transverse failure strain, being 0.05% for PP/glass compared to 0.14% for m-PP/glass [4]. Results are in good agreement with the predicted CDS value using the shear-lag analysis. Model parameters E_0 and E_{90} are taken from Ref. 4 (40 and 7 GPa, respectively). Parameters G_m, a_0, a_{90} and b are 0.6 GPa, 0.25 mm, 1.5 mm and 0.01 mm, respectively. The transverse strength of unidirectional laminates is used for the undisturbed stress $\sigma_{90,\infty}$ being 4 and 10 MPa for composites based on PP and m-PP, respectively [4]. The CDS is chosen to be twice the length in which 90% of the undisturbed stress is introduced in the 90° ply, leading to a crack spacing of 1.1 mm, and thus to a crack density of 9 cracks per cm.

Cross-ply cracking during Fatigue Loading

Tension-tension fatigue experiments were performed on a universal testing machine at a frequency of 0.1 Hz and an R ratio ($\sigma_{min}/\sigma_{max}$) of 0.1. In order to study the influence of maleic-anhydride modification on the relative resistance against the formation of transverse cracks in cross-ply laminates, the maximum stress in the fatigue experiments was chosen 20 and 32 MPa for the composites based on PP and m-PP, respectively, which corresponds with 0.15 and 0.25% strain and a crack density for both systems of 2 cracks per cm after one cycle (see Figure 1). Figure 2 shows the number of transverse cracks in $[0/90_3]_s$ laminates accumulated during fatigue loading.

Both composite systems show similar initial crack densities of about 2 cracks per cm and a gradual increase in transverse cracks with number of cycles. However, even after 10.000 cycles, the saturation level or CDS is not reached. Since the slope of the curves in Figure 2 can be regarded as a measure for the relative resistance against fatigue damage it is clear that there is no significant effect of matrix (interface) modification on fatigue damage development for this composite system.



2. *Transverse crack density in* $[0/90_3]_s$ *specimens based on PP (○) and m-PP (•) during tension-tension fatigue.*

Conclusion

The characteristic damage state in cross-ply PP/glass laminates, i.e. the saturation level of transverse cracks, is independent of fibre-matrix adhesion and corresponds very well with a predicted value using a shear-lag theory. Furthermore it can be concluded that improved adhesion, as a result from maleic-anhydride modification of the PP matrix, lead to an increase in the onset of cross-ply cracking, although the relative resistance against fatigue is similar for both the modified and unmodified composites.

References

1. Reifsnider, K.L., Henneke, E.G., Stinchcomb, W.W. and Duke, J.C. in: Mechanics of Composite Materials - Recent Advances, ed. Z. Hashin and C.T. Herakovich (Pergamon Press, New York, 1983) 399.
2. Ivens, J., Wevers, M., Verpoest, I. and De Meester, P. in: Proc. ECCM-3, (Bordeaux, 1989) 465.
3. Ivens, J., Wevers, M. and Verpoest, I. in: Proc. ICCM/9, ed. A. Miravete (Woodhead Publ. Ltd., 1993), Vol. II, 724.
4. Rijsdijk, H.A., Contant, M. and Peijs, A.A.J.M., Comp. Sci. Techn., 48 (1993) 161.
5. Parvizi A., Garrett K.W. and Bailey J.E., J. Mat. Sci., 13, 1978, 195.
6. Nairn, J.A. and Hu, S. in: Damage Mechanics of Composite Materials, ed. R. Talreja (Elsevier Sci. Publ., Barking, UK, 1992).
7. Peters, P.W.M. in: Composite Materials - Fatigue and Fracture, Second Volume, ASTM STP 1012, ed. P.A. Lagace (ASTM, Philadelphia, 1989) 103.