The effect of moisture ingress on mode-I fracture toughness of carbon/epoxy laminates with hybrid toughening using core-shell rubber particles and thermoplastic veils

Sheng Wang[1], Kali Babu Katnam[1a], Zhenmin Zou[1] and Prasad Potluri[2]

[1] Department of Mechanical, Aerospace and Civil Engineering, the University of Manchester, UK

[2] Department of Materials, the University of Manchester, UK

[a] kali-babu.katnam@manchester.ac.uk

Abstract. Core-shell rubber (CSR) particles and thermoplastic polyphenylene sulphide (PPS) veils are used to achieve hybrid interlaminar toughening of carbon/epoxy laminates by using vacuum assisted resin infusion and out-of-autoclave curing. Double cantilever beam (DCB) tests are carried out to investigate the effect of hydrothermal conditioning on the mode-I fracture energies and R-curve behaviour. It is shown that interlaminar fracture toughness is significantly enhanced by hybrid toughening (*e.g.* ~246% in mode-I initiation energy). However, the hybrid toughened specimens are more sensitive to moisture ingress compared to the baseline and non-hybrid toughened specimens. The results demonstrate that the mode-I fracture energies of hybrid toughened laminates are decreased after hydrothermal conditioning, and the facture energies are further reduced when the moisture is removed (*i.e.* ~31% and ~24% lower than the original initiation and propagation energies).

Introduction

Composite materials are increasingly used in many applications (e.g. aerospace and automotive structural components). However, traditional carbon/epoxy laminates are prone to delamination [1]. Adding modifiers to matrix and interleaving thermoplastic veils at interlaminar regions are two prevalent methods to improve the interlaminar fracture toughness of composite laminates. The content of matrix modifiers should be controlled due to the manufacturing problems caused by the increasing resin viscosity with high contents of modifiers. Similarly, the low areal weight of thermoplastic veils should be used for interlaminar toughening to reduce the adverse effect on in-plane properties. However, the low content of matrix modifiers and low areal weight of veils would not achieve significant toughening. Therefore, this study uses a hybrid toughening strategy using a low content of core-shell rubber (CSR) particles as modifiers and low areal weight of thermoplastic polyphenylene sulphide (PPS) veils, and investigates the effect of hydrothermal conditioning on the mode-I fracture energies and R-curves.

Materials and methods

Unidirectional carbon non-crimp fabric and two-part epoxy resin are used to manufacture composite laminates. The baseline and toughened laminates are manufactured with vacuum assisted resin infusion and out-of-autoclave curing. Non-hybrid and hybrid toughened laminates are manufactured with: (a) CSR particles with 10 wt% content, (b) PPS veils with 20 g/m^2 areal weight, and (c) CSR particles with 10 wt% and PPS veils with 20 g/m^2 areal weight. Three different types of conditioned specimens are prepared for the above baseline and toughened laminates: (a) oven dried at 60°C after manufacturing (i.e. dry), (b) soaked in a deionised water bath at 80°C for three weeks until saturation (i.e. wet), and (c) dried again at 60°C until all the moisture are removed (i.e. dried). Double cantilever beam (DCB) tests are used to evaluate the mode-I fracture toughness according to the ASTM D5528 [2]. The mode-I initiation fracture energy (i.e. $G_{I,C}$) is calculated based on the 5% offset/maximum load method, and the mode-I propagation fracture energy (i.e. $G_{I,R}$) is calculated as the average value of the fracture energy with crack growth, where the R-curves become stable.

Results and Discussion

The mode-I fracture energies of the baseline and toughened specimens with different environmental conditioning are compared in Fig. 1. The mode-I fracture initiation and propagation energies are significantly improved in the hybrid toughened specimens under dry conditions compared to that of the baseline and non-hybrid toughened specimens. For example, the $G_{I,C}$ of the hybrid toughened specimens under dry conditions is ~1016 J/m^2 (Fig. 1a), which is ~246% higher than that of the baseline. The presence of moisture has negligible effect on the $G_{I,C}$ but increases the $G_{I,R}$ of the baseline specimens. It is observed that drying the saturated baseline specimens results in a slight decrease of $G_{I,C}$ with no significant change in $G_{I,R}$. In the case of the CSR toughened specimens, the saturation results in a reduction of $G_{I,C}$, but has negligible effect on $G_{I,R}$. The $G_{I,C}$ is further reduced but the $G_{I,R}$ is slightly increased after drying the CSR toughened samples. The saturated PPS interleaved specimens has a higher $G_{I,C}$ with almost the same $G_{I,R}$. The $G_{I,C}$ and $G_{I,R}$ values are decreased after removing the moisture content. The effect of moisture is more prominent on the hybrid toughened specimens with a notable reduced $G_{I,C}$ and $G_{I,R}$. The fracture initiation and propagation energies are decreased to ~901 J/m^2 and ~1123 J/m^2, respectively. Besides, drying the saturated specimens results in further reduction of $G_{I,C}$ and $G_{I,R}$ (i.e. ~31% and ~24% lower than the original values, as shown in Fig. 1).

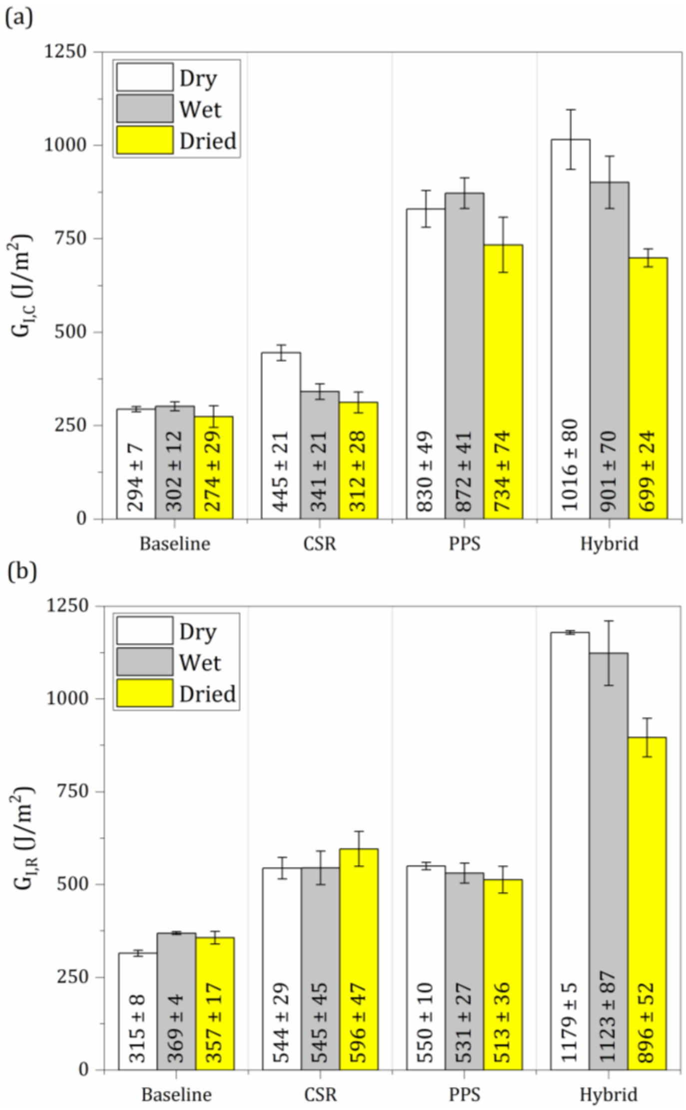

Fig. 1: *Comparison of the mode-I fracture energies of the baseline and toughened specimens with different environmental conditioning: (a) initiation fracture energies (i.e.* $G_{I,C}$*), and (b) propagation fracture energies (i.e.* $G_{I,R}$*).*

Conclusion

In this work, the combination of core-shell rubber particles and PPS micro-fibre veils is used to introduce hybrid toughening in the interlaminar regions of carbon/epoxy laminates. The mode-I fracture energies and R-curve responses are investigated for dry, saturated moisture and fully dried conditions. The hybrid toughening route, with 10 wt% CSR particle content and 20 g/m^2 PPS veil areal weight, significantly improved the mode-I interlaminar fracture toughness compared to that of the baseline and non-hybrid toughened laminates. The mode-I initiation and propagation are increased by ~246% and ~274%, respectively. However, the reduction of mode-I fracture energies related to the presence of moisture is observed to be more severe in the hybrid toughened specimens. In addition, the crack initiation and propagation energies of the dried specimens are further decreased (by ~31% and ~24% compared to the original dry specimens).

References

[1] K.B. Katnam, H. Dalfi and P. Potluri, Towards balancing in-plane mechanical properties and impact damage tolerance of composite laminates using quasi-UD woven fabrics with hybrid warp yarns, *Compos. Struct.* Vol. 225 (2019): 111083.

[2] ASTM D5528-01, *Am Stand Test Methods* (2014).