DURABILITY OF HYBRID FIBER METAL COMPOSITE LAMINATES

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ABSTRACT

Fatigue damage growth has been studied experimentally in TiGr (Titanium alloy/graphite fiber-reinforced polymer matrix composite) and GLARE (Aluminum alloy/glass fiber reinforced polymer matrix composite). In both materials the key damage mechanism has been found to be fatigue crack growth in the metal plies accompanied by delamination between the metal and composite plies. A fracture-mechanics model has been developed and applied to fatigue damage propagation in hybrid metal-composite laminates. A 3-D finite element simulation was used to obtain stress-intensity factors using the virtual crack closure technique. Literature values for the dependence of the metal fatigue crack growth behavior and delamination behavior on the local stress-intensity factor were utilized. The model was effective in predicting the dependence of fatigue damage growth on stress-level, specimen stacking sequence, specimen size and temperature. Extensions of the model have been used to predict stiffness reduction and fatigue lifetime.

1 INTRODUCTION

Hybrid metal laminates are receiving considerable attention due to their good specific strength and stiffness and, in particular, their potential to offer superior durability to aerospace systems. Two of the leading variants of such materials are GLARE, which consists of aluminum metal foils interspersed with glass fiber reinforced polymer matrix composite plies, and TiGr which consists of titanium foils interspersed with graphite fiber reinforced polymer matrix composite plies. Both materials are intended for use in fatigue-critical applications, with TiGr also offering durability at temperatures up to 175 °C, making it suitable for supersonic airframe and engine applications. GLARE is being considered primarily for airframe applications, including extensive use on the Airbus A380. Given the potential for high durability, particularly against fatigue failure, it is important to generate an understanding of the fatigue mechanisms and to develop models for them. This paper presents an overview of work done to identify the key fatigue mechanisms in TiGr and GLARE laminates, and the development of models for fatigue damage growth and resulting property degradation. The work presented herein is covered in greater detail elsewhere: Burianek et al [1-4] and Shim et al [5].

2 DAMAGE MECHANISMS

The principal mechanism of fatigue damage in hybrid laminates is the coupled evolution of fatigue cracks in the metal plies and delamination between the metal and polymer composite plies. There may also be damage solely in the composite plies, in the form of off-axis ply cracking, splitting and delamination, however, previous studies suggest that these are of secondary importance in determining lifetime and property degradation. Figure 1 shows an external view of a TiGr coupon showing fatigue cracks emanating from a hole and growing towards the specimen edge. Figure 2 shows specimens with the outer Ti plies removed revealing the area of delamination associated with the cracks in the exterior metal ply. Figure 3 shows a schematic view of the two damage types within a laminate. In the current work the TiGr laminates consisted of metal foils only on the exterior of the laminate, whereas the GLARE materials also had interior metal plies. In both cases the polymer matrix composite plies were laid up in a cross-ply (0/90) laminate.

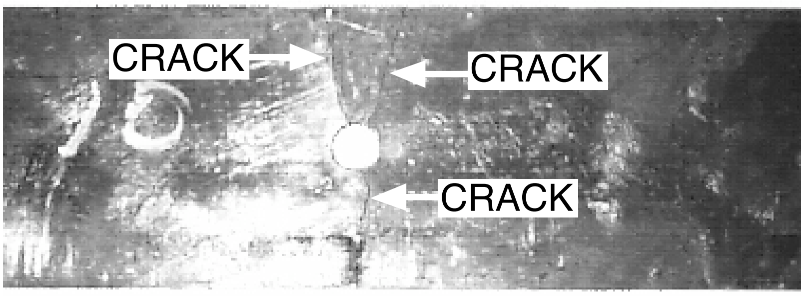
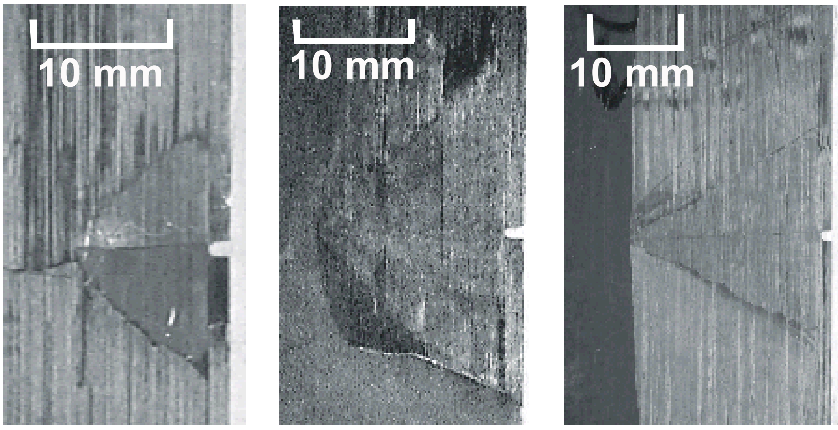


Figure 1 Facesheet cracking in a Titanium/Graphite hybrid laminate subjected to tension-compression fatigue (R = -0.2).



(a) (b) (c)

Figure 2. Delamination geometry in TiGr hybrid laminate revealed by use of a penetrant at fatigue crack lengths of:: (a) a=8.7 mm, (b) a=19 mm and (c) a=23 mm. The damage initiated from the small notches to the right of the figure.

3 DAMAGE MODELING

3-D finite element models were constructed, corresponding to the specimen and damage geometry shown in figure 3. A global-local scheme was implemented, resulting in a mesh refinement at the crack tip of 5-10 elements through the ply thickness in the local model. A 3-D virtual crack closure scheme was used to evaluate the stress-intensity factor at the crack tip. Literature values for the dependence of the crack growth rate on the applied stress intensity factor, for the relevant Ti and Al alloys were then used to predict the crack growth rate for the metal layers *in situ*. The resulting predictions were compared to fatigue crack growth data, as shown in Figure 4 for TiGr and figure 5 for GLARE. The prediction for TiGr is outstanding, with no additional calibration required. The prediction for GLARE required fitting the model to one of the sets of data, after which all the data was well-fitted by the model. Without this “tuning” the model under-predicted the data by a factor of 3. The discrepancy is likely to be due to residual stresses in the Al, resulting in an additional mean stress effect, it is also likely that the fatigue response of thin foils may differ from the bulk values obtained in the literature. Similarly good descriptions of data were found for other TiGr and GLARE laminates, using the same modeling parameters. In addition the model, in combination with models for the elevated temperature fatigue response of Ti and the elevated temperature fatigue-delamination response was found to provide a good description of the effect of elevated temperature on the fatigue damage growth rate in TiGr.

As can be seen in figures 4 and 5, in both the TiGr and GLARE data the crack growth rate asympotes to a value that is independent of crack length. Further investigation has revealed that the controlling dimension for this behavior is the metal ply thickness, rather than the crack length. This response is similar to that of transverse ply cracks in cross-ply laminates, and the models developed for such problems work quite well to predict the stress intensity factor for the cracks in the meal plies in the present study. The modeling also reveals that the crack tip stress intensity factor, and hence the crack growth rate is relatively insensitive to the exact shape and extent of the accompanying delamination. This suggests that the metal crack growth precedes the delamination, and that the delamination, although coupled to the fatigue-crack growth in the metal, is initially the secondary damage mode.

It is worth noting that previous work, (e.g Marissen [6], Lin et al [7] and Guo [8]) have used bridged crack models to predict the growth of fatigue cracks within the metal plies of hybrid laminates. We found that for both the GLARE and TiGr laminates and specimen geometries investigated in this study, such models were not appropriate. In particular such models are not capable of capturing the steady state crack growth behavior that was a feature of both materials fatigue response. This reflects the three-dimensional nature of the stress field at the crack tip, and the fact that the controlling dimension is the ply thickness.

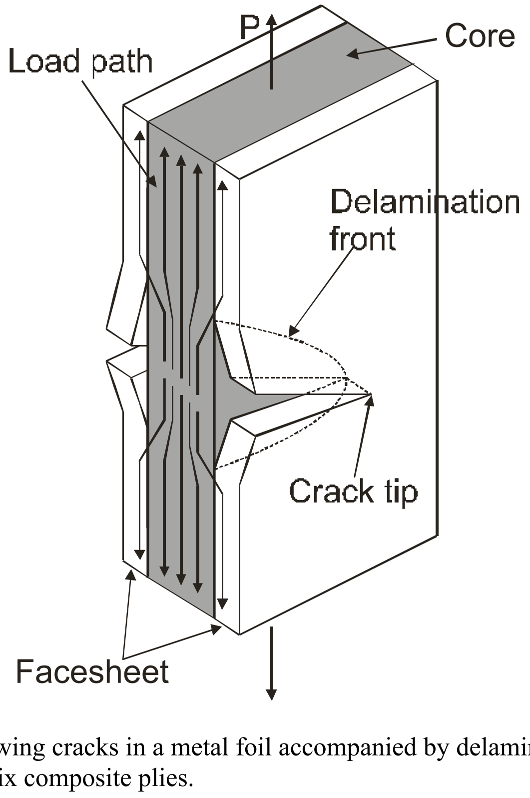


Figure 3. Schematic showing cracks in a metal foil accompanied by delamination from the polymer-matrix composite plies.

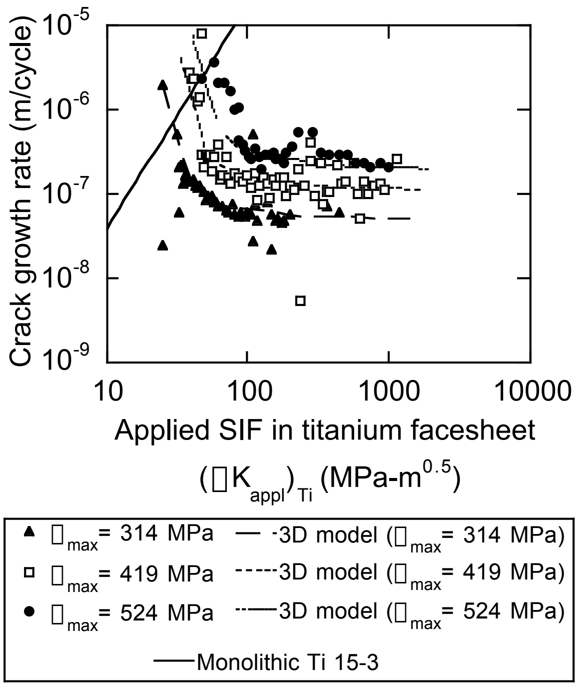


Figure 4. Comparison of model predictions and experimental data for $(Ti/0/90/0_2)_s$ loaded at three stress levels, R= 0.1.

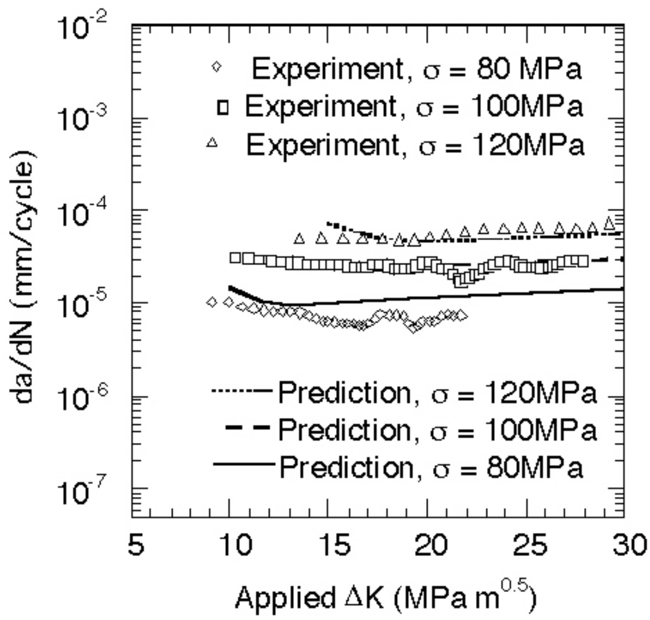


Figure 5. Comparison of model predictions and experimental data for a GLARE laminate at three stress levels.

The finite element models can also be used to predict the reduction in specimen stiffness with coupled metal fatigue crack and fatigue delamination growth, and these have been utilized to produce stress-life (S-N) curves, based on a stiffness-critical failure criterion.

CONCLUDING REMARKS

An experimental study has revealed that coupled metal crack growth and metal-composite delamination is the key fatigue damage mode in fiber-metal hybrid composite laminates. A fracture-mechanics based model has been developed and applied to fatigue damage propagation in TiGr and GLARE hybrid metal-composite laminates. A 3-D finite element simulation was used to obtain stress-intensity factors. Literature values for the dependence of the metal fatigue crack growth behavior and delamination behavior on the local stress-intensity factor were utilized. The model was effective in predicting the dependence of fatigue damage growth on stress-level, specimen stacking sequence, specimen size and temperature. Extensions of the model have been used to predict stiffness reduction and fatigue lifetime. The modeling scheme is easily extended to other hybrid-laminates or specimen/structural configurations. It has the potential to play an important role in allowing for a damage tolerant design approach to be used for this class of materials, consistent with how metallic airframe structures are currently designed.

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