INHIBITING DELAMINATIONS IN FIBRE REINFORCED PLASTIC LAMINATES WITH DROPPED PLIES

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Abstract
Cut plies were incorporated at the centre of unidirectional glass fibre laminates to simulate the loading conditions observed around dropped plies in tapered structures. Specimens were tested aggressively in tensile fatigue in order to initiate delamination at the ply cuts and propagate this along the interfaces between the continuous outer plies and discontinuous (cut) inner plies. Narrow strips of thermoplastic film were interleaved at specific locations along the delaminating interfaces to investigate their ability to slow or inhibit the delamination growth. Polyimide and EMAA thermoplastic films were investigated: whilst the polyimide film appeared to have minimal effect, the EMAA film proved highly successful in preventing delamination growth under the fatigue conditions.

1 Introduction

Structural components must often vary in thickness in order to optimise mechanical performance and minimise weight. In components manufactured from laminated fibre reinforced plastic, plies of material must be added or removed in order to effect these variations. In the tapered regions, these ply drops can be problematic in that they represent discontinuities within the structure which create stress concentrations and, therefore, provide a location at which damage can initiate, especially under cyclic loading. Predominantly, this damage manifests as delaminations at ply interfaces which, if allowed to propagate, can severely reduce the mechanical properties and potentially lead to total structural failure [1].

Augmenting the ply interface by interleaving additional material is a methodology for inhibiting delaminations which has demonstrated notable potential [2]. A number of different material types from additional matrix material [3] to exotic arrangements of carbon nanotubes [4] have been used as interleaves in fibre reinforced laminates and shown to increase fracture toughness in both mode I and mode II. Unfortunately, applied in a continuous fashion, interleaved layers affect the global properties of the laminate increasing weight and reducing stiffness and strength. To counter these effects, Yasaee et al recently investigated the propagation of delaminations into discrete strips of interleaved materials [5], [6]. The research demonstrated toughening in both mode I and mode II leading to the concept, developed in this study, of implementing discrete targeted toughening around features such as ply drops to retard delamination growth and thereby improve fatigue life.

Wisnom et al [7] demonstrated that the loading conditions and delaminations that develop around ply drops in laminates subjected to tensile fatigue could be simulated in simple specimens with discontinuous (cut) central plies. Under cyclic loading, delaminations were initiated at these pseudo ply drops and propagated along the interfaces between the continuous and cut plies at a constant rate.

In this feasibility study, discrete strips of thermoplastic film were interleaved in the delaminating interfaces of these cut central ply (CCP) specimens to investigate their potential to retard the delamination growth. Unidirectional glass fibre specimens were prepared with two cut / discontinuous plies at the centre of the stacking sequence. Two types of thermoplastic film strip were interleaved at discrete locations in the stacking sequence at the predicted delaminating interfaces in order to observe their effect on the rate of delamination growth. The interleaves comprised a polyimide film and a marginally thicker EMAA film. The stiffness of each specimen (proportional to the delamination size) was monitored via the maximum and minimum cross-head displacement whilst the growth of the delaminations was recorded using time lapse photography.

2 Experimental methodology

2.1 Materials

Specimens were manufactured from unidirectional glass fibre epoxy prepreg. The resin / glass material system was selected on the basis that it provided a translucent laminate following cure. This allowed the position of the ply cut and the subsequent delaminations to be tracked visually. The prepreg used was Hexcel 913 E-glass [8] with a nominal ply thickness of 0.125mm. The thermoplastic film interleaves used in the investigation were Upilex 50-RN, a polyimide film supplied by UBE Industries Ltd and ethylene-co-methacrylic acid (EMAA) supplied by Dupont as pellets with a diameter of approximately 3-5mm. Previous studies at Bristol [5], [6] showed notable increases in mode I and mode II fracture toughness with Upilex interleaves whilst Wang et al demonstrated increased toughness with EMAA interleaves [9]. The Upilex film was surface treated prior to lamination to promote matrix adhesion. The EMAA film was produced in house using a hot-press to melt and compact the pellets into a thin film of approximately 125 micron thickness.

2.2 Specimen manufacture

UD laminates 200mm square were manufactured using 10 plies of 913 E-glass prepreg. Four laminates were manufactured:

- A control laminate with no interleaves
- A laminate containing 5mm wide Upilex interleaves
- A laminate containing 5mm wide EMAA interleaves
- A laminate containing 3mm wide EMAA interleaves

Details of the specimens manufactured and tested and the interleaved films can be seen in table 1. The two central plies were cut in half perpendicular to the fibre direction and butted together to form the central ply cut. Strips of thermoplastic interleaved material were then placed between the continuous outer and discontinuous central plies, perpendicular to the fibre direction and approximately 15mm from the ply cut. Following autoclave cure [8], each laminate was sectioned into specimens 180mm in length by 10mm in width with the cut plies located at the centre of the gauge length. Figure 1 shows the specimen internals in addition to the general dimensions.

Specimen type	No. of specimens tested	Interleaf strip width,mm	Cured strip width, mm	Cured strip thickness (centre), µm
Control	7	-	-	-
Upilex 50-RN	5	5	5	50
EMAA	6	5	7	75
EMAA	6	3	4	75

Table 1. Thermoplastic film geometry pre and post laminate manufacture

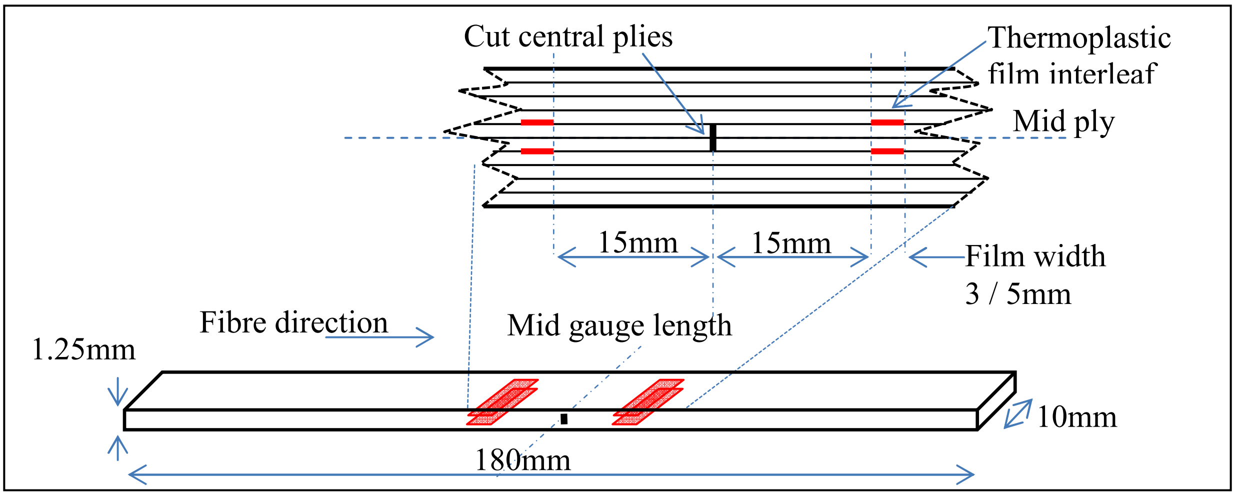

Figure 1. Internal and external specimen configuration

2.3 Testing

Specimens were tested in tension under static and fatigue conditions using a hydraulic Instron 8872 test machine (certificate number E11808231115900) equipped with a 25kN load cell. Results from previous static tests using identical centre cut ply specimens [7] showed a nominal static delamination propagation load of 12kN. This was the peak load that the CCP specimen could sustain before delamination was initiated at the ply cut. A number of control specimens were tested to confirm this load. Once determined, trial fatigue tests were conducted to find an appropriate combination of maximum fatigue load (percentage of the maximum static load), loading frequency and number of cycles. As this was a feasibility study, a combination of these parameters was selected which gave a good balance between delamination growth rate and test time. As noted in the previous research [7] a high frequency was not selected in order to avoid adiabatic heating.

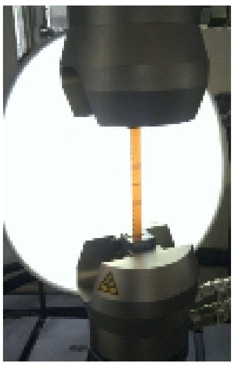

Figure 2. Tensile fatigue test of glass fibre specimen with centre cut plies and thermoplastic inserts.

The fatigue tests were conducted under load control with test machine operation and data acquisition implemented by Instron's Wavematrix software. The final parameters selected were:

- Maximum fatigue load was 60% of the static delamination load
- R ratio of 0.1
- Frequency of 4.2 Hz
- 25000 cycles.

Under backlighting the translucent nature of the specimens allowed the ply cut, delamination and interleaves to be clearly distinguished, the test set-up is shown in figure 2. Time lapse photography was used to monitor the delamination growth during each test (implemented via Labview software) with photographs taken every 120 seconds i.e. every 500 cycles.

3 Results and discussion

In all of the specimens tested, delamination onset was effectively immediate upon the start of cyclic loading. As reported previously [7], delaminations initiated at the interfaces between the cut (inner) and continuous (outer) plies, in both halves of the laminate and propagated outward towards the grips, figure 3.

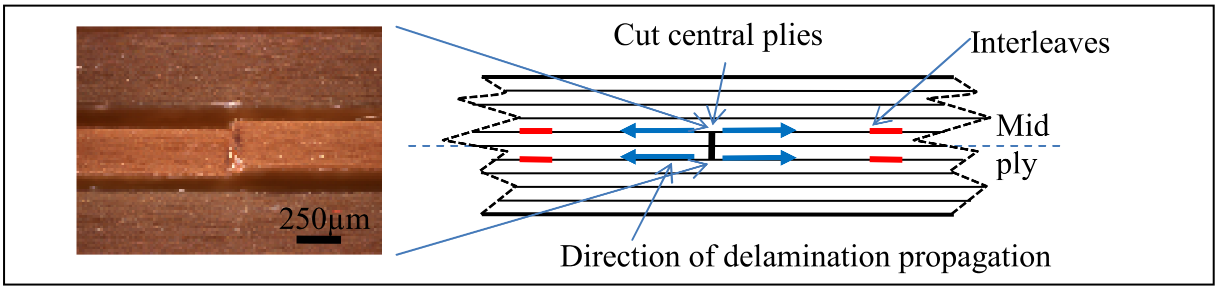

Figure 3. Delamination propagation direction

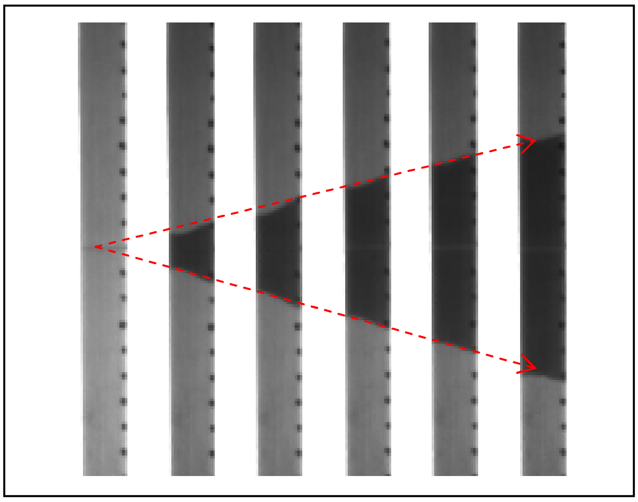

Figure 4. Delamination growth in a control specimen: from left to right 0, 5000, 10000, 15000, 20000 and 25000 cycles.

Figure 4 shows the delamination growth for a typical control specimen at increments of 5000 cycles. Across all of the control specimens, the delamination growth rates were approximately linear (as indicated by the red arrows). Delamination growth appeared to be closely mirrored about the mid plane but the growth rates observed in either half of the specimens were not necessarily identical, as can be seen from the differing delamination lengths in each photograph. The delamination growth rates observed in the Upilex specimens, e.g. figure 5 were also linear throughout each test with the addition of the Upilex films not appearing to slow or retard the delamination growth. A microscopic examination of the delaminated Upilex specimens is shown in figure 6 highlighting how the delamination appears to move through resin rich regions on either side of the interleaves. The research that served as a precursor to this investigation [5], [6] demonstrated the viability of the Upilex in significantly improving fracture toughness under both mode I and mode II quasi-static loading. Consequently, the inability of the Upilex to retard delaminations propagating under fatigue requires further investigation.

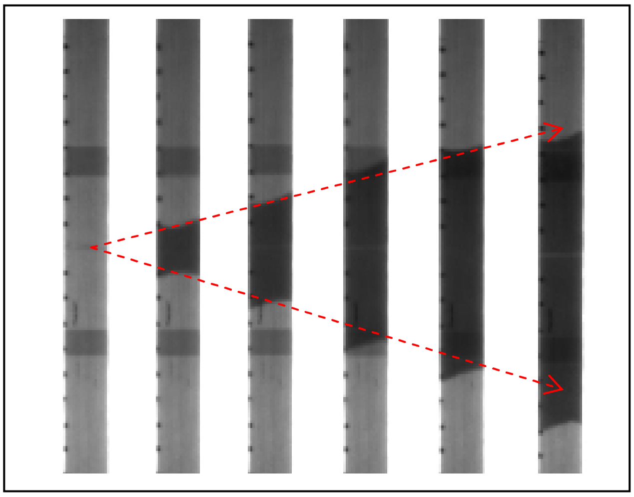

Figure 5. Delamination growth in a Upilex specimen: from left to right 0, 5000, 10000, 15000, 20000 and 25000 cycles.

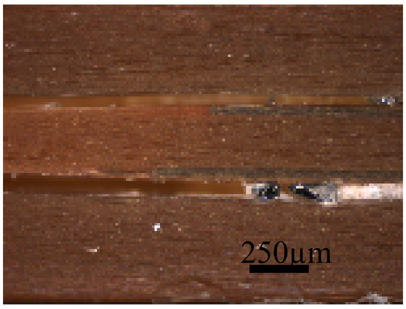

Figure 6. Microscope image of the delaminated interfaces with interleaved Upilex strips

An example of the delamination progression in the 5mm EMAA specimens is shown in figure 7. The initial growth rate is linear before the delaminations encounter the resin rich zone that exists ahead of the EMAA film. The delamination growth increases rapidly in the resin rich region but is then completely halted by the EMAA film. This behaviour was observed in all of the 5mm wide EMAA specimens. To examine whether a narrower width film would be less effective in preventing delamination growth, specimens were prepared with 3mm strips of EMAA film and tested over 50000 cycles. All of these specimens showed similar initial delamination growth rates to the previous specimens, a subsequent acceleration in growth through the resin rich zones with the delamination growth was again halted by the EMAA strip despite the doubled number of cycles.

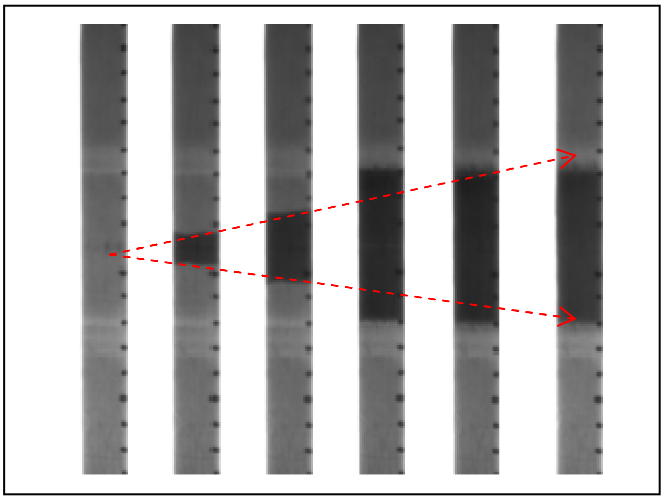

Figure 7. Delamination growth in a 5mm EMAA specimen: from left to right 0, 5000, 10000, 15000, 20000 and 25000 cycles.

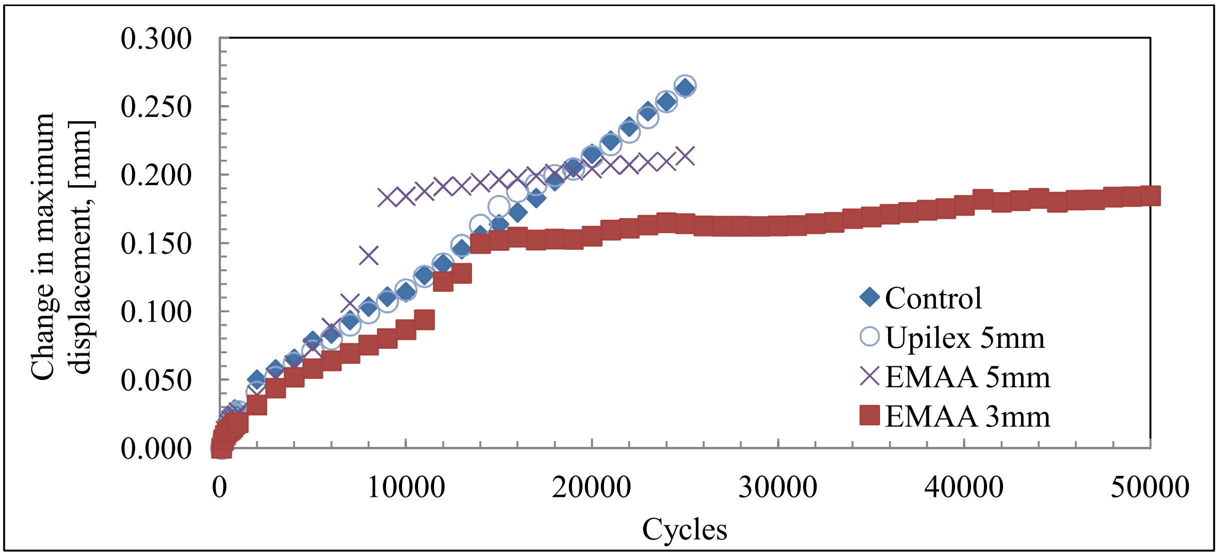

Figure 8. Maximum displacement vs. cycles for the control and interleaved specimens.

As reported by W*isnom et al* [3], the increase in total delamination length is directly proportional to the reduction in specimen stiffness and, therefore, the change in maximum crosshead displacement. A plot of maximum displacement vs. Number of cycles is shown for examples of each specimen type in figure 8 giving further resolution to the trends captured by the time lapse photography. Both the control and Upilex specimens exhibit a linear increase in maximum displacement indicating linear delamination growth and the negligible effect of the Upilex interleaf as a crack arrestor. The 3mm and 5mm EMAA interleaved specimens show initial delamination rates comparable with the control and Upilex specimens before the maximum displacement increases rapidly at around 10000 cycles. This acceleration in growth is due to the resin rich zone ahead of the EMAA interleaves which is thicker in the EMAA specimens than the Upilex specimens due to the sizeable increase in interleaf thickness (a slight acceleration is visible in the Upilex specimen at around 15000 cycles in this instance). Once the delaminations have reached the interleaves, the increase in maximum displacement per cycle is substantially reduced compared to control specimen indicating that, although delamination growth is still occurring, it is very significantly reduced and highly comparable for the 3mm and 5mm specimens. As the time lapse photography gives little indication of this further growth, a detailed examination of the EMAA specimens was conducted. This appeared to show some very slender finger like delaminations protruding into the interleaved regions indicating a much tougher interface region for the delamination to propagate through.

4 Conclusions

This feasibility study has demonstrated that a discrete thermoplastic strip interleaved in a composite laminate can arrest delaminations propagating under aggressive cyclic loading. The study compared the effectiveness of two EMAA strips of differing width and a polyimide Upilex strip. Although the Upilex strips proved consistently ineffective, time lapse photography and indirect measurement of the specimen stiffness both show that EMAA strips of both 3mm and 5mm were highly successful in retarding delamination growth. The next phases in this research are to understand the implications of the film's thickness and width on its ability to prevent delamination, to evaluate the nature of the film / composite interface and to understand how the specimen behaves if the delamination is able to propagate beyond the interleaves.

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