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Delamination Fracture Toughness Benefits of Inter-Woven Plies in Composite Laminates Produced through Automated Fibre Placement

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***Abstract*—An automated fibre placement method has been developed to build through-thickness reinforcement into carbon fibre reinforced plastic laminates during their production, with the goal of increasing delamination fracture toughness while circumventing the additional costs and defects imposed by post-layup stitching and z-pinning. Termed ‘inter-weaving’, the method uses custom placement sequences of thermoset prepreg tows to distribute regular fibre link regions in traditionally clean ply interfaces.

Inter-weaving’s impact on mode I delamination fracture toughness was evaluated experimentally through double cantilever beam tests (ASTM standard D5528-13) on $[\pm 15°]_9$ laminates made from Park Electrochemical Corp. E-752-LT 1/4” carbon fibre prepreg tape. Unwoven and inter-woven automated fibre placement samples were compared to those of traditional laminates produced from standard uni-directional plies of the same material system.

Unwoven automated fibre placement laminates were found to suffer a mostly constant 3.5% decrease in mode I delamination fracture toughness compared to flat uni-directional plies. Inter-weaving caused significant local fracture toughness increases (up to 50%), though these were offset by a matching overall reduction. These positive and negative behaviours of inter-woven laminates were respectively found to be caused by fibre breakage and matrix deformation at inter-weave sites, and the 3D layering of inter-woven ply interfaces providing numerous paths of least resistance for crack propagation.

***Keywords*—AFP, automated fibre placement, delamination, fracture toughness, inter-weaving.

I. Introduction

CARBON fibre reinforced plastic (CFRP) composites possessing continuous fibre reinforcement and epoxy resin matrices are seeing use in an increasing range of industries, from automotive to aerospace. CFRP composite laminates produced from stacks of prepreg plies are often used for thin structures such as panels and beams.

A. Composite Delamination

The lack of fibre reinforcement linking laminated plies makes them susceptible to delamination under inter-ply stresses, which can be initiated by factors including minor impact damage and corrosion, and is potentially overlooked during routine maintenance according to the 2008 Australian Transport Safety Bureau review of fibre composite use in Australian aircraft [1]. In 2016 Aslan and Daricik [2] determined experimentally the detrimental effects of large delaminations on compressive, flexural and tensile strength and stiffness. Delamination size correlated strongly with compressive and flexural property reduction, with tensile capability remaining unaffected. While only a small subset of laminate designs and delamination cases were explored, the results represent the general trend of delamination property reduction.

Improving delamination fracture toughness would increase energy absorption for equivalent material property losses. With the risk of catastrophic failure subsequently decreased, the structure would experience a more plastic, ductile failure. It is therefore important to find methods of increasing delamination fracture toughness of thin composite laminates, while avoiding excessive negative in-plane effects. Delamination analysis and prediction are complicated by dependence upon laminate design and component material structure. Chai [3] showed that mode I delamination fracture toughness depends on interface morphology (type), which is directly influenced by material properties, fibre-matrix interfaces, ply angle and loading. The works of Rehan et al. [4] and Kim and Sham [5] are supportive; merely changing ply angle alters surface form, including cracks splitting or jumping between multiple interfaces. Again only certain configurations were examined in each study; the variation relied upon by the analyses meant they could not examine all cases.

In keeping with these studies, thin laminates made from uni-directional (UD) plies of varying orientations were examined. The work of Nicholls and Gallagher [6] displayed four distinct delamination interface morphologies for this style of laminate (Fig. 1), with characteristics defined by the regions in which they were observed. Descriptions of these regions take the direction of delamination progression as the reference angle.

(a) Region I (b) Region II (c) Region III(d) Region IV

Fig. 1 Mode I Delamination Interface Regions [6]

- Region I (Fig. 1a)
  - Observed between plies of 0° orientation
  - No propagation between plies
  - Smooth surface, little to no fibre breakage

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    - Lowest fracture toughness
- Region II (Fig. 1b)
    - Observed between plies of dissimilar orientation
    - No propagation between plies
    - Microscopic resin deformations
    - Higher fracture toughness than Region I
    - No dependence upon ply orientation
- Region III (Fig. 1c)
    - Observed in plies of low orientation angle (0°-60°)
    - Crack moves between interfaces
    - Fibre bridging and breakage
    - Fracture toughness increase with fibre angle
    - Region of highest fracture toughness
- Region IV (Fig. 1d)
    - Observed in plies of high orientation angle (60°-90°)
    - Ridges and valleys represent oscillation of crack tip location
    - Lower fracture toughness than Region III

Understanding how laminate structure affects delamination morphology is therefore key to determining and predicting fracture toughness and behaviour (Fig. 2).

Fig. 2 Laminate Structure Link to Fracture Toughness

B. Through-Thickness Reinforcement

Through-thickness reinforcement is the application of fibres to the traditional z-direction of thin composite laminates, with the goal of improving inter-ply and transverse material properties. Multiple studies have proven the practice capable of increasing delamination fracture toughness in such structures [7]- [10], most notably the 1999 review of 3D composite reinforcement by Mouritz et al. [11].

In 2010 Mouritz and Cox [12] showed that stitching, a common form of thin laminate reinforcement, can increase mode I delamination fracture toughness by up to 20%. Stitching has been selected for comparison in this study, due to its relatively widespread use in thin prepreg laminates. Other methods such as weaving and braiding are more effective with dry fibres than prepreg material [11].

Dransfield's review of CFRP stitching [9] revealed key mechanisms through which it improves delamination fracture toughness; mainly by forcing increased matrix deformation, stitch breakage and fibre pullout. Conflicting accounts exist of how stitch type, pitch and diameter affect material properties, with Dransfield and others claiming that increasing stitch density improves delamination fracture toughness [10]. Mouritz's 2010 work [12] however asserts that properties are not strongly influenced by volume content or diameter of through-thickness reinforcement. Mouritz's review has been determined the more valid source, being a recent overview of a significant bank of published data. It was therefore assumed that inter-laminar properties are not heavily impacted by stitching parameters.

Through-thickness reinforcement is most effective for mode I (opening shear) delaminations, as found by Herszberg [7] who confirmed that it has little impact on pure mode II (in-plane shear) and mode III (anti-plane shear) behaviour. Robinson [13] also concluded that pure mode I fracture isolates toughness results from other mechanical properties.

The inter-laminar benefits of through-thickness reinforcement are balanced by decreased in-plane properties. Studies have found that fibre and resin damage during prepreg stitching reduce tensile and compressive strength and stiffness by 10-15% [8], [9], [11], [14]. The largest impacts stem from fibre crimping, breakage and misalignment (Fig. 3), although 'waviness' from the repeating stitch pattern is a contributing factor [4], [5].

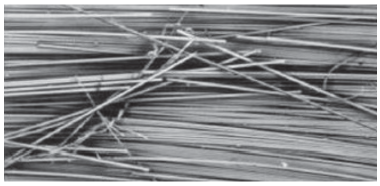


Fig. 3 Stitching Fibre Damage [12]

C. Ply Inter-Weaving

These defects and post-processing costs could be alleviated if inter-ply reinforcement were inherent to the laminate's constituent material, or 'inter-woven'. Such a state would result in linkage of all adjacent layers during production, but necessitates an alternate production method as it is not possible with the long, wide plies usually used for laminates. Automated fibre placement (AFP) can create inter-woven laminates by using tape placement machinery to build plies from thin strips of material (tows) in customised sequences (Fig. 4).

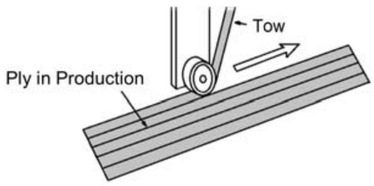
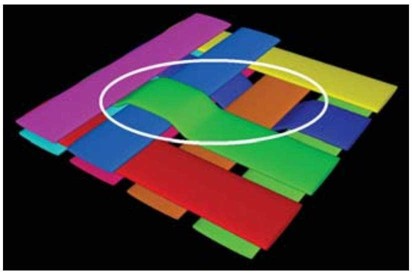


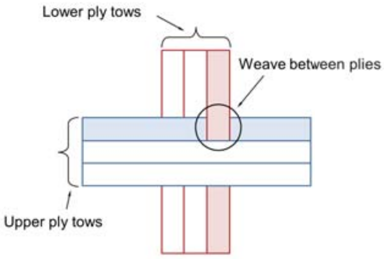
Fig. 4 AFP Ply Production

Fig. 5a provides a representation of an AFP inter-woven structure, where tows can be seen passing above and below adjacent plies, and Fig. 5b shows the AFP 3 x 3 unit cell layup by which such a setup can be achieved.

AFP inter-weaving capability was proven in a preliminary investigation [15], in which one of two otherwise identical AFP laminates was inter-woven using a specific tow placement sequence. The study's experimental results suggested that ply inter-weaving has a strong positive effect on mode I (opening) delamination fracture toughness wherever tows pass between plies, as well as a small constant overall increase (Fig. 6).



(a) 3D Representation



(b) Unit Cell Tow Arrangement

Fig. 5 Basic AFP Inter-Woven Structure

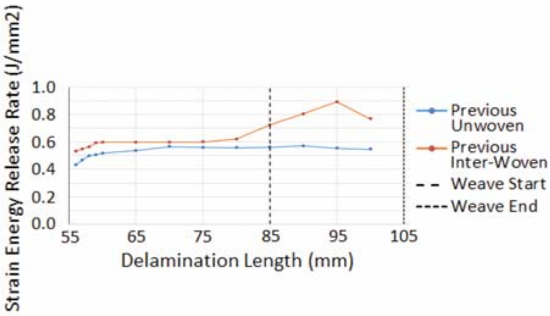


Fig. 6 Previous Experiment Fracture Toughness Results [15]

Lacking investigation in the study were observation of the described manufacturing defects, as well as delamination features of fibre bridging and cracks splitting to adjacent interfaces. Comparison to non-AFP laminates of the same material system would identify the differences between defects and features introduced by inter-weaving and AFP itself.

D. Identified Research Gap: Laminate Inter-Weaving

The literature has shown existing knowledge and research of traditional through-thickness reinforcement methods, as well as the mechanisms through which they impact delamination fracture toughness and reduce in-plane properties. Missing from the field due to their new conception as advanced composite structures is the behaviour, mechanisms and properties of AFP inter-woven laminates.

This project aimed to rectify that deficit by documenting the features of such structures from the beginning of their production through to during and after delamination, with a focus on experimental investigation of mode I fracture toughness and corresponding delamination interface features. Such efforts are required if inter-woven laminates are to be comparable to their standard counterparts for use as engineering structures.

II. Experimental Procedure

This section describes the performance of the project's double cantilever beam experiment. Major outcomes were the collection of data for calculation of delamination crack strain energy release rate (SERR), and the production of delaminated interface surfaces for examination and identification of key features, regions and failure modes. The tests were performed on AFP unwoven, AFP inter-woven and traditional flat UD laminates to assess and compare the properties, induced defects and features of each.

A. Laminate Design

The CFRP material system used was E-752-LT epoxy prepreg from Park Electrochemcial Corp. [16]. The ASTM D5528-13 DCB test standard ("Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites") [17] recommended 0° plies summing to 3 - 5 mm total laminate thickness, but as inter-weaving is not possible for plies of 0° relative angle, $\pm 15°$ was carried over from the previous experiment as an approximation of the standard to facilitate inter-weaving. Any valid ply angle is theoretically possible, and may provide interesting data if investigated in future research. In order to meet the recommendations of the ASTM standard, the number of plies was increased to 18 for this project, bringing total pre-cure thickness to 3.6 mm, or 17% more than the recommended 3 mm minimum (to account for curing thickness reduction). As determined from the literature review, thickness-based compliance has little effect on mode I delamination fracture toughness in DCB experiments [6].

A total of six laminate panels were produced, each corresponding to a set of test samples as shown in Table I, with the four originally planned sets above the dashed line. These original four consisted of one of each set type for DCB data collection, as well as an additional inter-woven set. Production setbacks necessitated the fabrication of an additional two sample sets (those below the dashed line), and only one set of each type reached the testing stage.

TABLE I
List of Produced Laminates

Panel/Set #	Description	Tested?
1	Flat UD 1	-
2	AFP Unwoven 1	Yes
3	AFP Inter-Woven 1	-
4	AFP Inter-Woven 2	Yes
5	AFP Unwoven 2	-
6	Flat UD 2	Yes

B. Sample & Experiment Design

Rectangular DCB specimens were designed to the ASTM D5528-13 [17] standard, using adhered brass piano hinges for load application due to their simplicity, availability and prior experience (Fig. 7a). The samples were dimensioned

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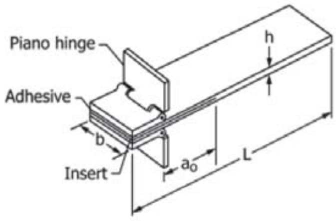
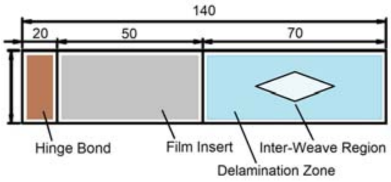


(a) ASTM D5528-13 Guidelines [17]



(b) DCB Sample Dimensions

Fig. 7 DCB Sample Design

TABLE II
DCB SAMPLE THEORETICAL DIMENSIONS

Dimension	Value (mm)
b (Width)	25
L (Length)	140
a0 (Insert Length)	50
h1 (Uncured Thickness)	3.60
h2 (Expected Cured Thickness)	3.02

at 25mm wide and 140mm long, with a release film insert for pre-cracking covering half (70mm) of the sample. The insert was introduced to the laminates' middle ply interface during production. Fig. 7b shows these features, as well as the location of the loading hinges and an inter-weave centred in the blue delamination region.

Table II lists the theoretical sample dimensions, where a prediction of cured thickness (h2) has been provided based on the previous experiment's 16% decrease [15].

Fig. 8 demonstrates the design of the panels from which the samples were cut. The hexagonal shape was employed to prevent dropping of short tows in the corners resulting from minimum tow length restrictions of the machinery. Note that the side corners of the hexagon do not lie on the horizontal insert line. This was due to elongation of the panel to correctly position inter-weaves in the desired location on each sample. Each panel was planned to possess six samples for redundancy and data robustness, however the aforementioned production difficulties resulted in only five of each set completing testing, a number which satisfied the ASTM guidelines [17].

III. SAMPLE PRODUCTION & PREPARATION

Production of samples from base material through to test-ready specimens was divided into panel layup, panel curing, sample cutting and sample preparation.

A. Panel Layup

The flat UD plies were cut out of the material roll by hand using a template, before being placed in their correct orientation and stacked (Fig. 9).

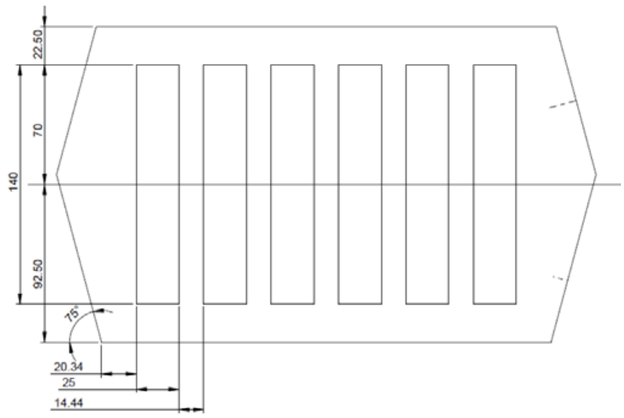


Fig. 8 Laminate Panel Design with Samples

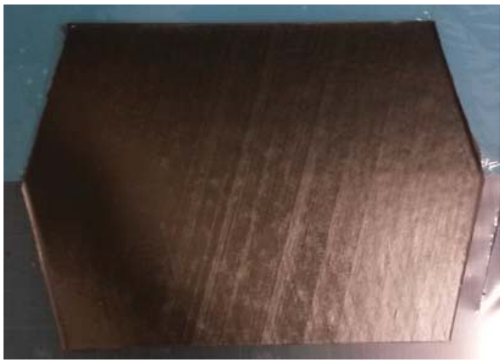


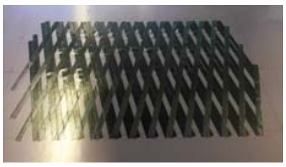
Fig. 9 Flat UD Panel Layup with Film Insert (Panel 6)

The unwoven AFP laminates were produced 4 tows at a time at the machinery's maximum placement rate. The inter-weaving process restricted the machinery to only one concurrent tow, significantly increasing production time. Fig. 10 shows the first stages and final state of the inter-woven layup.

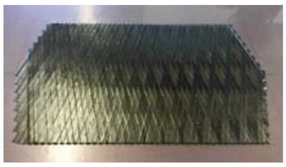
B. Panel Curing

A hot press cure cycle was adapted from the out of autoclave (OOA) process detailed in the material's datasheet [16]. The press (Fig. 11) possessed a maximum area of 400 x 400 mm, with pressure and temperature applied by a hydraulic press and electric heating elements.

The following procedure details the cure cycle, with system pressure calculated based on the relative areas of the sample panels and the hydraulic piston (10:1).



(a) Early Inter-Woven Layup



(b) Complete Inter-Woven Layup

Fig. 10 AFP Inter-Woven Layup

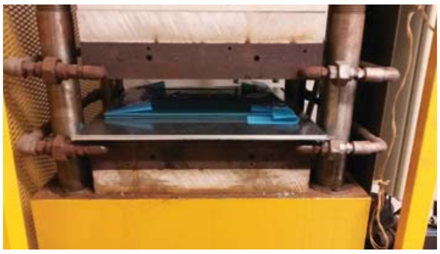
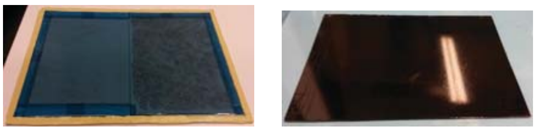


Fig. 11 Cure Cycle Hot Press

1) Apply 190 kPa to panels for 5 minutes prior to heat up (system pressure 1.9 MPa)
2) Ramp temperature at 1.5°C/min to 129°C ±2.8°C
3) Dwell at 129°C ±2.8°C for 260 ±10 minutes
4) Release pressure and ramp temperature at 1°C/min to 177°C ±2.8°C
5) Dwell at 177°C ±2.8°C for 120 ±10 minutes
6) Ramp down at <4.4°C/min and remove panels after temperature falls below 49°C

The panels were wrapped and sealed in a layer of release film with an encompassing dam of vacuum bagging 'tacky-tape' (Fig. 12a). These measures were employed as attempts to prevent resin and fibre movements, and were assisted by limitation of pressure top-up to 3 instances during initial temperature ramping to 129°C. Great success at containing the composite material was observed, and as seen in Fig. 12b there was almost no resin bleed or fibre wash and a high quality cure surface was achieved. The impressions made by the film-sealing tape near the edges of each panel occurred outside of designated sample regions.

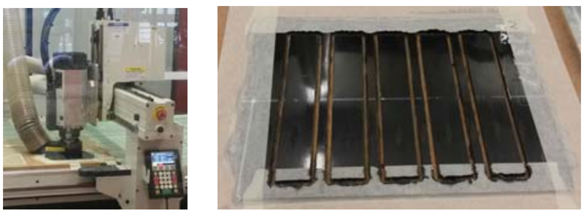


(a) Film Seal and Tape Dam (b) Contained Cure Outcome

Fig. 12 Revised Hot Press Panel Setup

C. Sample Cutting

Samples were cut using a numerically controlled (NC) table router (Fig. 13a) to ensure alignment of test coupons with inter-weave sites. The bridges employed to prevent sample shift during cutting were placed along the short sample ends, as these regions imparted no impact on the DCB test. Fig. 13b shows samples following NC cutting.



(a) NC Router (b) Samples Cut with Bridges

Fig. 13 Sample NC Routing

D. Sample Preparation

Following disconnection from the panel bridges, the samples were cleaned and their dimensions measured in accordance with the ASTM D5528-13 standard (Fig. 14) [17].

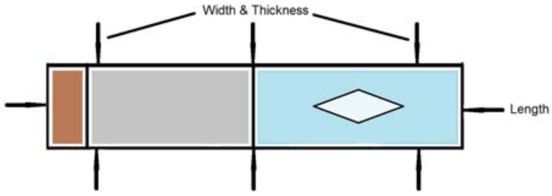


Fig. 14 DCB Sample Dimension Measurement Locations

Table III provides summarised dimension data for the three tested sets.

TABLE III
SAMPLE AVERAGE DIMENSIONS

Dimension (mm)	AFP Unwoven	AFP Inter-Woven	Flat UD
Width	25.00	24.91	24.96
Thickness	2.49	2.58	2.66
Length	140.27	140.49	140.22

The final steps of sample preparation were adhesion of loading hinges using 'Araldite Super Strength' three-day epoxy, and marking of delamination lengths along whitened edges of the samples. Fig. 15 shows the template used for marking delamination lengths on the DCB samples, featuring a mix of fine (1 mm) and course (5 mm) markings. The fine markings were divided into 5 mm starting from the insert for the loading pre-crack, and 5 mm for the beginning and end of the 50 mm main crack. Fig. 16 shows a completed sample ready for testing.

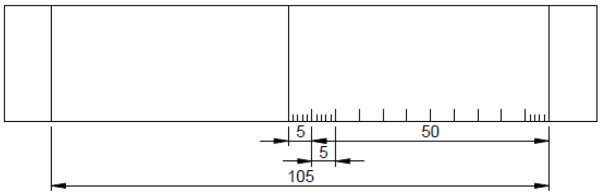


Fig. 15 Delamination Marking Template

Fig. 16 DCB Sample Ready for Testing

E. Double Cantilever Beam Experiment

The DCB experiment was performed on an 'Instron 3369' tensile loading machine with a 1kN load cell and adjustable jaws for sample hinge clamping (Fig, 17).

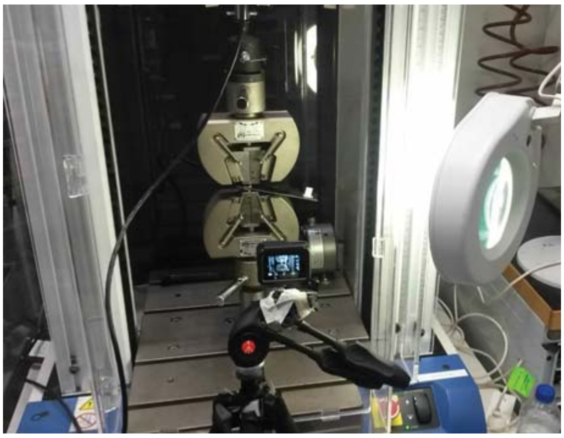


Fig. 17 DCB Experiment Setup

The DCB test was performed by applying constant cross-head displacement of 2 mm/min and recording the load and displacement at each delamination length marking. The test was split into two sections: a 5 mm pre-crack for delamination initiation from the insert, and the subsequent 50 mm main crack for data collection. The samples were unloaded between each crack. The computer controlling the loading rig recorded load and displacement at 0.1 second intervals, and delamination lengths were recorded visually to within 0.5 mm accuracy [17].

To ease data collection, rather than manually noting load and displacement values at each delamination length (difficult to coordinate), the time at which the lengths were reached was instead documented, and a second spreadsheet and VBA program pair used to extract the corresponding data using timestamps. This significantly reduced data processing time, as it produced reliable, accurate results for any arbitrary number of sets and samples.

Fig. 18 shows a sample nearing the end of main crack progression. As per ASTM suggestion the samples were not fully broken during the test, but rather split later to create examinable delamination interfaces.

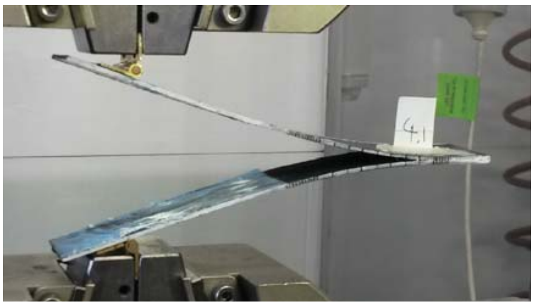


Fig. 18 Test Sample During Main Crack

The load, displacement and delamination length data obtained from the DCB experiment were used to calculate strain energy release rate at each point along the main crack.

IV. Results and Discussion

The collected data of load and cross-head displacement at each delamination length were the numerical outputs of the DCB experiment, with qualitative information of crack interface structure subsequently employed to explain the calculated results. Fig. 19 plots average load against delamination length for each of the sample sets against those of the previous experiment.

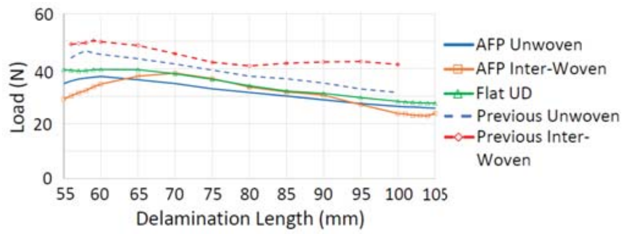


Fig. 19 Average Load v Delamination Length

The overall trend of the experimental data was that AFP unwoven laminates suffered a slight decrease in load required for delamination progression compared to flat UD, and that inter-weaving matched them in the centrally located weave region, but was lower elsewhere.

Of interest is the fact that the previous experiment's load values were noticeably higher than those of this project, with the previous inter-woven samples also above rather than below those of the unwoven comparison. These observations were further explored following fracture toughness calculation, and it is important to remember that the previous experiment's inter-weave was located towards the end of the experiment samples, as can be seen by the increase in load at higher delamination lengths.

A. Mode I Delamination Fracture Toughness

Modified Beam Theory was used to calculate strain energy release rate at each delamination length by (1) [17].

$$G_I = \frac{3P\delta}{2b(a+|\Delta|)} \quad (1)$$

Where G_I is strain energy release rate, P load, δ cross-head displacement, b sample width, a delamination length and Δ a compliance correction length to account for beam rotation at the delamination front. Δ was calculated from the x-intercept of a cube root plot of each sample's compliance C (2), Fig. 20) [17].

$$C = \frac{\delta}{P} \quad (2)$$

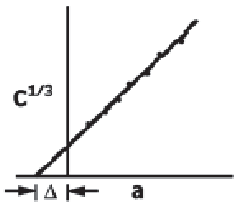


Fig. 20 Compliance Cube Root Intercept [17]

Table IV provides the compliance correction lengths of each sample.

TABLE IV
SAMPLE COMPLIANCE CORRECTIONS

Set	Sample Compliance Correction (mm) 1	2	3	4	5
AFP Unwoven	15.81	5.63	12.14	10.56	2.58
AFP Inter-Woven	18.33	10.83	6.64	4.57	7.71
Flat UD	7.21	8.12	12.6	6.32	4.05

Fig. 21 shows the strain energy release rates of this project's sets plotted against delamination length.

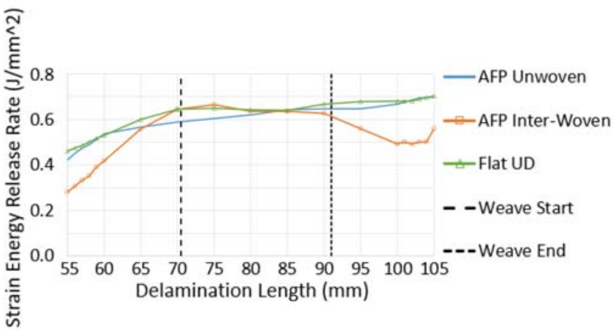


Fig. 21 Mode I Delamination Fracture Toughness Results

The first feature of note is that the AFP unwoven results are similar to those of the flat UD panel, with an almost constant 3.5% decrease in delamination fracture toughness. This suggests that AFP production itself does not impose significant fracture toughness penalties, a theory which could be confirmed by repetition of the experiment with larger sample batches, as well as differing ply angles and layups.

Where the results differ from expected is in the notably poor performance of the AFP inter-woven samples outside of the indicated weave region. This is contrary to the previous experiment's suggestion that inter-weaving provides a small overall increase in delamination fracture toughness [15]. Still present however is the large increase within the weave region, up to and even exceeding the unwoven and flat UD cases. This local strain energy release rate increase reaches around 50%, similar to the 60% observed in the previous experiment [15].

This compares favourably to the finding of Mouritz and Cox that stitching can increase delamination fracture toughness by up to 20% [12], however such benefits are limited to local inter-weave locations. Integrating over the entire delamination shows that the inter-woven case loses more than 10% total energy absorption (Table V).

TABLE V
TOTAL DELAMINATION ENERGY ABSORPTION

Set	Energy Absorbed (J/mm)	% Increase
AFP Unwoven	30.42	-3.5%
AFP Inter-Woven	28.15	-10.7%
Flat UD	31.53	-

This could be explained by the scale of the respective reinforcement structures; stitching is much smaller and more evenly distributed than inter-weaving. It is possible that up-sizing the part to include multiple inter-weaves simultaneously and continuously would cause the delamination fracture toughness to average out over the structure, resulting in more consistent benefit or deficit. However, it is also possible that the observed cyclic nature would constructively interfere under the influence of multiple inter-weaves and result in exaggerated crack jumping and halting. These prospects and their potential investigation methods are addressed in Section V-C on future work.

It appears as if the inter-woven data has simply shifted downwards without major alteration to its structure, which raises two questions, and comparison to the previous experiment in Fig. 22 begs a third:

1) What causes the large fracture toughness increase at inter-weave sites?
2) Why is the inter-woven case weaker overall, resulting in poor performance away from weave sites?
3) Why is the fracture toughness superiority of the the unwoven and inter-woven results switched between the prior and current experiments?

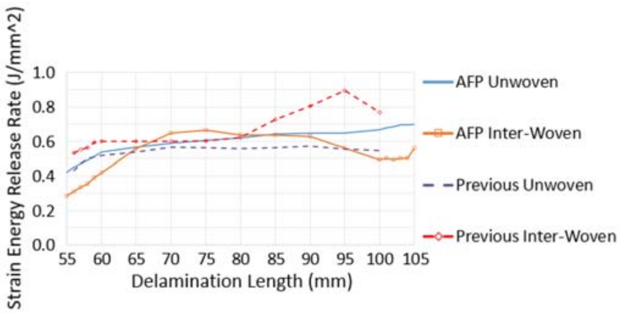


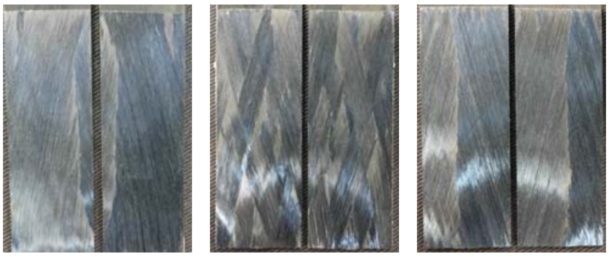
Fig. 22 Previous and Current Results Overlay

Other than the switch of the third question there were no significant differences between the general form of the previous and current experiments' data, aside from the differing inter-weave locations. The questions raised by these results were investigated through examination of the delamination interfaces of each sample type.

B. Delamination Interface Examination

Various levels of optical magnification ranging from 35x to 3000x were used for examination of delamination interfaces to explain the observed DCB results.

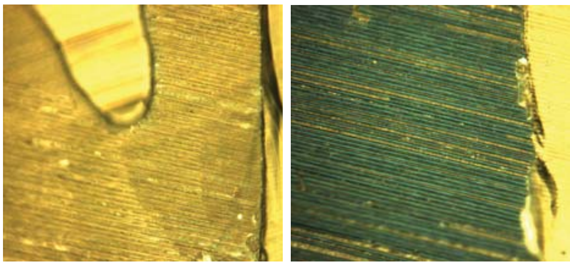
The first aspect investigated was the seemingly mirrored fracture interfaces seen on each sample type in Fig. 23. This pattern implied that when the two interfaces were joined, they contained fibres of the same orientation, meaning that the crack progressed within plies rather than between them.



(a) AFP Unwoven (b) AFP Inter-Woven (c) Flat UD

Fig. 23 Set-Representative Delamination Interfaces

This was disproven upon optical inspection at 500x magnification by the fact that, as seen in Fig. 24, one side of the interface did not possess fibres, but rather the grooves left by their separation. The plies therefore split apart along the expected interface, but not in the predicted manner.

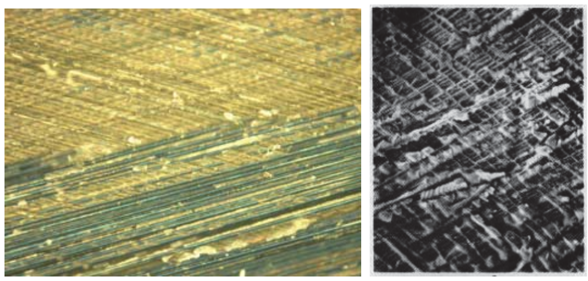


(a) Empty Fibre Grooves (b) Clean Fibres

Fig. 24 Fibre-Matrix Debonding Interfaces (500x)

Fig. 24 shows that failure of the material occurred via fibre-matrix debonding, as opposed to fibre or matrix cracking. This is illustrated by the cleanliness of the fibres and matrix grooves; they broke tidily from each other rather than leaving broken material behind. The implication of this observation is that the links between fibres and matrix were particularly weak, a possible outcome of the manufacturing (curing) process. Fortunately all samples of the current experiment were produced via the same hot press cure, however this raises issues with comparison to the previous experiment.

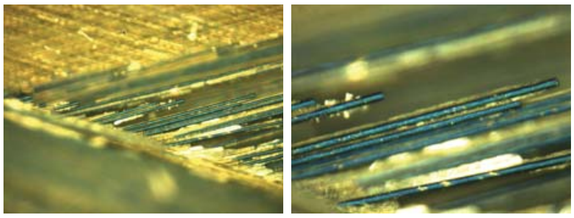
The observed interfaces were compared to the delamination regions categorised by Nicholls and Gallagher [6], and found to most closely match Region II (Fig. 25). This region exists between plies of dissimilar orientation and features no propagation between plies, lower fracture toughness than Region III's fibre bridging and breakage, the same empty grooves of the experimental interfaces and no dependence upon ply orientation. This list's final point suggests that further studies of different fibre angles would produce matching results, reducing the number of permutations required to characterise inter-woven behaviour. This would likely be material and layup dependent however, and not a universal condition.



(a) Delamination Interface (1200x) (b) Region II [6]

Fig. 25 Delamination Region Categorisation

Broken fibres at inter-weave sites (Fig. 26) answered the first question of their fracture toughness 'spike'. These regions also possessed 'dirtier' fibres (some matrix left behind), suggesting fracture toughness contribution from matrix breakage rather than fibre-matrix debonding.



(a) 500x Magnification (b) 1200x Magnification

Fig. 26 Inter-Weave Broken Fibres and Matrix Failure

This correlates with Dransfield's observations [9] that stitching causes matrix deformation and stitch breakage, though the remaining feature of fibre pullout was not known to have occurred in these samples. As such it can be concluded that inter-weaving's delamination fracture toughness benefits originate from induction of similar failure modes to stitching. Its efficacy as a replacement for traditional through-thickness reinforcement is therefore bolstered.

A failure mode change must have occurred in the vicinity of the inter-weave site, and so the early crack region was examined in an attempt to identify its location, nature and possible triggers. A point leading up to the inter-weave was observed in Fig. 27 to be the site of such a transition, featuring a sudden switch between which side of the matrix debonded from the fibres to reveal one side and hide the other. The specific cause of this is unknown however, and it likely occurs at the point where the transverse 'pull' on the fibres from the inter-weave outweighs the original resistance of the crack to changing propagation mode.

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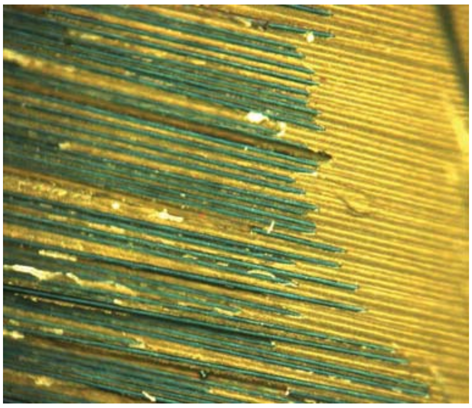
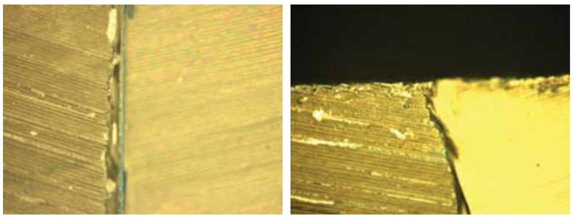


Fig. 27 Inter-Woven Interface Transition (2000x)

An investigation of the film insert edge and corners of the inter-woven samples uncovered no further insights into the mechanisms of their behaviour (Fig. 28). It was expected that the asymmetry of the samples about the middle interface could have caused strange effects at the corners of the insert, but this was observed to not be the case.



(a) Insert Edge (b) Insert Corner

Fig. 28 Inter-Weave Interface Edges (300x)

To answer the second question of the overall poor performance of the inter-woven laminate, a broader three-dimensional view of its interfaces was considered. While the fibre-matrix debonding of the delamination would have affected delamination fracture toughness, this phenomenon was observed for all samples, and doesn't explain the specific deficiencies of the inter-weave.

It does however lend evidence to the theory that the inter-weave and its highly layered crack interface (Fig. 29) allowed the delamination to easily traverse the path of least resistance by providing a number of options in terms of interface selection. There were also a large number of discontinuities and potentially resin-rich regions via which it could bypass fibres, with the combination of these factors resulting in the observed overall fracture toughness decrease.

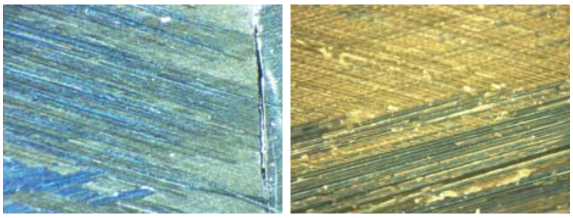
(a) Broad View (b) 300x Magnification

Fig. 29 Inter-Woven Layered Interface

The third question of the change in superiority of unwoven and inter-woven samples between the two experiments may be explained by similar reasoning, in that this behaviour could have made the inter-woven laminate more susceptible to the effects of the altered cure cycle. Unfortunately this is speculation and requires further investigation.

The use of delamination halting and mid-crack acoustic observation would shed additional light on the step-by-step behaviour of the crack, as well as its movements between the exposed layers of the inter-weave. These considerations are discussed in Section V-C on future work of the topic.

A weaker transition than those leading up to the inter-weaves was observed for the AFP unwoven samples near the film insert in Fig. 30a, for which unique colouring was used to better show the transition of fibres from covered to exposed. A related feature was observed on both the AFP unwoven and flat UD samples, with a transition running longitudinally along the delamination zone (Fig. 30b). These structures are thought to have increased delamination fracture toughness by virtue of requiring the matrix to break itself to expose either side of the transition, in addition to the original detachment from fibres. This is not thought to have played a significant role however, as the inter-woven samples possessed similar features and still displayed diminished fracture toughness.



(a) Near Insert (Colouring for Clarity, 500x) (b) Longitudinal (1200x)

Fig. 30 AFP Unwoven Surface Transitions

C. In-Plane Properties Prediction

As expected, inter-weaving prevented fibre and matrix damage as a result of not requiring stitching or other post-processing. This is expected to have prevented significant in-plane property reduction, a known symptom of such defects [8], [9], [11], [14]. However, as previously discussed the inter-woven delamination interface showed that the structure possessed significant three-dimensionally based geometry, which translated to fibre waviness and misalignment. It is therefore likely that the in-plane property gains of inter-weaving, in particular stiffness, would be accordingly diminished [4], [5].

A study into the in-plane property effects of inter-weaving would consequently produce results of significant interest, especially if paired with assessment of their sensitivity to delamination, as was shown to be a key property by Aslan [2].

V. Conclusion

The major findings, experience-based recommendations and identified future work avenues of this research project have been collated and outlined.

A. Findings & Significance

Findings and their significance have been summarised from discussion of results.

- AFP Inter-Weaving Capability
  The AFP inter-weaving process is capable of applying through-thickness reinforcement, and has an appreciable effect on delamination fracture toughness.
- AFP Unwoven Similar to Flat UD
  Unwoven AFP samples displayed only a slight decrease in delamination fracture toughness compared to standard flat UD laminates, implying that the flat UD control might not be necessary for assessing inter-woven behaviour, as it can be represented by the AFP unwoven case, reducing the cost of future investigations.
- Local Inter-Weave Delamination Fracture Toughness Increase
  Fibre breakage and matrix deformation were found to be the cause of local delamination fracture toughness increases at inter-weave sites.
- Overall Inter-Weave Delamination Fracture Toughness Decrease
  The overall decrease in delamination fracture toughness of AFP inter-woven laminates was found to be due to their layered structure providing extensive options for cracks to traverse the path of least resistance.

B. Recommendations

The experience of the projects' completion has lead to the realisation of ways in which similar work could be performed with increased efficiency or reliability.

- Hot Press Cure Guidelines
  Panel sealing and tape damming were major improvements to the hot press cure cycle, and should always be employed for future projects. Knowledge of the impacts of pressure top-up has allowed for prevention of material movement and subsequent panel loss.
- Data Reduction Code Flexibility
  The VBA code for data collection and reduction was built with the very specific requirements of this project in mind. As such it would be prudent to work greater flexibility into its design in terms of data inputs and set numbers.

C. Future Work

Suggestions of future research directions building upon this project have been highlighted throughout the report, and are summarised here.

- Multiple Weave Sites (Large Scale Samples)
  Similar to stitching, a large difference in scale between a structure and its inter-weaves may either smooth or exaggerate the observed oscillating fracture toughness, a study on which would provide particularly interesting characterisation of real-world inter-woven behaviour.
- In-Plane Properties Investigation
  The predictions of in-plane properties being affected by fibre waviness and lack of stitching damage require experimental assessment, which would build a broader picture of the behaviour of inter-woven laminates.
- Cross-Reference of Results by Reproduction
  Repetition of the experiment with varying materials, ply angles and cure cycles would confirm or dispute the drawn conclusions of how delamination fracture toughness of inter-woven laminates is affected by these factors.
- Mid-Delamination Halting and Acoustic Observation
  Examination of in-progress delaminations via acoustic observation would describe the crack front's 3D movement through the inter-woven structure, and assist in explanation of calculated results.

This project achieved its specified aims, and has produced not only a novel automated fibre placement method, but also an assessment of its impact on the identified key property of inter-laminar fracture toughness. It is expected that pursuit of the discussed future work avenues would contribute valuable knowledge to the research basis of the field.

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