MODE I AND II FRACTURE TOUGHNESS TESTING OF INTERLEAVES FOR BALLISTIC IMPACT

Daniel Turkenburg[1], Jamie Hartley[2], Hartmut Fischer[3], Geert Roebroeks[4], Carwyn Ward[5] and Sander Gielen[6]

[1,3,6]TNO, Locatie Eindhoven, De Rondom 1, 5612 AP Eindhoven, Netherlands
Email: daniel.turkenburg@tno.nl, Web Page: https://www.tno.nl/en
[2,5]Advanced Composites Centre for Innovation and Science, University of Bristol, Queens Building, University Walk, Bristol BS8 1TR, UK
Email: jh9799@bristol.ac.uk, Web Page: http:// http://www.bristol.ac.uk/composites
[4]TNO Ballistics, Locatie Rijswijk, Lange Kleiweg 137, 2288 GJ Rijswijk, Netherlands
Email: geert.roebroeks@tno.nl, Web Page: https://www.tno.nl/en

Keywords: Interleaves, Fracture Toughness, Delamination Control

Abstract (200 words)
Due to their brittle nature, fibre-reinforced polymer (FRP) laminates are vulnerable to failure from high velocity ballistic impact. Fibre-Metal Laminates (FMLs) provide promising impact improvements over classical monolithic FRP materials due to the increased ductility introduced by the presence of metal layers. An important mechanism within this is the delamination between layers, allowing the laminate to act as a number of thin separated layers in efficient membrane deformation. Being able to control this delamination mechanism is important to absorb the large amounts of energy required.

In this investigation a series of materials were trialled as interleaves in mode I and II fracture to determine their ability to modify the interlaminar properties within an FML. The interleave types were tested both with (surface porosity of 20%) and without surface patterning. Results of the both sets of tests demonstrate a relatively low adhesive strength between the various interleaves and the glass fibre laminates as expected. This resulted in significantly reduced fracture toughness values over the reference laminate material. Trends between the individual interleaves are more difficult to identify although generally the Teflon-like ETFE material had the lowest performance of all samples tested. The effect of adding patterning to the interleaves is not clear from this testing although there are some signs of a slightly improved adhesion as a result of the patterning.

1. Introduction

Advanced composite materials are rapidly becoming popular in the manufacture of a range of engineering structures as a result of their low weight. However, due to their brittle nature, fibre-reinforced polymer (FRP) laminates are vulnerable to failure from high energy impact, such as from ballistics or blasts. Rather than absorbing the energy of the impact through deformation, brittle failure results in significant delamination, penetration and potentially catastrophic failure of the structure.

By combining FRPs with metallic layers in the form of Fibre-Metal Laminates (FMLs), promising impact improvements over monolithic materials can be achieved. This is due to the increased ductility provided by the metallic layers [1]. Fibre metal laminates are hybrid laminates containing layers of metallic and fibre reinforced polymers (FRPs). The general use of FMLs has been summarised by Sinmazçelik et al. [2]. Generally FMLs have been used in three configurations, based upon the fibre reinforcement type used. Glass fibre reinforcement (GLARE) is the preferred choice for impact

Excerpt from ISBN 978-3-00-053387-7

resistance. GLARE has demonstrated promising impact improvements over monolithic aluminium as demonstrated by Vlot and Krull [1]. GLARE laminates showed small increases in cracking energy at low velocity when compared to monolithic aluminium, but significantly improved performance at high velocity. This performance was improved if the relative amount of glass/epoxy in the laminate was increased. This is partly due to the strain rate sensitivity of the glass fibres; however an important mechanism was thought to be the delamination between layers, allowing the laminate to act as a number of thin separated layers in efficient membrane deformation.

More recently, Moriniere investigated the behaviour of FMLs under low energy impact [4], One of the conclusions highlighted by this work was the effect interlaminar adhesion has on the impact performance. The author highlighted that a lower adhesion quality in specific areas of the laminate increased the ability of the panel to deform, resulting in a greater energy absorption.

In this paper a series of interleaves materials will be investigated for their effectiveness at modifying the adhesion between layers within a laminate. Relatively low adhesion materials have be chosen that would allow delamination between layers within a laminate and thus increase the possible deformation of a panel being impacted. The material types will be characterized for their interlaminar fracture toughness using mode I and II testing.

2. Materials and Methods

Materials

The chosen reference laminate material was a SE70 E-glass fibre/epoxy prepreg by Gurit. In total 3 interleave types were chosen, a polyimide film, an Ethylene tetrafluoroethylene (ETFE) release film and an aluminum foil. A surface patterning was also used to explore it's effect on adhesion. The polyimide and aluminum interleaves were tested both with and without surface patterning, created by punching a close packed pattern of circles of 5mm in diameter (surface porosity of 20%). The ETFE film was tested only without patterning.

Prior to insertion into the prepreg laminate, the interleaves were first treated to avoid contamination and help with adhesion. Each of the interleave materials was first cleaned on both sides by wiping with acetone. For the aluminum foil interleaves a further surface treatment was applied. Each of the foils was soaked for 60 seconds in a sodium hydroxide solution (10 wt%) then in water for two minutes, one minute in highly contaminated water then a further minute in clean water, to clean off any alkaline solution. As the surface treatment process lead to wrinkles within the foil it was rolled flat with a hand-held roller then held under vacuum for 5 minutes. This provided a relatively smooth foil for interleaving.

Methodology

The chosen test standards for this investigation were ASTM standards D5528 (Mode I DCB) and D7905 (Mode II 3PB ENF). The chosen test coupon designs are shown in Figures 1 and 2.

Excerpt from ISBN 978-3-00-053387-7

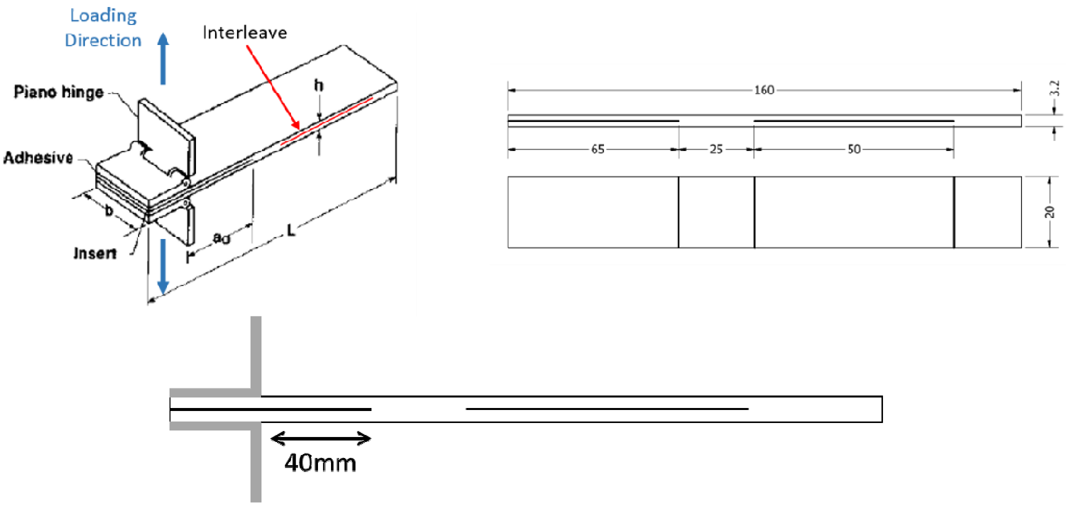

Figure 1. Mode I DCB Test Configuration

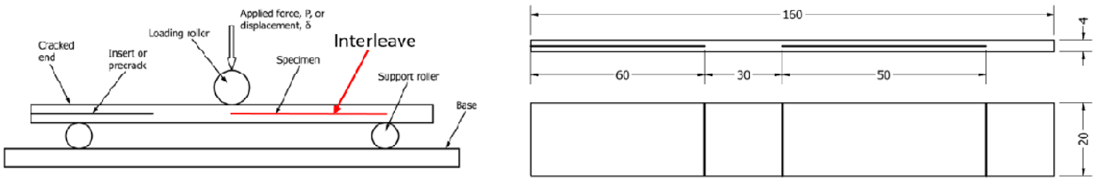

Figure 2. Mode II ENF Test Configuration

Test laminates were created by hand laminating unidirectional layers to the required thickness (16 plies for Mode I and 20 for Mode II). Vacuum consolidations of the laminate were carried out first for each set of two plies and then for the half and full laminate stacks. The interleaves were created by laying down a strip of the material at the mid-plane. A sheet of the ETFE release film was also added to create a starter crack at the end of the specimens, as shown in Figure 3.

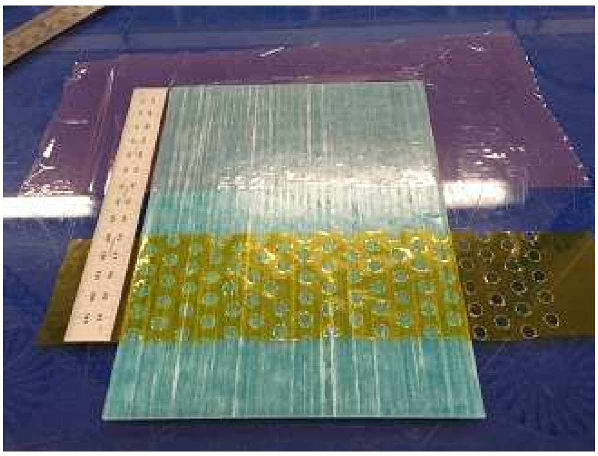

Figure 3. Positioning of Interleave and Crack Starter

Each of the laminates was cured under vacuum pressure within an oven for 100 minutes at 100 °C. Cured panels were then cut into test samples using a diamond saw.

For the Mode I samples an additional stage was required to attach loading hinges. The bonding surfaces were prepared using sand blasting, followed by surface degreasing with acetone. A thin layer of adhesive (Araldite 2014-1) was then applied to the hinge and the sample to provide the bond. The bonded samples were cured in an oven at 80 °C for two hours.

For both sets of testing, a desktop Shimadzu test machine was used. For the Mode I testing a 1 kN load cell was used, with adjustable wedge grips to grip the specimen (Figure 4). The initial pre-crack length was 40 mm, although 30 mm was used for the reference. A loading rate of 3 mm per minute was used to pull the specimen apart and propagate the crack. The edge of the specimen was coated in a white corrector fluid to help track the crack propagation. A pixelink camera was used to take incremental photos to provide the crack propagation information (Figure 5). Testing was continued until ultimate failure of the specimen.

Figure 4. Mode I Test Set-Up

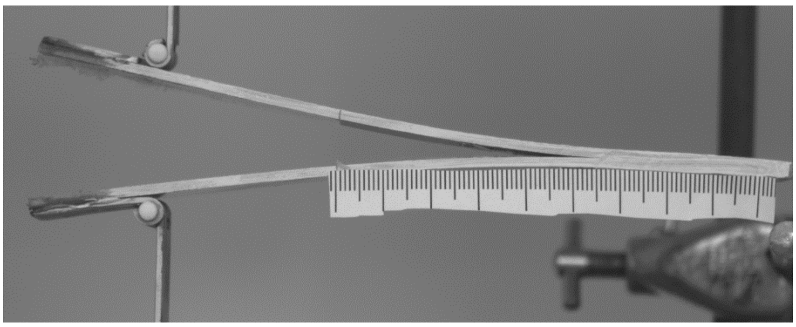

Figure 5. Pixelink Crack Tracking Image

Excerpt from ISBN 978-3-00-053387-7

For the Mode II testing, a 3-point-bend method was applied. Samples were positioned within a test fixture spanning 100 mm and loaded through a central roller at a displacement rate of 0.8 mm per minute (Figure 6). Samples were positioned to give an initial pre-crack length of 30 mm. Before testing, a compliance method was used to calibrate the results. This involved positioning specimens to give pre-cracks of 20mm and 40 mm and loading these until a load approximately half of the ultimate failure load (~500 N was chosen). The samples were then repositioned to give a pre-crack of 30 mm and tested until crack propagation.

Figure 6. Mode II Test Set-Up

This test method does not provide stable crack propagation and so only an initial fracture toughness can be obtained, at first failure of the sample. At this point the crack jumps to a point just below the central roller. As this was not enough distance to propagate the crack into the interleave region a secondary test had to be carried out. To ensure fracture of the interleave was being recorded the crack was first propagated to the edge of or into the interleave region by continued loading of the specimen. The test fixture was then adjusted to provide a shorter beam span, but with an initial pre-crack length of 20 mm. The chosen span length was 70 mm for the second test. The samples were then loaded as before until first failure and this was chosen as the initiation fracture load of the interleave.

Excerpt from ISBN 978-3-00-053387-7

RESULTS AND DISCUSSION

Mode I

Testing of the Mode I samples showed unstable crack propagation in all but one of the samples (B2). This behaviour is highlighted by the unsteady ‘zig-zag’ nature of the load-displacement plot, as the load drops each time the crack jumps. The initial fracture loads for the reference/baseline samples are slightly higher than the rest, most likely as a result of the slightly shorter initial crack length. For most of the interleave types a rapid jump of the crack through the interleave region was observed, as well as a significant drop in load. Only the patterned aluminium samples showed any steady propagation through the interleave region.

The fracture toughness can be calculated based on the load-displacement results and crack length obtained using the modified beam theory method.

$$G_I = \frac{3P\delta}{2ba} \tag{1}$$

Where:
P = load
δ = load point displacement
b = specimen width
a = delamination length

Due to the unstable nature of the crack propagation through each specimen the characterisation of the fracture toughness was not clear. As each specimen begins to fail at a very similar load the reference mode 1 fracture toughness was calculated from this point. After this the value varies as the crack jumps irregularly and also an increase in fibre bridging occurs. For the interleaved samples the characterisation was made more difficult as the crack would tend to jump across the entire interleaved region in one step. As a result the lowest fracture toughness value observed was taken. This is a reasonable assumption as the adhesion at the interleave was clearly low by the ability of the crack to pass through so quickly. However these values are probably not representative of the trend between each interleave type, for example the unpatterned aluminium appears to be overestimated using this method as it showed a similar performance to the other interleave types.

Table 1. Mode I Fracture Toughness Results

Interleave	Mode I Fracture Toughness (J/m^2)
None/Reference	521
Patterned Aluminium	61
Unpatterned Aluminium	235
Teflon/ETFE	64
Patterned Polyimide	111
Unpatterned Polyimide	90

By evaluating the failure surface after testing it can be seen that in most cases the interleave material remains intact and that adhesive failure between the glass and interleave has occurred. For the unpatterned polyimide film there are traces of discolouration on the surface of the glass fibre laminate, implying some cohesive failure is occurring. In the case of the unpatterned aluminium there is slight tearing of the foil although this very small. The patterned aluminium interleaves do show significant tearing and imply a more cohesive failure has occurred where the crack has passed through the foil rather than around it.

Excerpt from ISBN 978-3-00-053387-7

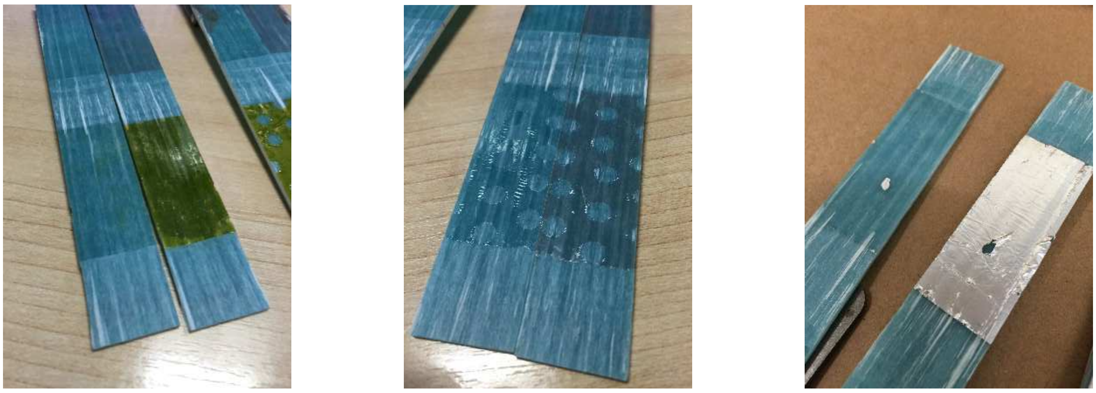

Figure 7. After failure view of interleaves, with small tear in Aluminium

Figure 8. Significant tearing within patterned aluminium foil

Mode II

The Mode II fracture toughness was calculated using the following equation:

$$G_{II} = \frac{3mP_{max}^2 a_{pc}^2}{2B} \tag{1}$$

Where:
P_{max} = Maximum load at first failure
a_{pc} = length of initial precrack
B = specimen width
m = gradient of specimen compliance against crack length cubed

The initial load-displacement results for the mode 2 testing are very consistent, resulting in a better trend between mode II fracture toughness.

Excerpt from ISBN 978-3-00-053387-7

Table 2. Mode II Fracture Toughness Results

Interleave	Mode I Fracture Toughness (J/m^2)
None/Reference	2298
Patterned Aluminium	1290
Unpatterned Aluminium	914
Teflon/ETFE	467
Patterned Polyimide	1223
Unpatterned Polyimide	1436

Mode II test results showed good consistency of the initiation fracture toughness within the reference glass material at around 2kJ/m^2. The secondary test within the interleave section also showed relatively consistent results, between the individual data sets. Of all the interleave types the lowest performance was from the release film (ETFE) as expected. This set of tests showed a significant drop in fracture toughness when compared to the baseline. The unpatterned aluminium showed a marginal performance increase over the release film, however in one case it was observed that the crack length would increase without any drop in load (specimen A3). The other 3 interleave types showed similar performances, giving values for fracture toughness around half that of the baseline glass material.

3. Conclusions

Overall, despite a few issues with the testing procedure the results demonstrate a relatively low adhesive strength between the various interleaves and the glass fibre laminates as expected. This resulted in significantly reduced fracture toughness values over the reference laminate material. Trends between the individual interleaves are more difficult to identify although generally the Teflon-like ETFE material had the lowest performance of all samples tested. The effect of adding patterning to the interleaves is not clear from this testing although there are some signs of a slightly improved adhesion as a result of the patterning.

If this testing was repeated it would be suitable to manufacture test coupons with the interleave material over the entire plane of the glass fibre interface, rather than in smaller strips. This would help to eliminate some of the uncertainty in identifying the correct fracture toughness and also negate the need to adjust the specimen length to promote failure at the correct position.

Acknowledgments

References

[1] Krull M, Vlot A. Impact Damage Resistance of Various Fibre Metal Laminates. J Phys Iv Fr 1997;7:1045–50.

[2] Sinmazçelik T, Avcu E, Bora MÖ, Çoban O. A review: Fibre metal laminates, background, bonding types and applied test methods. Mater Des 2011;32:3671–85.

[3] Sadighi M, Alderliesten RC, Benedictus R. Impact resistance of fiber-metal laminates: A review. Int J Impact Eng 2012;49:77–90.

[4] Moriniere F. Low-velocity impact on fibre-metal laminates. 2014.

Excerpt from ISBN 978-3-00-053387-7