INTERLEAVING FOR EASY REPAIR OF INTERLAMINAR DAMAGE – CAN IT BE DONE?

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Abstract

An easy-repair laminate concept is investigated to address the repair problem posed by interlaminar damage due to impact. A carbon epoxy laminate interleaved with PLA is shown to preferentially fail in shear within the interleaf. Good strength recovery is achieved when the laminate is heated and subjected to external pressure.

1. Introduction

Laminated carbon fibre polymer composites offer excellent specific strength and stiffness and so are attractive materials for a range of weight critical applications including the aerospace, wind energy and automotive sectors. The Achilles' heel of these laminated materials is their susceptibility to impact damage. Even impacts which cause little or no visible damage on the exterior of the laminate can produce interlaminar failure and this can significantly reduce the compression strength [1]. Repair strategies to restore structural performance usually involve removing the damaged material by machining to form a 'scarfed' surface to which a repair patch is bonded. An alternative, for those cases involving no significant fibre damage, is to drill a hole at the centre of the damaged area and then to inject a liquid resin which is subsequently cured [2].

To avoid the complexity of these repair processes, self-healing composites have been devised [3]. Typically these composites contain microcapsules or hollow glass fibres separately storing a suitable resin and its hardener [3-7]. Providing the damage ruptures the embedded resin/hardener storage systems and satisfactory infiltration of the crack takes place then good self healing can be achieved. For example, self repair of impact damage restoring upto 78% of the pristine compression strength has been reported [7]. The drawbacks of such self-healing composite systems include the additional complexity in manufacture of the material, degradation of the specific properties of the composite and the fact that once healing has occurred in a particular location subsequent damage at that location cannot be self-healed [8].

This paper explores an alternative strategy which does not target self-healing but aims to ensure that interlaminar damage can be readily, and repeatedly, repaired.

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2. The concept

Conventional laminated carbon fibre polymer matrix composites are susceptible to interlaminar damage when impacted because of their relatively low through-thickness shear strength and interlaminar toughness.

One strategy to provide an alternative to the traditional repair process is to include in a thermoset matrix a thermoplastic component which is suitable for bonding by thermal treatment [9]. Hayes et al demonstrated that using this approach the impact strength of the modified matrix could be restored to upto 65% of the pristine value but the healing efficiency reduces significantly on repeating the impact/repair process (no mechanical properties were reported for the healed composites).

The combination of a thermally bondable thermoplastic and a thermoset matrix is further explored in the current work but in this case an interleaved strategy is adopted. In this strategy a conventional carbon epoxy laminate is interleaved with a material which can be thermally bonded. The interleaf material must be chosen so that the impact damage occurs predominantly within the interleaf and not at its interface with the composite or within the epoxy matrix. The interleaf film must therefore have the following properties:

- i) Be capable of thermal bonding at a temperature which will not damage the carbon epoxy laminate.
- ii) Be able to withstand the cure temperature of the carbon epoxy system and remain as a distinct layer in the cured composite.
- iii) Possess a shear strength that is lower than the through-thickness shear strength of the carbon-epoxy composite but not so low that the interleaved composite is too susceptible to impact damage.
- iv) Possess a good bond to the carbon epoxy layer so that failure will occur within the interleaf rather than at the composite-interleaf interface.

The idealised damage-repair cycle of the proposed interleaved composite is shown in Figure 1. On impact the interleaved composite would preferentially fail within the interleaf layer due to impact. The laminate could then be heated to initiate bonding, perhaps accompanied by external pressure, and so restore the initial pristine state.

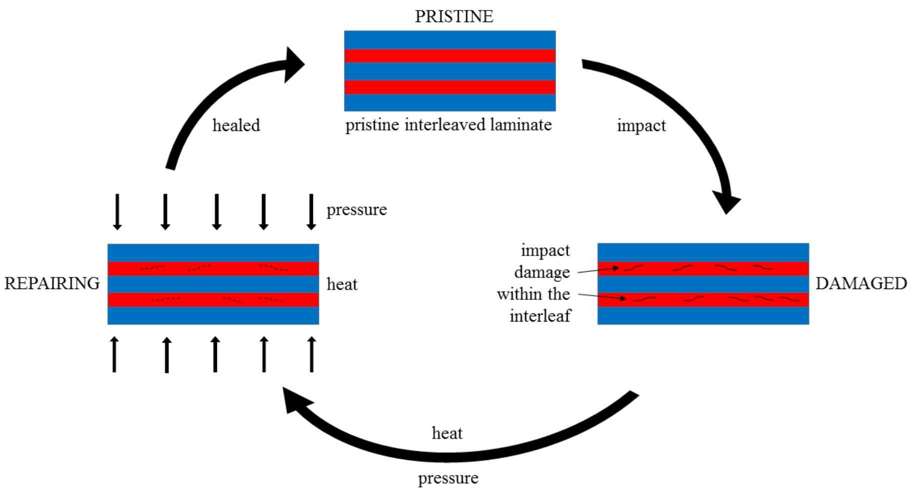

Figure 1. A sketch of the idealised damage-repair cycle of an interleaved composite subjected to impact

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3. Experimental investigation

3.1. Material

The carbon epoxy system used in the experimental trials was TS300/914 produced by Hexcel. This composite has a cured ply thickness of 0.125mm. The interleaf material was Ingeo™ 2003D polylactide (PLA) produced by IDES. The PLA was formed into a film of thickness 0.14mm. The interlaminar shear strength (ILSS) of the carbon epoxy composite is 78MPa, whereas the shear strength of the PLA film was measured to be approximately 23MPa in short beam shear tests conducted according to ASTM D2344M. For a practical application an interleaf material with a shear strength closer to (but still less than) that of the composite will be required but PLA is a suitable model material with which to investigate the easy repair concept.

3.2. Test specimens and test procedure

Flexural specimens (10mm wide and 80mm long) were prepared from a laminate consisting of 24 plies of carbon epoxy composite with a single PLA interleaf at the mid-plane. The laminate was cured according to the manufacturer's recommended procedure. Three separate batches of specimens were prepared. The first set used the standard PLA film as supplied. For the second set the PLA film was plasma treated for 5 minutes using low pressure oxygen plasma. The third set also used plasma-treated film but the interleaved laminate was post-cured at 190°C for 5 minutes while vacuum bagged.

The specimens were subjected to a three-point bend test with a span of 64mm at an applied displacement of 1mm/min. The specimens were loaded until total separation had occurred at the specimen mid-plane. The upper and lower parts of each specimen were then fitted back together, placed on an aluminium plate, enclosed in a vacuum bag and placed in an oven. The specimen was heated to 190°C for 10 minutes. The vacuum was applied and maintained at this temperature for a further 5 minutes. The specimens were then cooled while maintaining the vacuum and then re-tested in three-point bending as described previously.

3.3. Results

Figure 2 shows a micrograph of the cured interleaved laminate. It can be seen that the PLA has remained as a distinct, continuous interleaf.

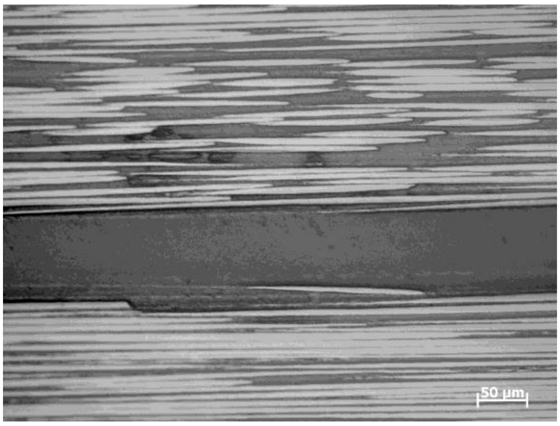

Figure 2. A micrograph of the PLA interleaf of an interleaved carbon epoxy composite specimen.

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Figure 3 shows typical load-displacement curves from three-point bend tests performed on a standard PLA specimen before and after repair. It can be seen that the repaired specimen recovered about 70% of the initial strength. Table 1 contains the shear strengths for 4 specimens using the standard PLA film. It can be seen that the initial shear strengths were in the range of 8.5 to 10.2MPa and the strength recovery varied from 36% to almost 80%. An examination of the fracture surface revealed that some failure had occurred at the interface of the PLA interleaf with the carbon epoxy plies.

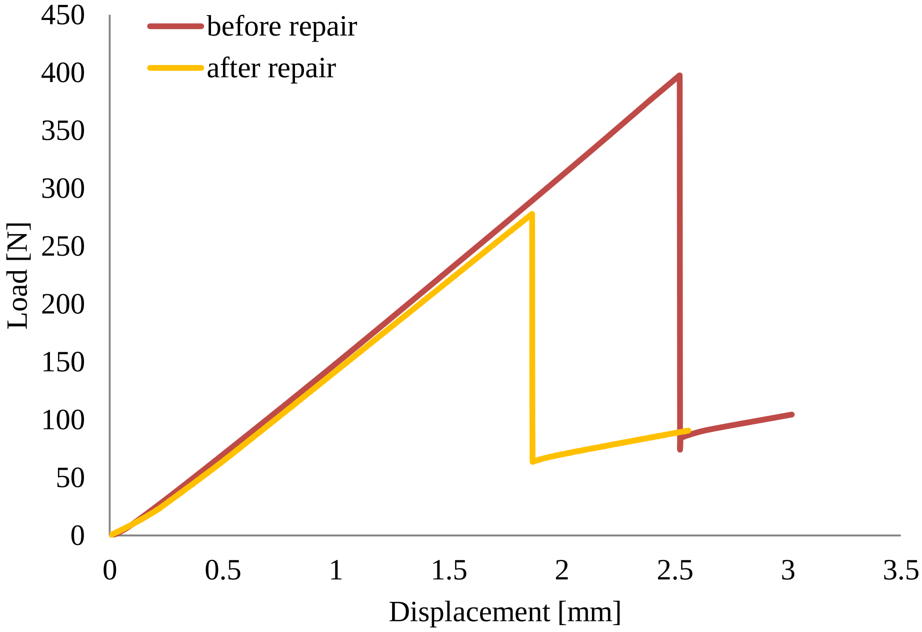

Figure 3. The load-displacement curves of a typical standard PLA specimen subjected to three-point bending test.

To improve the bond of the PLA to the epoxy composite, the PLA was plasma treated as described earlier. The test results in Table 1 show that the initial shear strength of these specimens was relatively low, with an average of 3MPa. Examination of the fracture surface showed that PLA had remained well bonded to the carbon epoxy composite and it therefore appeared that the PLA had a very low shear strength after plasma treatment. However after repair the average repair strength increased to 9.4MPa. Selected specimens were repaired again and then subjected to a further three-point bend test. These showed very good strength recovery ranging from 88% to 104% of the strength after the first repair which was an improvement over the results from the standard PLA specimens.

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Table 1. The shear strengths of different batches of PLA specimens measured in three-point bending tests.

	Standard PLA			Plasma-treated PLA					Post-cured plasma–treated PLA				
	Shear strength (MPa)		Recovery* (%)	Shear strength (MPa)		Recovery* (%)	Shear strength (MPa)	Recovery* (%)	Shear strength (MPa)		Recovery* (%)	Shear strength (MPa)	Overall recovery** (%)
	before repair	after repair		before repair	after repair		after repair		before repair	after repair		after repair	
	9.0	6.9	76	3.4	11.4	335	10.1	88	11.0	9.2	84	8.6	78
	10.2	3.7	36	1.7	8.4	507	8.7	104	12.2	9.2	76	8.2	67
	9.7	6.8	70	3.0	6.7	223	6.7	100	13.0	10.8	83	3.7	28
	8.5	3.4	40	1.7	9.6	571			12.0	8.1	69	7.2	61
				4.9	11.5	233	10.5	91	6.8	7.5	111	6.8	101
				3.0	8.9	295			9.0	5.4	59	5.5	61
average	9.4	5.2	55	3.0	9.4	361	9.0	96	10.6	8.4	80	6.7	66
standard deviation	0.7	1.9		1.2	1.8		1.7		2.3	1.8		1.8	

*Recovery (%) = $\frac{\text{strength after a repair}}{\text{strength before that repair}} \times 100$ **Overall recovery (%) = $\frac{\text{strength after repair}}{\text{pristine strength}} \times 100$

Because of the considerable improvement in the strength of the specimens with the plasma-treated PLA after the first repair, a further batch of specimens was prepared and subjected to post-curing, as described in 3.2, prior to the three-point bend tests. The initial average shear strength was 10.6MPa but with some variation (the standard deviation was 2.3MPa). The average shear strength recovery after the first repair was 80%. After a second repair the overall recovery (i.e. compared to the initial pristine strength) averaged 66% but one specimen showed a significantly lower recovery at 28%.

4. Conclusions

The easy repair concept has been demonstrated using a carbon epoxy composite interleaved with PLA. The interleaved composite showed good strength recovery but further work needs to be done to improve the consistency of the performance of this system. Other interleaf materials offering strength and processing temperatures better suited to practical application are being investigated.

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