EASY REPAIR OF INTERLAMINAR DAMAGE USING INTERLEAVED CARBON FIBRE/EPOXY COMPOSITES

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ABSTRACT

Laminated carbon fibre/epoxy composites are susceptible to interlaminar damage when impacted. An easy repair concept for such damage using an interleaving concept has been proposed. Trials of polylactide (PLA)-interleaved composite have previously been conducted to investigate the repair effectiveness of this material in three-point flexure testing and have shown a strength recovery of up to 90%. This paper reports on a further investigation of the PLA-interleaved composite for the repair of interlaminar damage caused in static indentation testing. Another interleaved composite using thermoplastic polyurthane (TPU) interleaves has been tested in three-point flexure has shown excellent strength recovery on repair.

1 INTRODUCTION

Laminated carbon fibre/epoxy composites have been widely used in aerospace applications as they possess excellent stiffness and strength and low weight. However, this material is prone to interlaminar damage after impacts which significantly reduce its compressive strength. Commonly, such damage is repaired by removing the damaged material and then replacing this with a new patch of the same material by adhesive bonding [1], or drilling a hole at the damaged material and then injecting a resin to fill in the damage [2]. To avoid the complexity and expense of such repair methods, self-healing composites have been developed. Self-healing composites using embedded capsules or hollow glass fibres can initially achieve reasonable repair strengths but subsequent repairs at the same or nearby locations can show a considerable loss of strength [3-8].

An alternative concept of a repairable interleaved composite has previously been proposed by the authors of the current paper. This consists of carbon fibre/epoxy laminae separated by thermoplastic interlayers. The interleaf material is chosen to ensure that shear damage occurs preferentially within the interleaf and that this damage can be repaired with the use of heat and pressure. Figure 1 shows the damage-repair cycle of an interleaved composite laminate. The author has demonstrated this concept by a model system consisting of carbon fibre/epoxy laminae with interleaves of polylactide (PLA). Tests showed that shear failure induced in three point bend tests could be repaired and the measured strength recovery was within 60-90% of the pristine value [9].

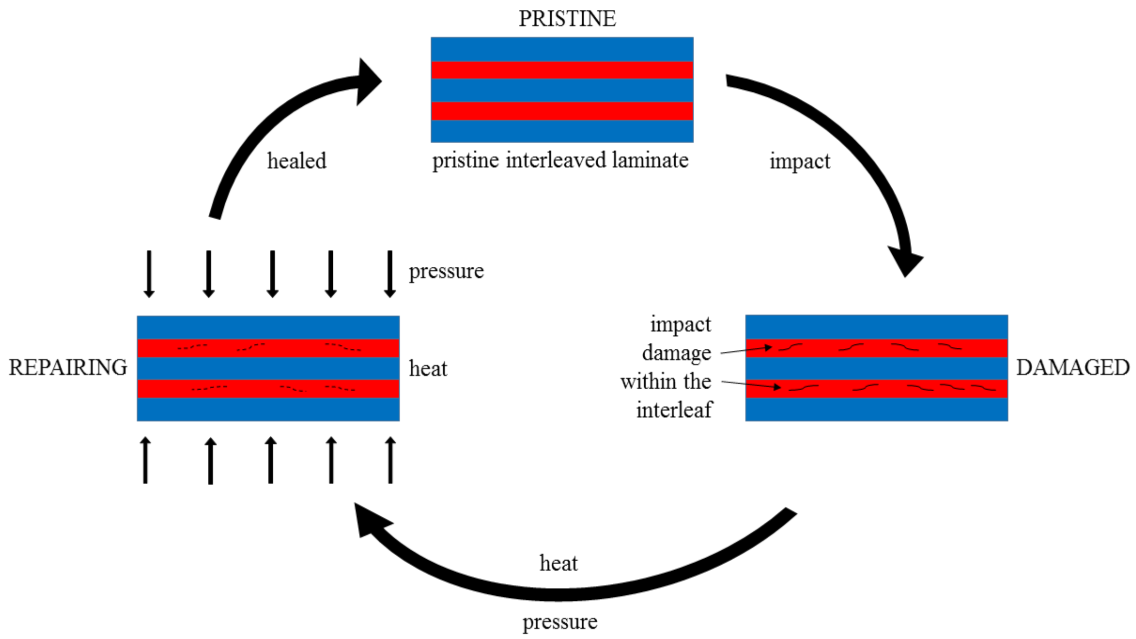


Figure 1: Damage-repair cycle of an interleaved composite laminate in impacts.

This paper further investigates this PLA-interlaved composite for the repair of impact-like damage induced using a static indentation test. An alternative interleaved composite using thermoplastic polyurethane (TPU) interleaves is also investigated to excess its ease of repair.

2 EXPERIMENTAL INVESTIGATION

2.1 Materials

Carbon fibre/epoxy composite (TS300/914, cured ply thickness of 0.125mm, purchased from Hexcel, UK) was used in the current study. Ingeo^{TM} 2003D polylactide film (thickness of 0.14mm, supplied by TCKT company, Austria) was selected as the interleaf material. PLA is a suitable material to demonstrate this concept because preliminary characterisation of the PLA has shown that it possesses a shear strength of 24 MPa measured from short beam shear tests performed according to ASTM D2344M. This is relatively smaller than the interlaminar shear strength (ILSS) of the composite at 78 MPa and so ensures that failure occurs preferentailly at the interleaf. Calleno 36.004 thermoplastic polyurethane (TPU) film (thickness of 0.02 mm) was also selected as an alternative interleaf material for this study.

2.2 Specimen design and manufacture

Two types of test specimens were prepared in the current investigation. For static indentation tests, interleaved panels (140 mm long and 100 mm wide), consisting of carbon fibre/epoxy laminae and the PLA interleaves, were manufactured by hand layup in a quasi-isotropic configuration [0°/PLA/90°/PLA/+45°/PLA/-45°/PLA/-45°/PLA/+45°/PLA/90°/PLA/0°], as shown in Figure 2. The PLA interleaf was surface-treated in a low pressure, oxygen plasma at room temperature for 5 minutes, prior to the layup. These panels were cured in a hot press at 175°C for one hour. After curing, the panels were post-cured at 190°C in vacuum for 5 minutes.

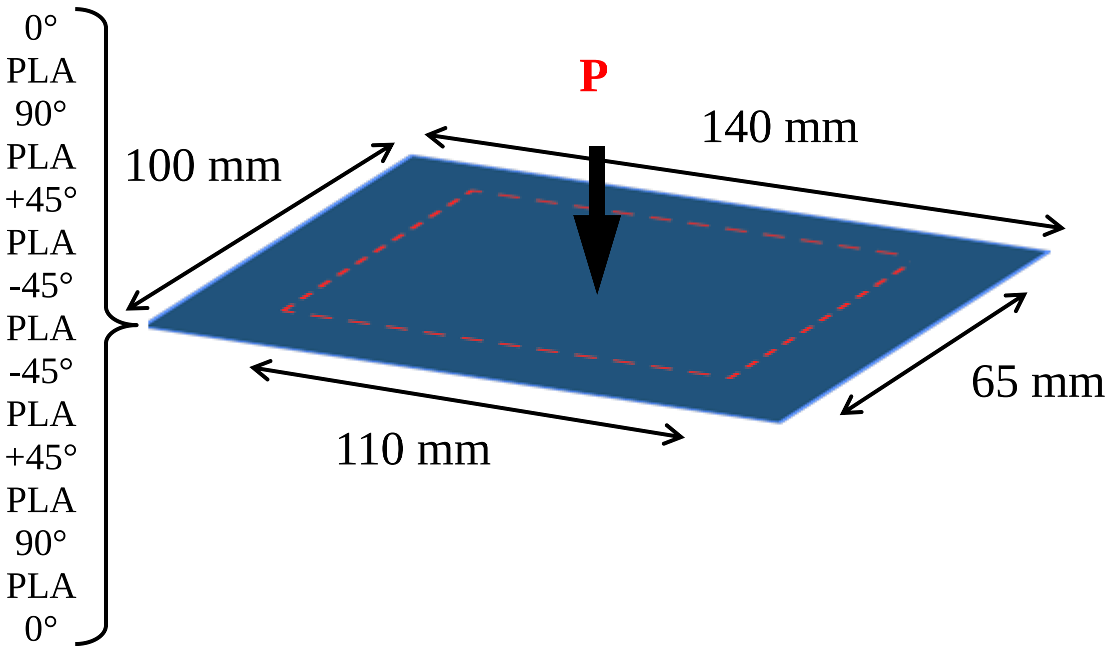


Figure 2: A sketch of an interleaved panel for indentation test with the layup configuration.

For the flexure test, interleaved carbon fibre/epoxy composite panels with a TPU interleaf at the mid-plane of the composite were manufactured in a layup configuration of [$0°_{12}$/TPU/$0°_{12}$]. These panels were cured in an autoclave according to the composite manufacturer's recommendation. Flexure specimens (80 mm long and 10 mm wide) were prepared from the cured panels.

2.2 Mechanical testing

Static indentation tests were conducted according to ASTM D6264M standard to investigate the stiffness recovery of the PLA-interleaved panels. An interleaved panel was clamped between two metal frames (250 mm long and wide) shown in Figure 3 and the assembly was tightened by four screws at a torque of 30 N.m given by a torque wrench. The metal frames provide an unsupported rectangular area on the specimen of 100 mm long and 65 mm wide. A hemispherical indentor of 6mm diameter was used. This test was performed on an Instron universal test machine (Instron 5969 fitted with a 50 kN load cell) at a loading speed of 1mm/min until a significant load reduction can be observed and then unloaded at the same rate. After testing, the interleaved panel was c-scanned to measure the delaminated area.

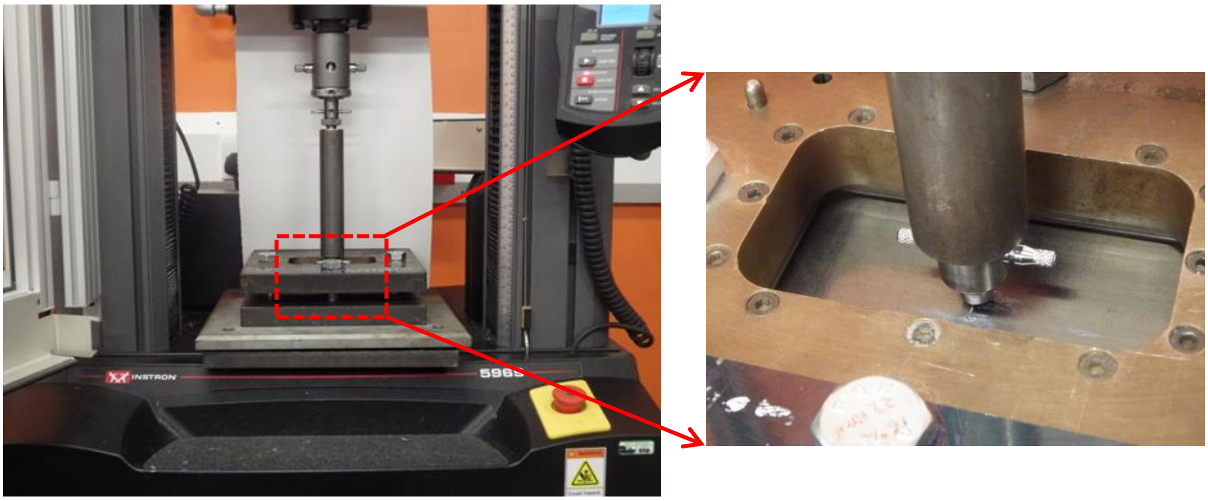


Figure 3: The test setup of the static indentation tests.

The flexure tests were performed on the TPU interleaved specimens. In this test, the flexure specimens were tested in three-point bending with a support span of 64 mm, according to ASTM D7264M standard. A flexural specimen was loaded in an Instron universal test machine (Instron 5969 fitted with a 50 kN load cell) at a crosshead speed of 1mm/min until the load-displacement curve indicated significant damage had occurred and then unloaded at the same speed.

2.3 Repair process

The ‘indented’ PLA-interleaved panels were placed on an aluminium plate, enclosed in a vacuum bag, then heated to 190°C in an oven and kept at this temperature for 5 minutes, followed by a further 15 minutes with a vacuum pressure. After the repair, they were c-scanned and then tested again at the same position in the same manner as described previously. The damaged TPU-interleaved flexure specimens were repaired in the same procedure described here, except the repair temperature was 110°C. The overall damage-repair cycle was repeated one further time for the indentation test and for three further cycles for the TPU flexure tests.

3 RESULTS AND DISCUSSION

3.1 Static indentation of PLA-interleaved panels

Figure 4 shows the recorded load-displacement curves of one particular specimen subjected to static indentation tests. It can be seen that after the first repair the panel returns to its original stiffness and recovers 58% of the force required to cause shear damage in the pristine panel. After the second repair, the stiffness is again fully recovered, but the force causing shear damage drops to 50% of the pristine value. Table 1 contains the applied force measured from the indentation tests for the interleaved panels.

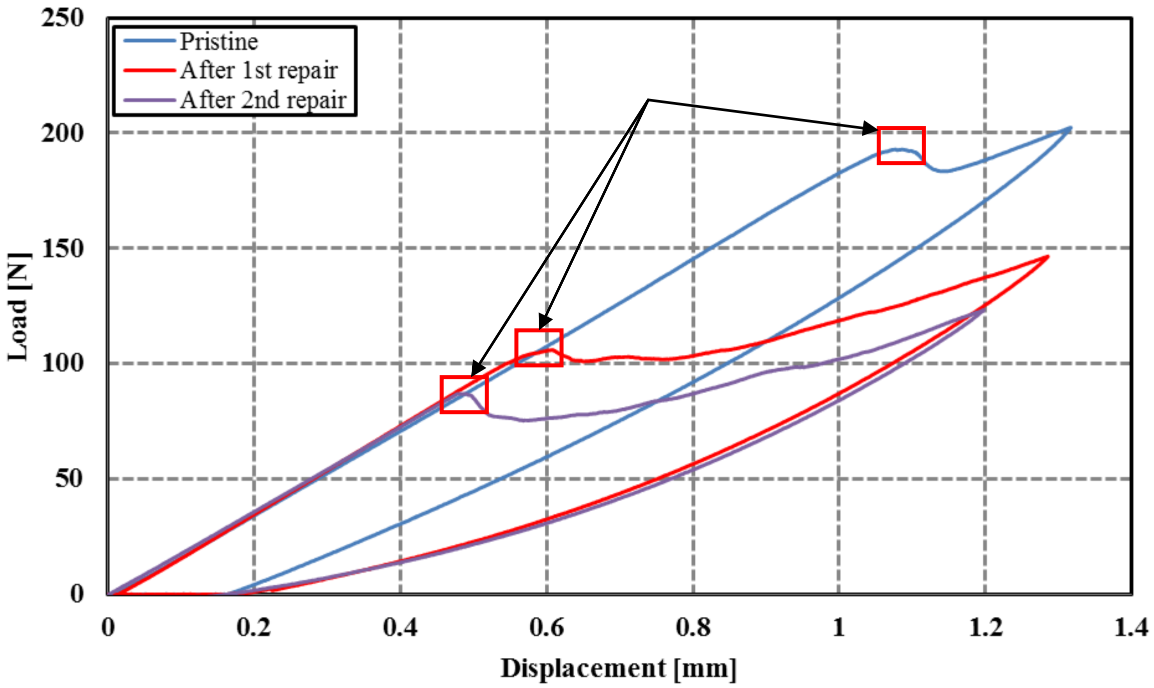


Figure 4: The load-displacement curves of the interleaved panel B in static indentation testing.

Interleaved panels	Maximum applied load (N) before repair	Maximum applied load (N) after repair	Recovery (%)	Maximum applied load (N) after repair	Overall recovery (%)
A	114	90	79	59	52
B	193	106	55	87	45

Table 1: The measured applied force for the interleaved panels subjected to static indentation tests.

Figure 5 shows the load recovery versus repair times plot for the two interleaved panels. It can be seen that after the 1st repair, the load can be restored to 55% and 79% of the pristine load required to cause indentation damage and after the 2nd repair, this value drops to 45% and 52%. This reduction can be attributed to the loss of the PLA interleaf from the panels at the elevated temperature during repair. (PLA was evident on the surface of the panel at the damage site and the edge of the panel after the repair process, indicating that it has leaked out at the elevated temperature of the repair.)

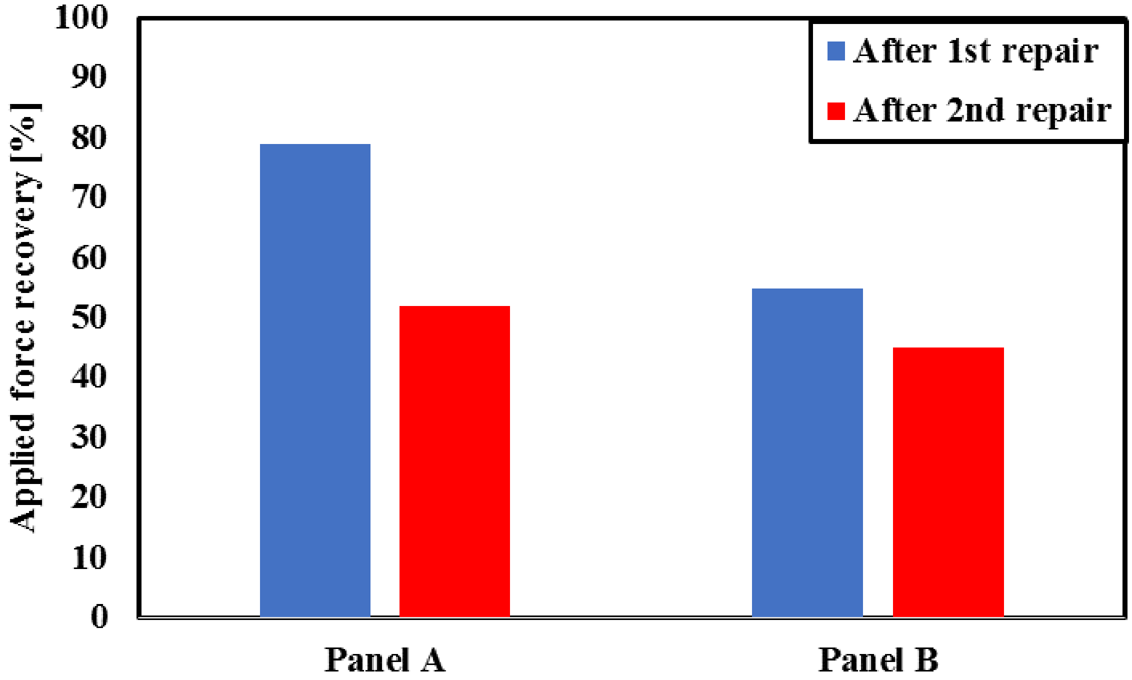
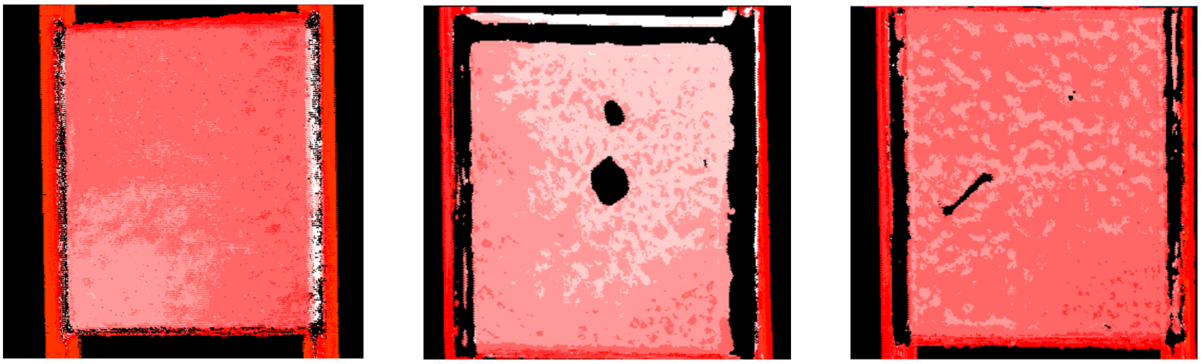


Figure 5: The maximum applied load measured in indentation tests for the interleaved panels.

Figure 6 shows the c-scan images of the specimen. The c-scan images confirm that the intended damage in the centre has been repaired.



(a) (b) (c)

Figure 6: The c-scan images of a PLA-interleaved carbon fibre/epoxy composite panel (a) after curing, (b) after static indentation test and (c) after repair. It can be seen that the intended damage at the centre of the panel has been repaired.

3.2 Flexure tests of TPU-interleaved specimens

Figure 7 shows the measured load-displacement curves of a typical TPU-interleaved flexure specimen. It can be seen that after a repair, the flexural stiffness of the specimen can be fully restored. However, the force required to cause the yielding/initial damage of the interleaf reduces from 0.25 kN to almost 0.18 kN.

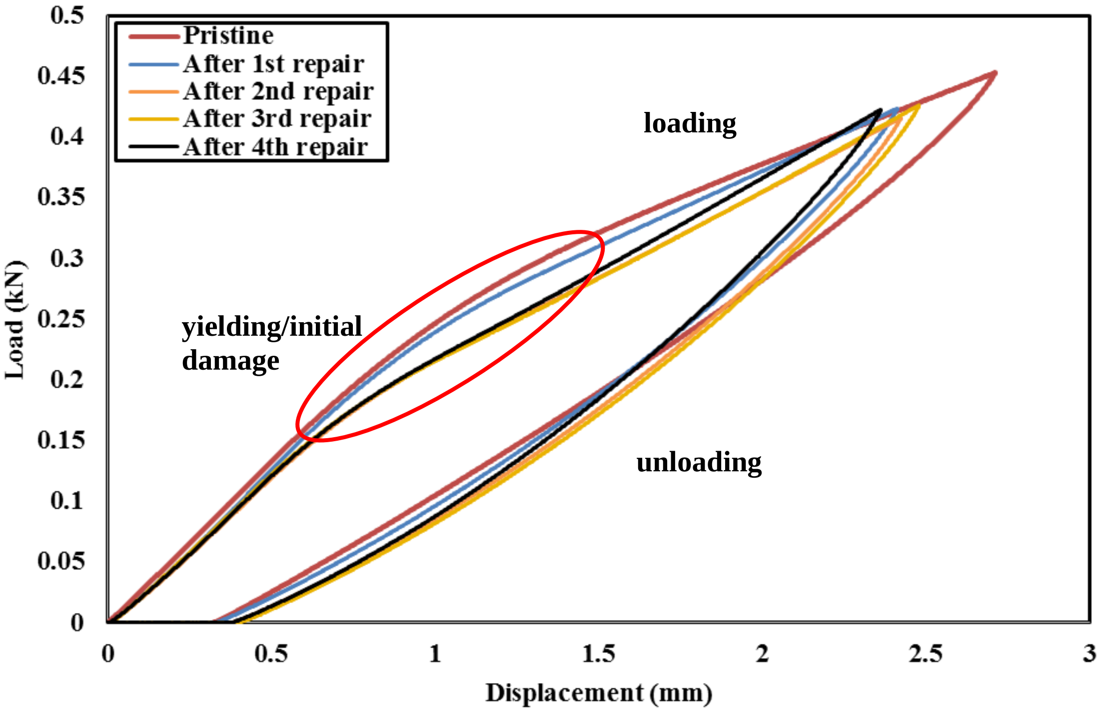


Figure 7: The recorded load-displacement curves of the TPU-interleaved specimen subjected to three-point bend tests.

Table 2 summaries the shear stress associated with yielding/initial damage, τ^u, of the TPU specimens in three-point bend tests. It is found that the yield stress after the first repair, the average yield stress of the specimens is 4.8 MPa which recovers 101% of the pristine value. After the fourth repair, the recovery of the yield stress of the specimens is averaged at 97% of the pristine value (a specimen shows a relatively recovery level of 87%).

TPU-interleaved panels	τ^u (MPa) before repair	τ^u (MPa) after repair	Recovery (%)	τ^u (MPa) after repair	Recovery (%)	τ^u (MPa) after repair	Recovery (%)	τ^u (MPa) after repair	Recovery (%)
	4.8	5.0	103	4.8	100	4.6	96	4.2	87
	4.6	4.1	90	4.3	94	4.4	96	4.5	99
	4.6	5.0	110	4.6	100	4.4	97	4.6	100
	4.9	5.0	102	4.6	94	4.6	94	4.6	95
	4.8	5.0	103	4.7	98	4.9	102	4.8	99
	4.5	4.4	97	4.4	97	4.4	97	4.6	102
Average	4.7	4.8	101	4.6	97	4.6	97	4.6	97
Standard deviation	0.2	0.4		0.2		0.2		0.2	

* Recovery (%) = $\frac{\text{strength after repair}}{\text{pristine strength}} \times 100$

Table 2: The yield/initial damage shear stress (τ^u) of the TPU-interleaved specimens measured in three-point bending tests.

Figure 8 plots the τ^u recovery % versus repair cycles for the TPU-interleaved specimens. It can be seen that after the first repair, τ^u recovers between 85% to 110% of the pristine value. After the fourth repair, the τ^u of these specimens is continuous to show excellent recovery.

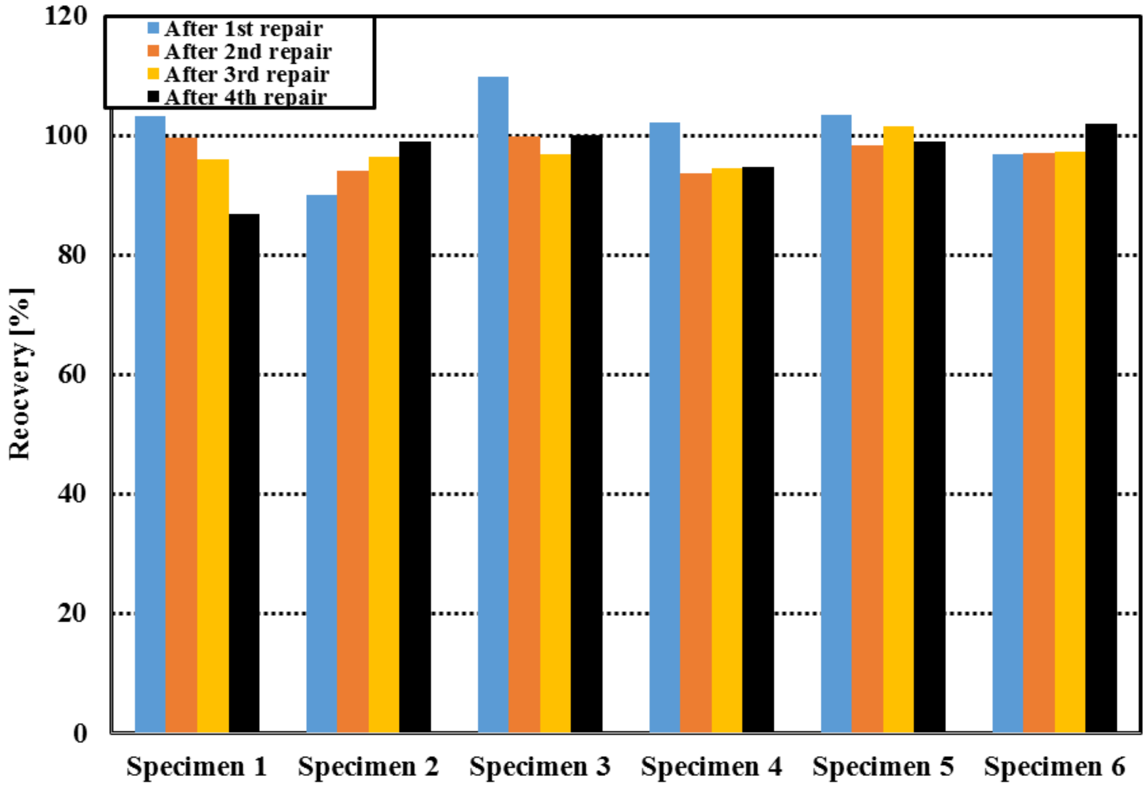


Figure 8: The yield stress recovery versus repair cycles plot of the TPU-interleaved specimens subjected to three-point bending tests.

5 CONCLUSIONS

The easy repair concept using carbon fibre/epoxy composite interleaved with PLA has been further investigated in static indentation tests. The composite showed a good stiffness and strength recovery but further work should be done to avoid the loss of PLA during repair. A new composite system using TPU interleaf was also investigated. This material showed an excellent recovery after repair of the shear stress at yield/initial damage when tested in three-point bending tests.

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