

Interlocking thin-ply reinforcement concept for improved fracture toughness and damage tolerance

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Abstract

An original concept for improving the delamination resistance and damage tolerance of a composite laminate is proposed. The concept is to insert interlocked thin-ply reinforcement units between the laminae. Each reinforcement unit consists of two thin-ply layers with tabs cut into one layer, and slits cut into the other layer. The slits, and the long axis of the tabs, are parallel to the fibre direction in their respective layers. The two thin-ply layers are placed together, and the tabs are inserted through the slits, creating an interlocked reinforcement unit.

The effect of the reinforcement units was quantified via mode I (DCB) and mode II (4ENF) fracture toughness tests, as well as compression after impact tests. Mode I propagation fracture toughness was increased by 77.6%, while mode II fracture toughness was not affected. In the compression after impact tests, an 11.4% reduction in delamination area was achieved but this only resulted in a 5.1% increase in CAI strength.

Keywords: B. Fracture toughness, B. Impact behaviour, C. Damage tolerance, Ply-level structures

Note

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1. Introduction

It is inevitable that composite structures will sustain damage during operation. In order to ensure safety, these structures therefore need to be sufficiently damage-tolerant to be able to carry operational loads, even when damaged. In many cases, this damage tolerance requirement, rather than the undamaged strength, is the main design driver.

A common way to quantify the damage tolerance of a composite laminate is by measuring impact and compression after impact (CAI) performance. Delamination formation occurring during the impact itself, and the further delamination growth and/or local buckling during the subsequent compression, are generally considered key for CAI performance [1, 2]. However, recently, Nettles and Sharber [3] have argued that it is in fact fibre failure, rather than delamination growth or local buckling, that triggers the final failure during

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compression loading. Regardless of what mechanism triggers the final failure, Nettles & Sharber [3], and the literature more generally [4–8], report a strong correlation between the size of the delaminations formed during impact, and the CAI strength.

Consequently, most attempts to improve CAI performance have focussed on improving the laminate’s interlaminar fracture toughness, to prevent or reduce delamination growth. Reduction of delamination growth is of course beneficial for damage tolerance in general, not just CAI performance.

Methods that have been used for improved fracture toughness include matrix modification [2, 9–19], interlaminar reinforcements such as interleaves [20–22], thermoplastic powder [23], thin-ply [24], and fibre veils [25–30], or translaminar reinforcements such as stitching [9, 31–42], needle-punching [43, 44], Z-pinning [45–47], tufting [40, 48], and 3D fibre architectures [49–53].

Advances in materials and manufacturing techniques are making possible a new class of reinforcements: those created by creating mesostructures in the composite laminate at the ply level. An example is the original interlocked crack arrester developed by Minakuchi and Takeda [54–57] to arrest crack growth in an adhesive bond. This arrester was able to increase the toughness of an adhesive bond by a factor of 5 to 7, but at the cost of introducing a ply drop in the adherends, and locally introducing an additional 90° ply in the lay-up.

The arrester geometry is somewhat similar to that of a woven fabric; both produce an interlocking structure at the ply level. For regular ply thicknesses, woven fabrics are known to have a higher fracture toughness than equivalent lay-ups of UD plies [58], though at the cost of reduced in plane properties, due to fibre waviness [59]. Recent work in the literature reports on woven fabrics [60] that are potentially sufficiently thin to apply as interlaminar reinforcements. While woven thin-ply fabrics may have potential as interlaminar reinforcement, the necessity of a 90° angle between warp and weft yarns would create a fibre-angle mismatch when applied in a standard quasi-isotropic laminate with a 45° fibre orientation change between adjacent plies. Even if the fibre orientations could be matched, then a balanced weave would only match the fibre orientation of an adjacent ply over 50% of the surface area. Matching the fibre orientation of the adjacent ply is important to prevent the reinforcement from delaminating from the adjacent ply. Furthermore, if one is only applying a woven fabric in order to increase interlaminar toughness, the effect of fibre waviness can potentially be further reduced by spacing the fibre cross-overs further apart than in a standard weave.

In this paper, we present a new reinforcement concept within the emerging class of ply-level structures. The concept consists in inserting interlocked thin-ply reinforcement units within a composite laminate. We designed and manufactured these reinforcements, and then experimentally quantified their effect on the mode I and mode II fracture toughness, and the CAI performance, of a carbon-fibre reinforced polymer (CFRP) laminate. This is the first time ply-level structures were explored in the literature for increasing interlaminar toughness and CAI performance.

In Section 2, we first present the concept in more detail. In Section 3 we discuss in turn the specimen designs and experimental procedures for the fracture toughness tests and the CAI tests. Subsequently, we present results of each test in Section 4, with a further discussion in Section 5. We finish in Section 6, with a brief summary of the conclusions of this research.

2. Reinforcement concept

Our reinforcement concept is to insert interlocked thin-ply reinforcement units between the plies of a composite laminate, to reinforce the desired interfaces. In the case of CAI, every interface needs to be reinforced, as delaminations can potentially occur at every interface where there is a fibre orientation mismatch [2, 61–64].

The reinforcement concept is shown schematically in Figure 1. Each reinforcement unit consists of two thin-ply layers (made from SK Chemicals Skyflex prepreg in the present work, see Figure 1a). Tabs are cut into one layer, and slits are cut into the other layer. The slits, and the long axis of the tabs, are parallel to the fibre direction in their respective layers.

The two thin-ply layers are placed together, and the tabs are inserted through the slits (Figure 1b), creating an interlocked reinforcement unit (Figure 1c). The required reinforcement units are manufactured

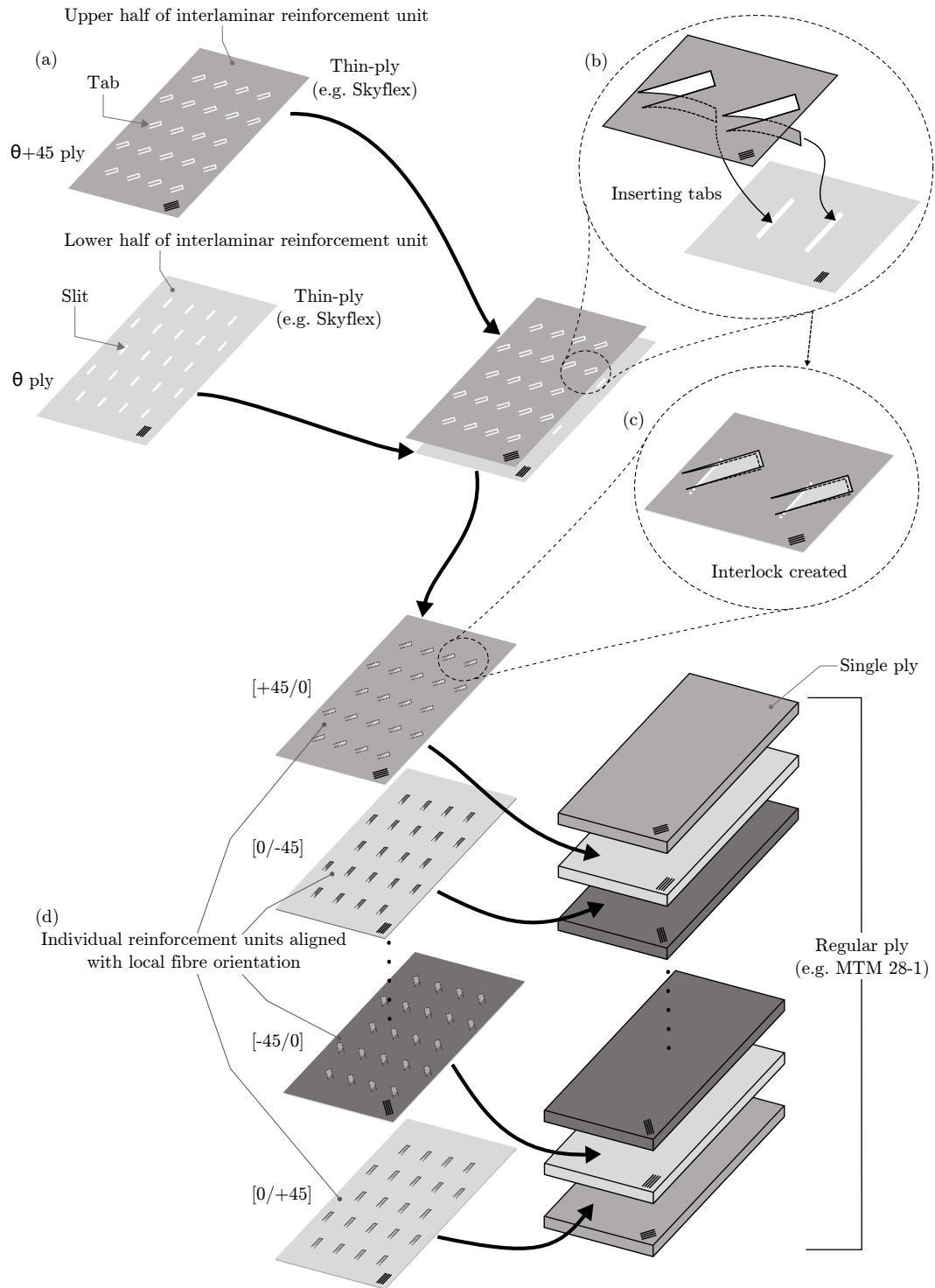


Figure 1: Schematic illustration of the reinforcement concept, showing: (a) the two halves of a reinforcement unit, (b) insertion of the tabs, (c) an interlocked reinforcement unit, and (d) insertion of reinforcement units in a composite laminate.

first, and then inserted at the desired locations in the final laminate during a regular lay-up process (Figure 1d). In the present work, Cytec MTM 28-1 prepreg was used for the regular thickness layers of the laminate.

A key feature of this concept is that the orientations of the two layers of each reinforcement unit are chosen to match the orientations of the adjacent regular-thickness layers in the laminate. This helps ensure that no delaminations occur between the thin-ply and regular-thickness plies. Instead, all delaminations should be confined to the mid-planes of the reinforcement units (because this is where there is an angle mismatch), where they can be bridged by the tabs, slowing their growth.

In this research we developed units to reinforce a standard quasi-isotropic laminate, such as recommended in the ASTM D7137 CAI standard [65]. This means that there was a 45° fibre angle difference between the tab and slit plies in each unit.

Compared to existing toughening approaches, our concept has the advantage that it limits the disturbance to the overall laminate. Where adding interlaminar interleaves implies reducing the fibre volume fraction, if the thin-ply used in the proposed reinforcement units are properly matched to the regular-thickness plies in the main laminate, the fibre volume fraction will remain constant. When using translaminar reinforcements such as Z-pinning or stitching, the reinforcements typically pass through the entire laminate, creating fibre damage, waviness, and/or resin pockets in all plies. In contrast, in our concept the fibres in the main plies of the laminate remain completely undisturbed. Passing the tabs through the slits does introduce some waviness, but as the reinforcements are made from thin plies, the amount of waviness is limited. It should also be noted that as our concept relies on mechanical interlocking, at the scale of the tabs, as its toughening mechanism, there is the potential for synergy with toughening methods which rely on different mechanisms (e.g. matrix toughening).

3. Specimens and test methods

3.1. Fracture toughness

3.1.1. Fracture toughness specimens

To investigate the effect of the proposed reinforcement concept on the fracture toughness, two classes of specimens were used. Mode I fracture toughness was investigated using double cantilever beam (DCB) specimens, while mode II toughness was investigated using four point end notch flexure (4ENF) specimens.

Composite laminates used in service are usually multi-directional. Additionally, the ASTM standards for CAI testing [65, 66] recommend a quasi-isotropic lay-up, with a 45° fibre orientation change between adjacent layers. This means that fracture toughness results for a unidirectional interface may not be directly applicable to either actual structures, or CAI specimens. Consequently, we decided to measure the effect of the reinforcement concept on fracture toughness for a 0//45 interface. To focus specifically on the effect of the tab and slit geometry on the interface toughness, the fracture toughness specimens were manufactured solely from the Skyflex USN 020 thin-ply material.

When a laminate contains such a multi-directional interface at the mid-plane, it is by definition non-symmetric. Prior investigations reported in the literature have shown that in order to avoid issues such as the crack jumping to other interfaces, or non-uniformity of the strain energy release rate (SERR) across the specimen width, one should minimise two flexural rigidity ratios: (i) D_c [67, 68], which indicates the amount of longitudinal/transverse bending coupling and (ii) B_t [69], which indicates the amount of bend/twist coupling. These ratios are defined as:

$$D_c = \frac{D_{12}^2}{D_{11}D_{22}} \quad (1)$$

$$B_t = \left| \frac{D_{16}}{D_{11}} \right| \quad (2)$$

where D_{ij} are the components of the bending stiffness matrix from classical lamination theory, with i or $j = 1, 2, 6$ referring to, respectively, the longitudinal, transverse, and shear directions. Based on finite element analysis, Davidson et al. [68] suggest $D_c = 0.25$ as an upper bound for specimen design, to ensure correct measurement of G_{II} from the test. Sun and Zheng [69] do not provide a specific number for B_t , but state it should be as close to zero as possible.

For both the DCB and the 4ENF tests, we therefore adapted the lay-up from Tao and Sun [70]. The selected lay-up was $[(0_{10}/90/0_{10})_3/0//45/(0_{10}/90/0_{10})_3]$, where $//$ indicates the laminate mid-plane. For this lay-up, and the material properties for Skyflex USN 020 given in Table 1, $D_c = 0.0033$ and $B_t = 4.6 \cdot 10^{-7}$, avoiding issues due to mechanical coupling. A $13 \mu\text{m}$ thick PTFE film was placed at the mid-plane to act as a crack starter.

Table 1: Material properties for the prepreg materials used in this research. Skyflex USN 020 A is a thin-ply prepreg, and MTM-28-1 has a regular ply-thickness.

Property	Material	
	Skyflex USN 020 A ^a	MTM-28-1 ^b
E_{11} (GPa)	125.3	127
E_{22} (GPa)	8.4	8.4
G_{12} (GPa)	5.1	3.69
ν_{12} (-)	0.28	0.28
G_{Ic} (kJ/m ²)	0.19 ^c	0.4 ^d
Nominal ply thickness (μm)	25	125

^a Data from [71, 72].

^b Data from [73].

^c Data from [74]

^d Data from [75]

Note that for the ENF specimens, the lay-up was such that the 0° ply was on the tension side of the $0//45$ interface, in order to prevent crack jumping during the 4ENF test.

For both the DCB and the 4ENF tests, two different configurations were created: baseline and reinforced. The baseline specimens consisted purely of UD layers, whereas in the reinforced configuration, part of the $0//45$ interface was interlocked using the tab-and-slit concept described in section 2. Specifically, the tabs were cut into the 45° layer, and the slits in the 0° layer, so that the tabs would present only a narrow edge to the delamination front, as shown in Figure 2. The motivation was to prevent the delamination from travelling ‘up’ the tab, out of the desired interface.

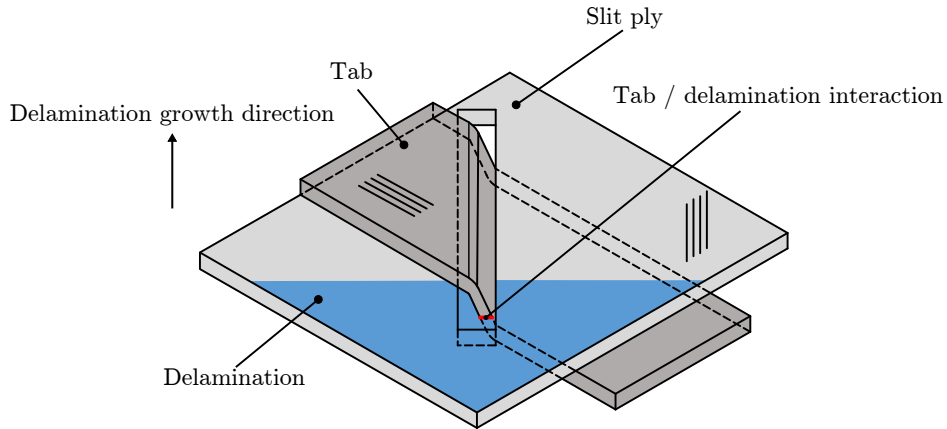


Figure 2: Schematic illustration, showing that with the tab and slit orientation used in this research, delamination propagation will be blocked by the edge of the tab.

Both the tabs and slits were cut using a CNC fabric cutting machine, which was also used to cut the plies themselves. The tabs were pulled through the slits with a crochet hook.

Figure 3 shows the nominal dimensions of the specimens, and the regions that were interlocked in the reinforced configurations. Figure 4 shows the applied reinforcement pattern in greater detail.

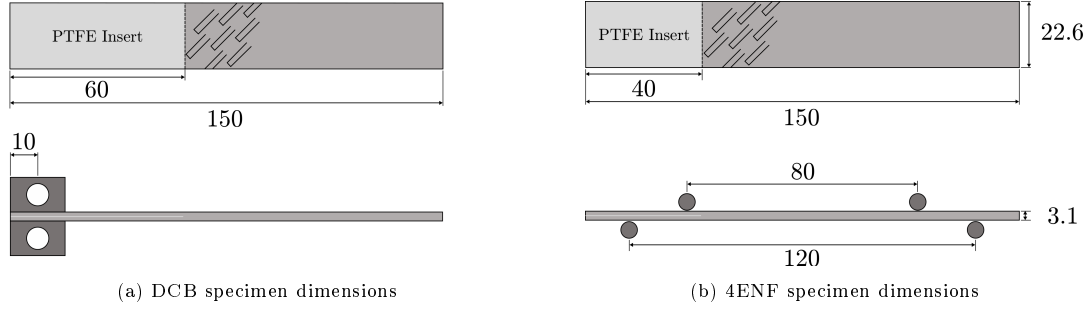


Figure 3: Top and side views of the DCB and 4ENF specimens, showing the load application points and the PTFE inserts. The location of the reinforced regions for the reinforced configurations is also shown. All dimensions are in millimetres.

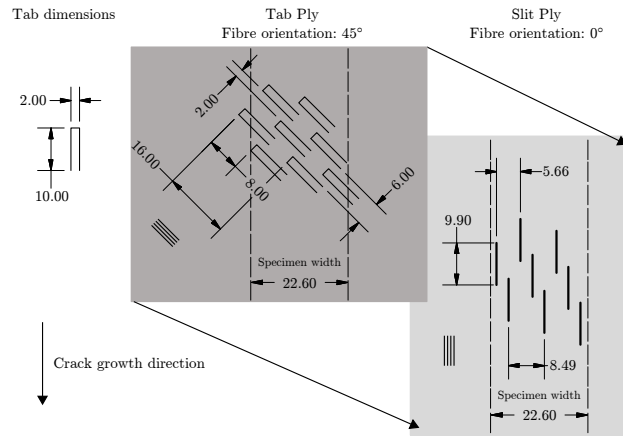


Figure 4: The tab and slit patterns applied to create the interlock reinforcement in the fracture toughness specimens. All dimensions are in millimetres.

The reinforcement pattern was chosen to represent a single unit of the pattern that was applied to the CAI specimens (shown in Figure 5, in Section 3.2.1). In order to minimise the number of fibres that are cut, it is desirable to minimise the width of the tabs. However, making the tabs too narrow makes it very difficult to manually insert the tabs through the slits without damaging them. After a series of manufacturing trails we chose the dimensions in Figure 4 to give sufficiently small tabs, without undue manufacturing difficulties. The spacing of the tabs was similarly chosen to minimise the distance between tabs —without creating manufacturing difficulties— so the delamination could not bypass an interlocked region.

As shown in Figure 3, reinforcements were not applied over the entire length of the fracture toughness specimens. Instead, we applied a single unit of the pattern applied to the CAI specimens (see Section 3.2.1), giving a reinforced length of about 28 mm. This allowed us to measure whether the effect of the reinforcements would persist, even after the delamination grew beyond the reinforced area.

The material used for the fracture toughness specimens was SK Chemicals Skyflex USN 020 A thin-ply prepreg (K51 epoxy resin, T700 carbon fibres), with a nominal ply thickness of $25\mu\text{m}$ and areal weight of 33g/m^2 , (see Table 1 for further properties). Curing was done in an autoclave, following the manufacturer's recommended cycle. After curing, specimens were cut from the manufactured plates by water-jet cutting. The sides of the specimens were coated with white paint, and marked at 1 mm intervals to aid the crack length measurements. In order to control the pre-crack formation, we manually pre-cracked the specimens by clamping them in a vice grip and then using a wedging procedure, as detailed by Narducci et al. [74]. Six baseline and six reinforced specimens were manufactured for each class of specimen.

3.1.2. Fracture toughness tests

Both mode I and mode II tests were conducted on an Instron screw-driven load frame with 50 kN maximum capacity. An iMetrum system was used to optically measure the displacement between two target points. Force and displacement were recorded at a rate of 5 Hz.

Two synchronised video cameras were used to monitor both sides of the specimen simultaneously. After the tests, the videos were down-sampled to 0.2 Hz and analysed frame-by-frame in order to measure the crack length. The crack lengths measured at the front and the back of the specimen were averaged, and the average crack length was used for the compliance calibration, as described in Appendix A.

Mode I. The DCB tests were performed at a displacement rate of 1 mm/min. The iMetrum system tracked the displacement of the two loading pins. Data reduction followed the modified beam theory (MBT) method given in ASTM D5528 [76].

As there was a very strong correlation between compliance to the power $1/3$, $C^{1/3}$, and crack length, a , ($R^2 > 0.99$, see Appendix A), a crack length could be calculated from the measured compliance for each recorded pair of force-displacement data points, rather than only using the optical crack length measurements. This allowed the calculation of a SERR value for each force-displacement pair as well.

The initiation fracture toughness was determined using the 5%/MAX criterion [76]. The propagation fracture toughness was determined by averaging the peak SERR values after initiation had occurred. For the reinforced specimens, only those peaks were considered that corresponded to the crack tip being inside the reinforced region.

Mode II. The 4ENF tests were performed at a displacement rate of 0.5 mm/min. The iMetrum system tracked the displacement between a point on the fixed part of the loading fixture, and a point on the moving part of the fixture, just below the central hinge.

Data reduction was performed using the method of Martin and Davidson [77]. Correlation between compliance and crack length was again excellent ($R^2 > 0.99$, see Appendix A), allowing a crack length and corresponding SERR to be calculated for every recorded force-displacement data point.

Initiation fracture toughness was again determined using the 5%/MAX criterion, and propagation toughness was calculated by taking the mean SERR value of the stable plateau region.

3.2. Impact and CAI

3.2.1. Impact and CAI specimens

The design of the CAI specimens was based on the quasi-isotropic laminate suggested by ASTM Standards D7136 and D7137 [65, 66]. Two configurations were produced: baseline and reinforced.

To create the reinforced specimens, we first created reinforcement units by interlocking two thin-ply layers, as described in Section 2. The tab and slit patterns used for the CAI specimens are shown in Figure 5. The patterns were rotated appropriately to ensure that the tabs and slits were always parallel to the fibre direction in the ply. We will use the notation $R_{\theta/\theta-45}$ to refer to a reinforcement unit with tabs in a ply with fibre orientation θ and slits in a ply with fibre orientation $\theta-45^\circ$.

As was discussed in Section 3.1.1 for the fracture toughness specimens, the tab dimensions and spacing were chosen to minimise tab width and maximise reinforcement density, without creating manufacturing issues.

The final lay-up was built up from six blocks of plies. The blocks had the lay-up $B = [45/R_{45/0}/0/R_{0/-45}/-45/R_{-45/90}/90]$. The lay-up of the final laminate was $[B/(R_{90/45}/B)_2]_S$. This lay-up is essentially equivalent to the quasi-isotropic lay-up recommended by the ASTM standards (D7136 and D7137, [65, 66]), but with a reinforcement unit inserted at each interface at which there is a fibre orientation mismatch.

The baseline specimens had the same lay-up, i.e. with thin-ply layers in between regular-thickness layers, except that the thin-ply layers had no tabs, slits, or interlocks. The lay-up is illustrated schematically in Figure 6 and a micrograph of a cross-section through a cured laminate is shown in Figure 7.

Each reinforcement unit was manufactured such that the slits were in the bottom ply (i.e. furthest away from the impact). As the preferential delamination direction is the fibre direction of the bottom ply in each interface [1, 78], this geometry ensured that the slits (which are parallel to the fibres) were parallel to

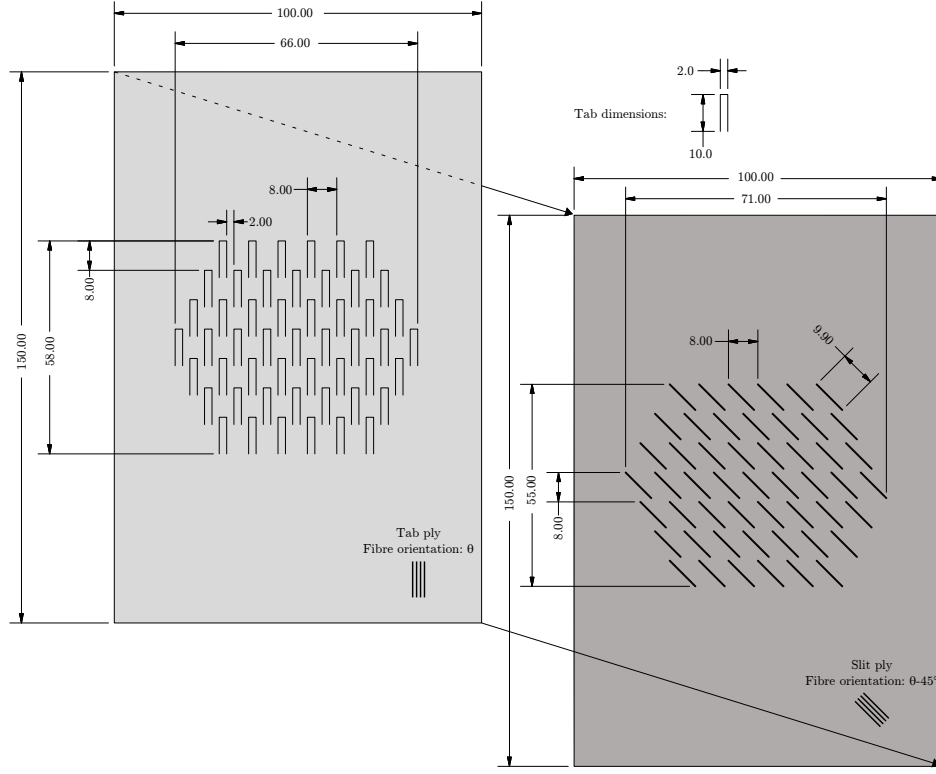


Figure 5: Tab and slit patterns used to create the reinforcement units for the CAI specimens.

the preferential delamination direction. This was thought to help ensure the delamination remains in the bridged plane, rather than following the tab into the thin-ply / thick-ply interface.

As can be seen in Figure 5, all tabs pointed in the same direction, introducing an in-plane asymmetry in the tab pattern. For an in-plane symmetrical pattern, half of the tabs should be rotated by 180° . This was not done because in an actual structure, the impact location would not be known *a priori*, so one could not determine during design which tabs to rotate. The effect of this slight in-plane asymmetry should be very small however, because the delamination growth direction is parallel to the direction of the slit. This means that the delamination front will be normal to the edge of the tab (Figure 2), and therefore the delamination will not ‘feel’ the difference if the tab is rotated by 180° .

For the thin-ply layers, again Skyflex USN 020 A was used. The regular thickness plies consisted of Cytec MTM28-1 / T800 prepreg. The material properties for both materials are given in Table 1. The recommended cure cycles for the two prepreg systems are not the same. For Skyflex/K51 the manufacturer

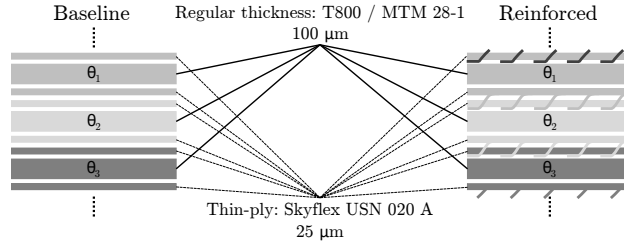


Figure 6: Schematic illustration showing a portion of the lay-up of the CAI specimens. Three regular thickness plies are shown, as well as the adjacent thin-ply layers, in both the baseline (left) and reinforced (right) configurations.

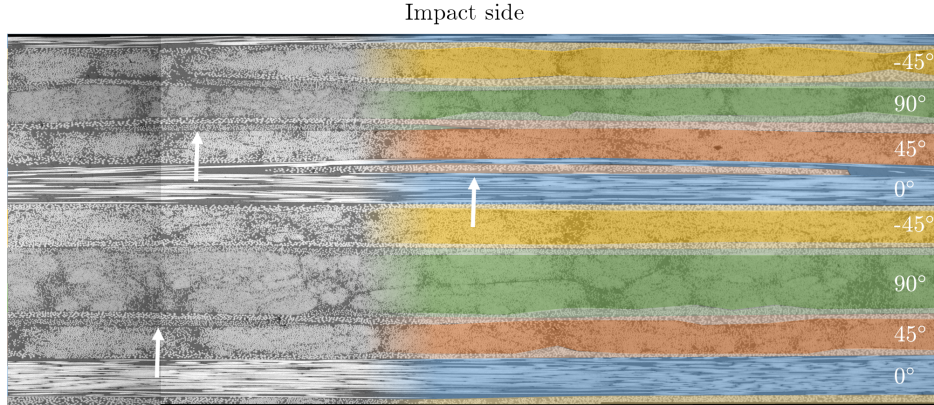


Figure 7: Cross-section showing interlocked tabs in a cured lay-up. The arrows show the location of the tabs. The section plane is parallel to the 0 degree fibre direction.

recommends a 90 minute hold at 125 °C [72], while the recommended cycle for MTM28-1 is a 60 minute hold at 120 °C, +5/-0 °C [73]. Both cycles require an applied pressure of 0.6 MPa (6 bar). As the K51 cure cycle recommends a longer hold at a slightly higher temperature, we assumed that applying this cycle to the combined laminate would produce a satisfactory degree of cure in both materials. Following autoclave curing, the specimens were cut from the manufactured plates using a water-jet cutter. Five baseline specimens and five reinforced specimens were manufactured and tested.

3.2.2. Impact tests

Impact tests were conducted on an Instron CEAST 9350 drop-tower, following the ASTM D7136 standard [66]. In accordance with the standard, a normalised impact energy of 6.7 J/mm laminate thickness was used. The impactor had a mass of 5.392 kg and a hemispherical tip with a diameter of 16 mm.

Following the impact tests, the specimens were inspected using a TechniTest Triton 1700 TT ultrasonic scanner. The scanner was operated in pulse-echo mode, with a 10 MHz transducer. The resulting C-scans were analysed to find the projected delamination area.

3.2.3. CAI tests

Compression tests were performed following ASTM D7137 [65] on an Instron 250 kN screw-driven test frame. The tests were performed in displacement control, with a 1.25 mm/min load rate. Four strain gauges were applied to each specimen in order to check the alignment and ensure any bending remained within acceptable limits. Per the standard, the specimen was considered to have failed when a load drop of more than 30 % was detected.

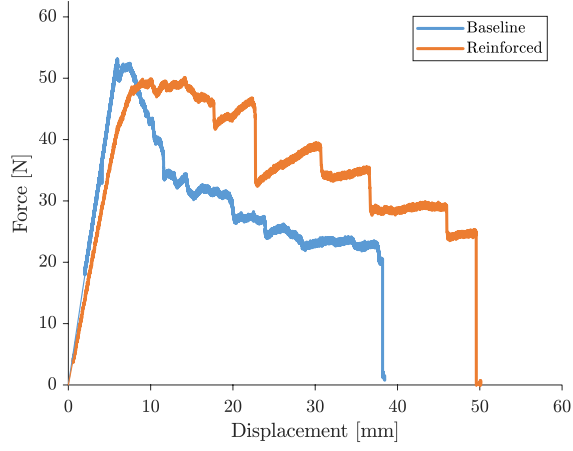
4. Results

4.1. Mode I delamination

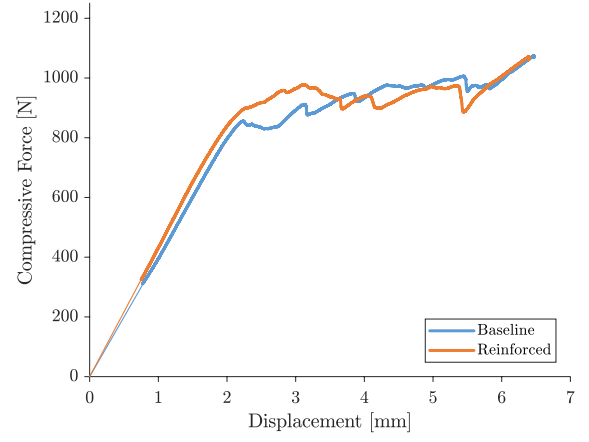
The results of the DCB tests are shown in Figures 8a, 8c, and 8e, and in Table 2. Figures 8a and 8c show results for a typical specimen of each configuration, while Figure 8e and the table show the average and standard deviation for all specimens together.

As is shown in Figure 8a, the measured displacement values were corrected so that the extrapolation of the initial linear elastic portion of the curve passed through the origin.

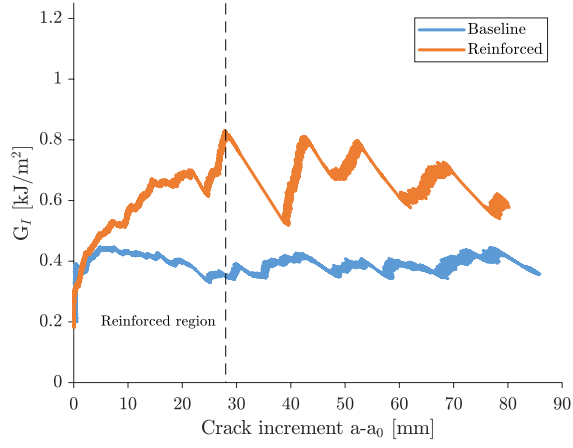
Focussing first on the force-displacement curves in Figure 8a, the peak force reached in the reinforced case is slightly lower than for the baseline specimens. However, whereas the baseline specimens showed an



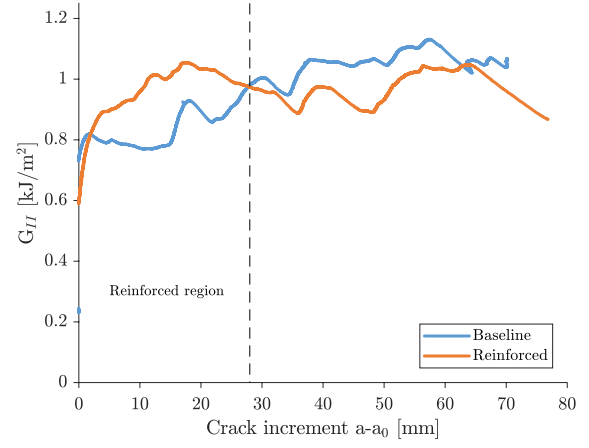
(a) Typical DCB force-displacement curves.



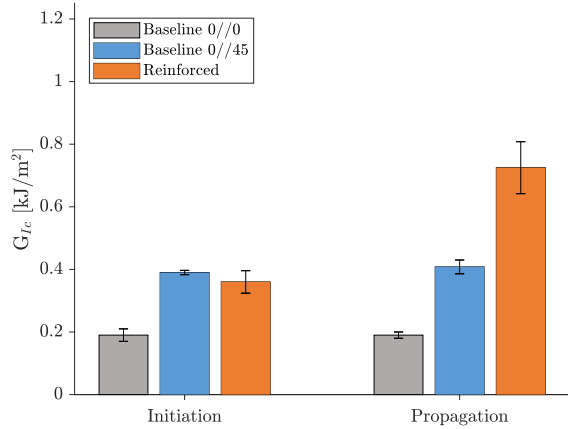
(b) Typical 4ENF force-displacement curves



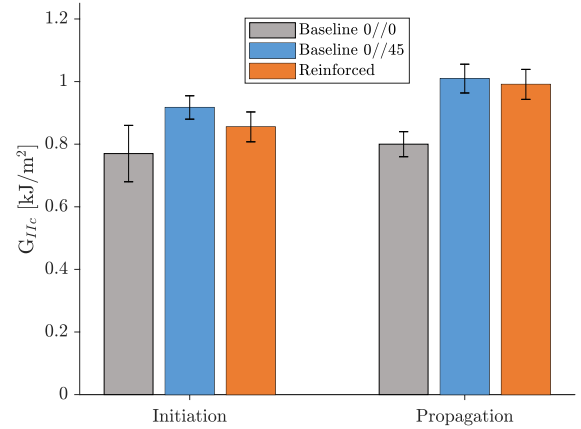
(c) Typical mode I R-curves.



(d) Typical mode II R-curves.



(e) Mode I initiation and propagation toughness. Values for the 0//0 interface were obtained from [74].



(f) Mode II initiation and propagation toughness. Values for the 0//0 interface were obtained from [74].

Figure 8: Results of the mode I (left column) and mode II (right column) fracture toughness tests. Panels 8a through 8d show results for typical specimens. Panels 8e and 8f show the average and standard deviation for all specimens together.

Table 2: Fracture toughness results for both mode I and mode II. As a comparison the results found by Narducci et al. [74] for a 0//0 delamination interface are also shown.

Interface	G_{Ic} [kJ/m ²]		G_{IIc} [kJ/m ²]	
	Initiation	Propagation	Initiation	Propagation
Baseline 0//0 ^a	0.19 ± 0.02	0.19 ± 0.01	0.77 ± 0.09	0.80 ± 0.04
Baseline 0//45	0.39 ± 0.007	0.41 ± 0.02	0.92 ± 0.04	1.00 ± 0.05
Reinforced 0//45	0.36 ± 0.04	0.72 ± 0.08	0.86 ± 0.05	0.99 ± 0.05

^a Data from [74].

immediate force drop after reaching the peak load, the reinforced specimens exhibited a stable plateau. The force remained constant at roughly the peak value until the displacement had increased quite considerably. The difference in the initial stiffness of the specimens is due to the difference in the initial crack lengths resulting from the pre-cracking procedure, as well as normal material variability.

Focussing now on the R-curves (Figure 8c) and fracture toughness values (Figure 8e and Table 2), the initiation toughness in the reinforced case is slightly lower (7.8 % reduction). However, as the delamination grows, the tabs bridge the crack (see Figure 9), and consequently the SERR needed for further propagation increases. As a result, the propagation toughness of the reinforced specimens was 77.6 % higher than that of the baseline specimens.

Although the propagation toughness for the reinforced specimens is significantly higher, the variability of the toughness is also substantially increased. This is most likely due to the manual interlocking process and the heterogeneity created on the interface.

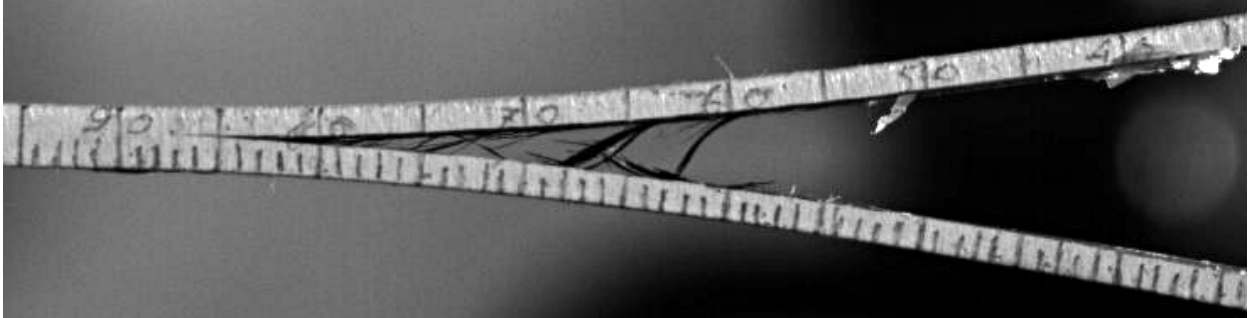


Figure 9: Side-view of a reinforced DCB specimen during the test, showing the tabs bridging the crack. The crack growth direction is from right to left.

It is notable that the toughening effect of the tabs persists even after the crack tip has exited the reinforced region (Figure 8c). This is because the tabs continue to bridge the crack until the crack opening becomes large enough to cause them to fail. This does not happen until the crack tip has advanced well beyond the reinforced region.

To investigate the effect of delaminating along a 0//45 interface, rather than a 0//0 interface, the 0//0 interface data reported by Narducci et al. [74] is also shown in Figure 8e and Table 2. Narducci et al. used the same Skyflex material, but with the lay-up [0₁₃₀]. Changing from a unidirectional to a multi-directional interface increases the initiation toughness by 107 % and the propagation toughness by 115 %. For clarity, we emphasise that the 77.6 % toughness increase due to the reinforcements reported in this work, comes on top of the toughness increase due to changing the fibre angles at the interface.

A comparison between the fracture surfaces of a baseline and a reinforced specimen is shown in Figure 10. In the baseline specimen, two different regions can be identified, labelled ‘insert location’ and ‘crack region’ in the figure. The insert location region corresponds to the location of the PTFE insert, whereas the crack region is the region in which the delamination grew, starting at the end of the PTFE insert,

and propagating towards the right. For the reinforced specimen, the crack region can be separated into two subregions: the ‘reinforced region’, which corresponds to the area of the specimen where the interlocked tabs and slits were located, and the ‘post-reinforcement’ area, where there were no interlocks. In the reinforced region, the locations where the tabs crossed through the slits can be seen, as can the corresponding resin pockets. These features correlate with the tab locations (Figure 3a); the fracture path through the tabs will be discussed in section 5.1.

In both specimens regions with different reflectivity can be identified, as well as areas in which there are linear features either running parallel to the specimen sides, or diagonally across the surface. This indicates that the crack did not remain in only one interface as it propagated, but that it jumped to other interfaces. In the baseline specimen only one such jump appears to have occurred, whereas in the reinforced specimen there is evidence of many crack jumps at different locations.

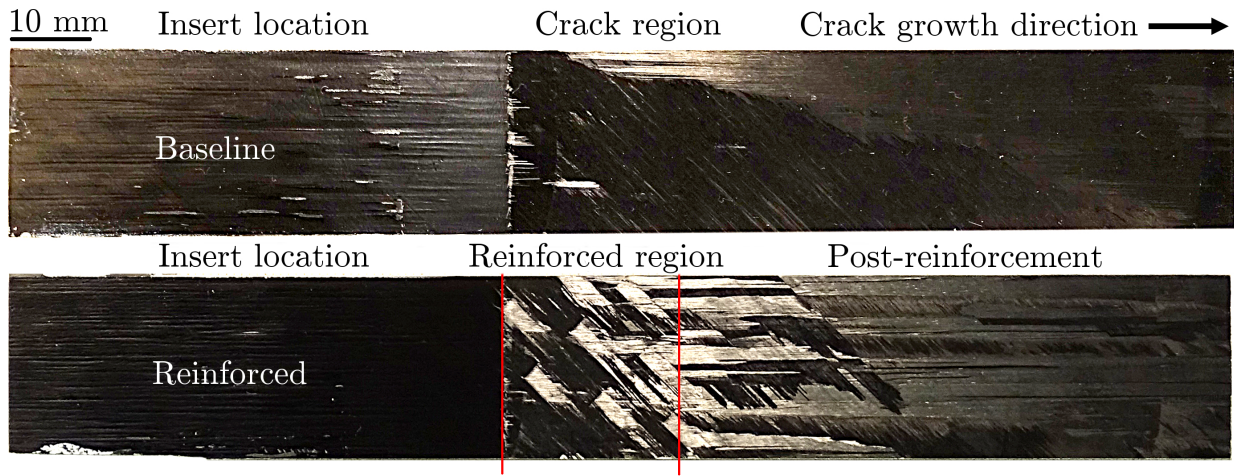


Figure 10: Comparison of the fracture surfaces of a baseline (top) and reinforced (bottom) DCB specimen.

4.2. Mode II delamination

Results for the mode II delamination are shown in Figures 8b, 8d, and 8f, and Table 2. As in the previous section, Figures 8b and 8d show results for a typical specimen of each configuration, whereas Figure 8f and Table 2 show the mean and standard deviation for all specimens.

As was done for the mode I specimens, the displacement values were corrected to ensure that the extrapolation of the initial linear portion of the force-displacement curve passes through the origin, see Figure 8b. As for the DCB specimens, the difference in the initial stiffness is due to the difference in the initial crack lengths, as well as normal material variability.

It is clear that the interlocking has no effect on the mode II fracture toughness. The reason for this will be discussed in more detail in section 5.2.

The effect of having a multi-directional delamination interface was also investigated for the mode II specimens, as shown in Figure 8f and Table 2. Having a 0//45 delamination interface, rather than a 0//0 interface, increased the initiation toughness by 19.1 % and the propagation toughness by 26.2 %.

After testing of the reinforced 4ENF specimens was completed, loading blocks were bonded to the specimens and they were pulled apart as in a DCB test, in order to expose the fracture surfaces, as shown in Figure 11.

As for the DCB specimens (Figure 10), the insert region, the reinforced region, and the post reinforcement region can be clearly identified in the reinforced specimen. The tab features correlate with the location of the tabs (Figure 3b). There is an additional region visible on the right side of both specimens, which corresponds to the final increment of crack growth under mode I loading, during the opening of the specimen. In both the baseline and the reinforced specimen, there is evidence of multiple crack jumps having occurred, with the

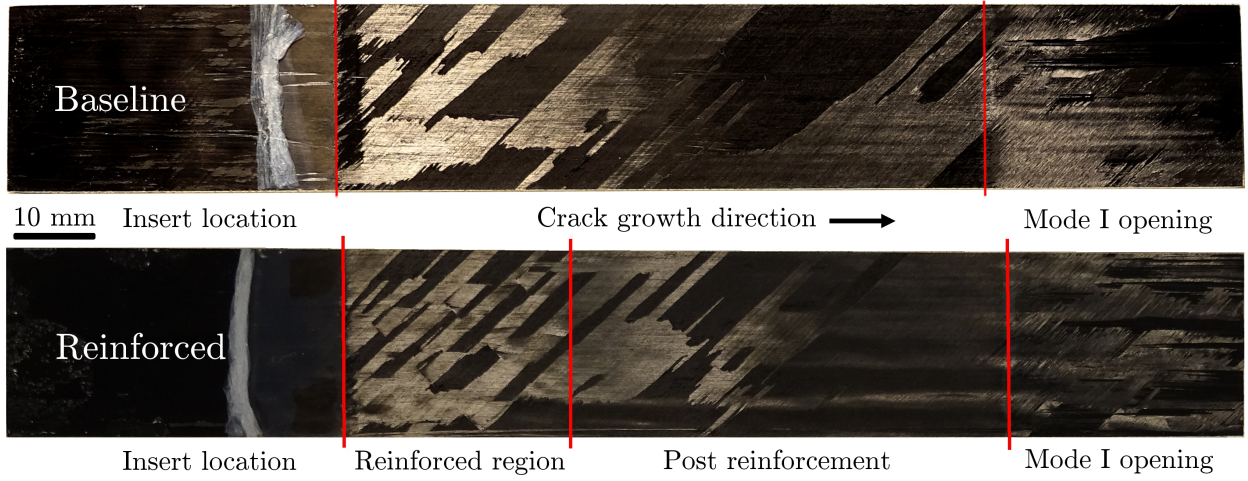


Figure 11: Fracture surface of a baseline and a reinforced ENF specimen. The final increment of crack growth was caused by the mode I loading used to expose the fracture surfaces.

295 delamination jumping back and forth between the interfaces on either side of the 45° ply. For the reinforced specimens, these crack jumps are visible in both the reinforced region and the post reinforcement region. The crack path in the reinforced specimen will be discussed further in Section 5.2.

4.3. Impact tests

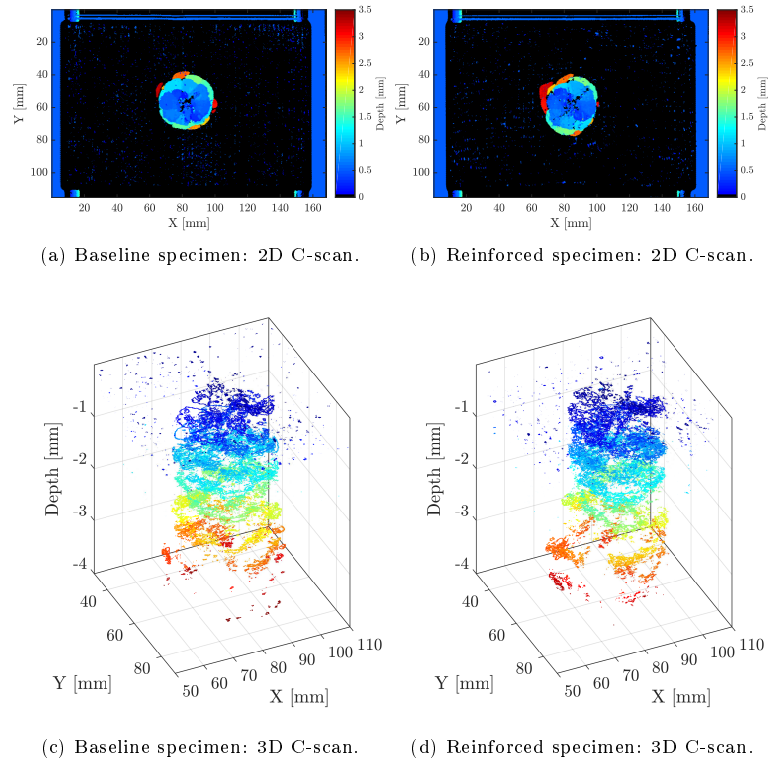


Figure 12: C-scan data for a representative baseline specimen (left) and reinforced specimen (right).

After the impact tests, all specimens were ultrasonically scanned. Figure 12 shows data from these C-scans for a representative baseline and reinforced specimen. Both 2D and 3D representations of the data are shown. For the 3D data, note that the ultrasonic signals from delaminations in lower layers of the composite are masked by the returns from the delaminations above. As would be expected from the literature, delamination occurred at each interface at which there was a fibre-angle mismatch. This is why reinforcement units were inserted at all interfaces in the reinforced specimens.

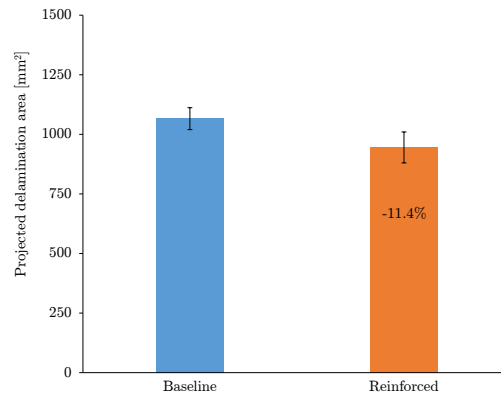


Figure 13: Projected delamination area.

Although the baseline and reinforced C-scans shown in Figure 12 look similar, the average projected delamination area for the reinforced specimens was 11.4% smaller, as illustrated in Figure 13. Figure 12 suggests that in the reinforced specimens the delamination size was successfully reduced in all interfaces.

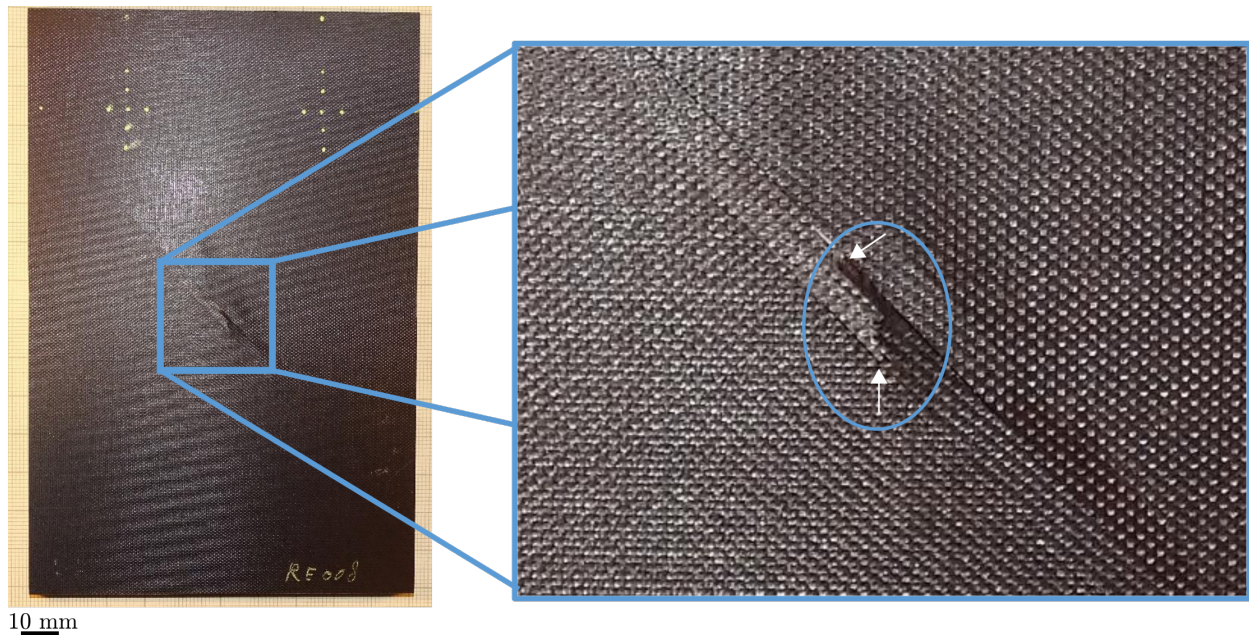


Figure 14: Photograph of the back-face of an impacted CAI specimen, showing evidence of broken fibres.

Apart from the delaminations, there was also visible impact damage on both sides of the specimens. In particular, the back-face of the impacted specimens exhibited splitting and fibre damage, as shown in Figure 14.

4.4. CAI tests

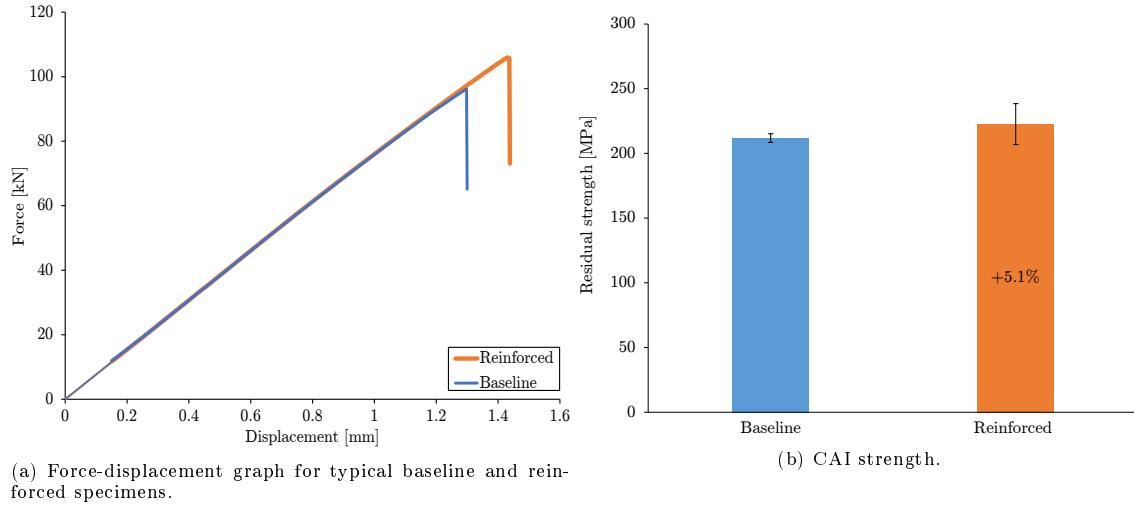


Figure 15: Results of the compression after impact tests showing the effect of the reinforcements.

Figure 15a shows typical force-displacement curves for a baseline and a reinforced specimen during the compression after impact test. Again the displacement was corrected so the extrapolation of the linear portion of the curve passed through the origin. The average CAI strength values obtained from the test are shown in Figure 15b.

Failure for all specimens was due to localised compressive failure, passing through the centre of the specimen. Figure 16 shows a side view of a failed baseline specimen and a failed reinforced specimen, displaying the typical failure pattern.

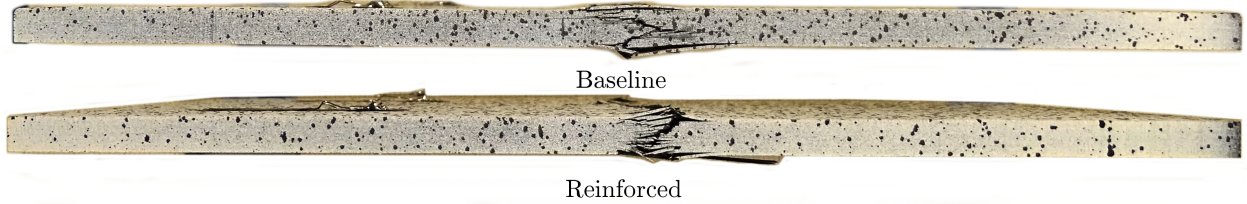


Figure 16: Photographs of the side of a baseline and a reinforced specimen, showing the compressive failure pattern.

The average CAI strength for the reinforced specimens was 5.1 % higher than for the baseline specimens. However the variability for the reinforced specimens was also much larger. Consequently the increase in average CAI strength is not statistically significant ($p = 0.21$; two sample Kolmogorov-Smirnov test).

5. Discussion

5.1. Mode I delamination

The mode I delamination results show that the reinforcement units produce a small reduction of initiation toughness, and a large increase of propagation toughness (Figure 8e). The slight reduction of initiation toughness is likely the result of the tabs leaving resin pockets in their ply of origin when they are inserted through the slits.

In the baseline specimens, once the delamination initiated, crack growth continued in a stable manner. The propagation toughness was roughly equal to the initiation toughness (Figures 8c and 8e). In contrast, the reinforced specimens exhibit an R-curve type behaviour (Figure 8c). As the crack extends stably through

the reinforced region, the toughness continues to increase until a maximum is reached. This increase of propagation toughness is caused by the tabs bridging the crack (see Figure 9). The process of forming the crack bridges is shown schematically for one tab in Figure 17. The delamination grows in the plane between the tab and the slit plies. Because the tab is interlocked through the slit, it crosses the delamination plane, and remains connected to the sublaminate on either side of the delamination. This allows the tabs to bridge the crack.

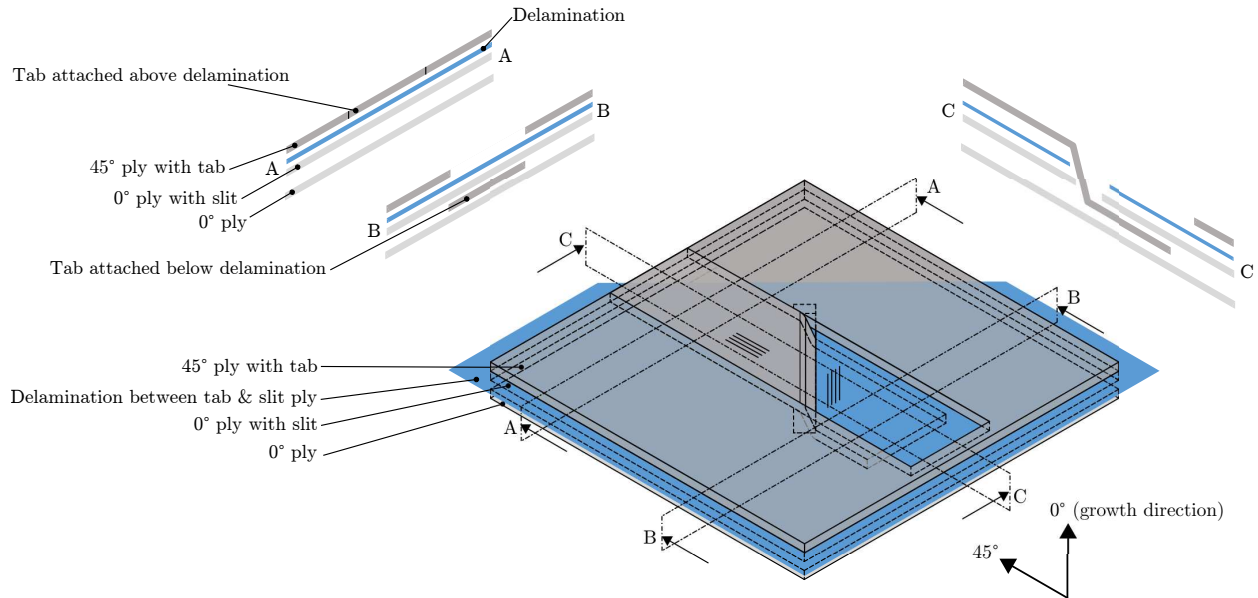


Figure 17: Schematic illustration of the process by which the crack bridges are formed. The tabs remain attached to sublaminate on either side of the delamination, thereby bridging the cracks.

Once the crack opening displacement becomes sufficiently large, the tabs fail. As not all the tabs fail simultaneously, this results in stick-slip type crack growth.

Because a certain amount of crack opening displacement is required to fail the tabs, the reinforcing effect persists even when the crack tip has already exited the reinforced region. As shown in Figure 8c, the toughness remains higher than the baseline value.

In fact, the propagation toughness remains higher than the baseline case even when all the tabs have failed. This is likely caused by crack jumping induced by the tabs, which can be seen on in the fracture surfaces shown in Figure 10. In the baseline specimens, only a small amount of crack jumping was seen, and the crack mainly propagated through the 0//45 interface. In the reinforced specimens on the other hand, the crack front is quite tortuous (Figure 10). After passing the tabs, the crack progressed in different interfaces at different points across the width of the specimen (Figure 10). This means that the propagation SERR values reported in Figure 8e and Table 2 should be considered to be structural values, rather than material properties. Nevertheless, it is clear that the overall effect of this induced crack jumping is to increase the work required to propagate the crack.

5.2. Mode II delamination

Figures 8d and 8f show that the reinforcement did not affect the mode II fracture toughness. The reason for this can be understood by examining the fracture surfaces (Figure 11).

In order for the tabs to bridge the crack, it is important that the tab remains connected to its ‘parent’ ply. This means the delamination should grow in between the tab and the 0° ply containing the slit, as illustrated in Figure 18.

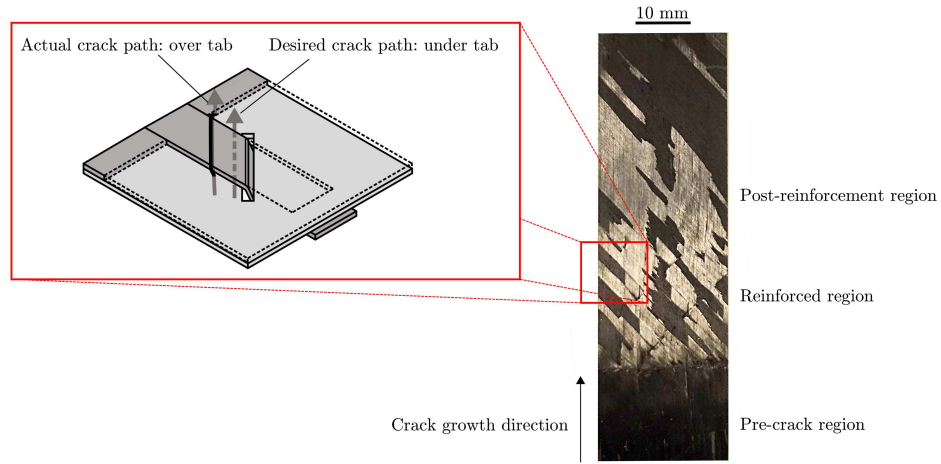


Figure 18: Photograph of the fracture surface of a reinforced 4ENF specimen (right) and a schematic illustration showing difference between the desired and actual crack paths (left). In this illustration the ply containing the tab is drawn as partly transparent.

However, as can be seen in the figure, the actual fracture surface shows that in practice the crack jumped around the tab, splitting it from its parent ply. In this case the tab is unable to bridge the crack, explaining the lack of effect on the fracture toughness.

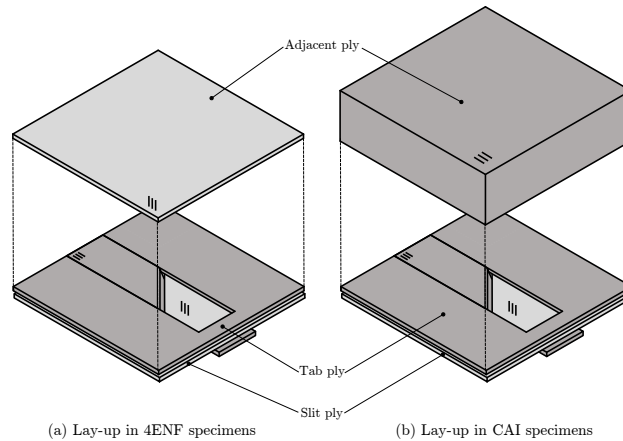


Figure 19: Schematic illustration showing the ply adjacent to the tab ply in (a) the 4ENF configuration and (b) the CAI configuration. In the 4ENF case the adjacent ply is a thin ply, and the adjacent and tab plies have different fibre orientations. In the CAI case, the adjacent ply is a regular thickness ply, and the fibre orientation is the same.

That the crack jumps around the tab suggests that the tab either (i) locally increased the toughness of the interface between the plies containing the tab and the slit, and/or that (ii) the tab created a weaker path for the crack to follow.

In order to compare the results from the 4ENF tests to those of the CAI tests, we need to take the difference in lay-up into account. In the 4ENF specimen, the ply adjacent to the 45° tab ply was a 0° thin-ply, as can be seen in Figure 19a. However, in the CAI specimens, the ply adjacent to the tab ply was always a regular thickness ply with the same fibre orientation (see Figure 19b). This would make it harder for the crack to jump over the tab. Consequently, in the CAI specimen lay-up, the tabs may indeed have had some effect on the mode II toughness. This is further supported by the impact-induced delaminations (which are mode II driven) being smaller for the reinforced CAI configuration.

If the tabs were more effective at increasing mode II toughness in the CAI specimens than in the ENF

specimens, this may also explain why the variability in post-impact delamination area was higher for the reinforced specimens than for the baseline specimens (see Figure 13), even though in the ENF tests there was no difference in scatter (Figure 8f). If the tabs do increase the mode II toughness in the CAI specimens, then this toughness increase would be sensitive to the manual interlocking process, therefore resulting in greater variability in the reinforced specimens.

5.3. CAI

Considering the improvement to mode I fracture toughness (Figure 8e) and the reduction of delamination area (Figure 13), the fact that the reinforcement had little or no effect on the CAI strength could be seen as rather surprising.

A correlation between delamination width or area, and CAI strength has often been reported (see e.g. [3–8]). This correlation has been used as the basis for successful prediction models (e.g. [7, 8, 79–81]). One would therefore expect the reduction of delamination area to correspond to an increase in residual strength.

Similarly, the increase in mode I fracture toughness should prevent delamination growth during compressive loading. In addition, as the tabs prevent crack opening by acting as bridges, one would expect them to similarly resist local buckling of the delaminated sublaminates. As unstable delamination growth and local buckling are the mechanisms that typically lead to final failure [1, 2, 5], one would again expect the tabs to have a beneficial effect on the residual strength.

The lack of increase in CAI strength in the present case can be explained by the presence of fibre damage. Evidence of fibre damage could be seen on the back-face of the specimens after impact, as shown in Figure 14.

When a region of fibres is damaged or broken by the impact, then, during the compressive loading, a stress concentration will be generated around this region. This stress concentration then induces fibre failure in the surrounding fibres, triggering final failure of the specimen, without delamination growth or local buckling [3]. Since the critical failure mechanism is now fibre failure induced by the fibre damage, the delamination size and any restraint against local buckling no longer affect the CAI strength.

Further support for this hypothesis can be found in the literature. For example Byun et al. [41] investigated the effect of stitching on CAI strength. They found that stitching patterns that increased CAI strength at low impact energies were no longer effective at high impact energies, where fibre failure may be expected. Petit et al. [82] investigated composite laminates with and without a cork thermal shield covering. They found that when the thermal shield was applied, more fibre damage was induced in the laminate, and the CAI strength was reduced even without detectable delamination. Nettles and Scharber, comparing different resin systems, found that for a given damage size CAI strength was not correlated to mode I fracture toughness for their experiments, implying final failure, in that case, was not triggered by delamination growth [3]. Unlike the present case, Nettles and Scharber did not report any fibre damage.

In the present study, the resin system was kept the same, and the (apparent) mode I toughness was altered by geometric changes; the CAI strength was mostly unaffected. In view of the results of Nettles and Scharber [3], this suggests that final failure was not triggered by local buckling and/or delamination. The most likely source of final failure is therefore the fibre damage created during the impact.

Our tests therefore suggest that, if final failure is triggered by the fibre damage, then the delamination area does not determine the residual strength. This explains why the significant decrease in delamination area for the reinforced specimens is not matched by a corresponding increase of CAI strength.

Our conclusion therefore is that mode I fracture toughness does not affect the CAI strength, when fibre damage triggers the final failure.

At lower impact energies, where a lack of fibre damage means that delamination growth and / or local buckling are the critical failure modes, we can however expect our concept to increase the CAI strength, based on the improved delamination area and mode I toughness.

Concepts for improving CAI strength reported in the literature tend to focus on improving interlaminar fracture toughness. The present results suggest that to improve CAI for higher impact energies, more attention should be paid to preventing or ameliorating fibre damage instead. Furthermore, methods that improve CAI strength for lower energies may no longer provide an improvement when the impact energy is sufficiently high to cause fibre damage.

6. Conclusions

In this work, we designed, manufactured, and tested an original interlaminar toughening concept, consisting of reinforcement units created by interlocking two thin-ply layers with a tab-and-slit geometry. These units were inserted between the layers of a composite laminate in order to improve its fracture toughness and damage tolerance.

Mode I propagation fracture toughness increased by 77.6 %, due to the tabs bridging the crack. The crack bridging, and the consequent fracture toughness increase, was effective even after the crack front had propagated out of the reinforced area.

The tabs did not affect the mode II fracture toughness, as the delamination path split the tabs from their parent ply, preventing them from acting as bridges. In the CAI specimens the projected delamination area was nevertheless reduced. This suggests that this crack jumping did not occur in the CAI specimens, allowing the tabs to have a reinforcing effect.

In the compression after impact tests, the reinforcement units reduced the projected delamination area by 11.4 %. However, the increase in CAI strength was only 5.1 % and not statistically significant, because the ASTM standard energy levels used during impact led to fibre failure at the distal face. Our results show that when fibre damage triggers the final failure of the laminate during the compressive loading, the mode I fracture toughness does not affect the CAI strength.

The results of the CAI tests show that in order to improve CAI strength at higher impact energies, reinforcement concepts are needed that prevent or mitigate fibre damage, rather than focusing on interface toughness.

In this study we have proposed an original reinforcement concept that can increase the interlaminar toughness significantly. This concept has potential to be used in large scale engineering applications, as the reinforcing units can be pre-manufactured, potentially in an automated manner. The units can then be shipped, for instance as a pre-assembled prepreg roll, which can be used to easily insert reinforcements at desired locations, during manufacturing of a composite structure.

Data Access Statement

The data underlying this publication is publicly available on the Zenodo repository: <https://doi.org/10.5281/zenodo.1476887>.

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Appendix A. Crack length measurements

When conducting fracture toughness tests on a multi-directional interface, straightness of the crack front is an important concern. Therefore, in the present research, we monitored both sides of the specimen simultaneously, using two synchronised video cameras. This allowed measurement of the crack length on both sides of the specimen at the same time.

Figure A.1 shows representative graphs for crack length versus displacement on both sides of the specimen. Although the crack lengths on either side of the specimen are in general not equal, the difference in crack lengths does remain limited. When there are sudden jumps in the crack length, this happens on both sides simultaneously. Therefore, we assumed that the crack front was straight, and used the average of the front and back crack lengths as ‘the’ crack length for all calculations.

Figure A.2 shows the correlation between crack length and either $C^{1/3}$ (DCB) or C (ENF) for four representative specimens. In both cases, the correlation is excellent ($R^2 > 0.99$). Therefore linear fits could be used to relate the crack length to the measured $C^{1/3}$ (DCB) or C (ENF). This allowed calculation of the crack length for all pairs of recorded force and displacement data.

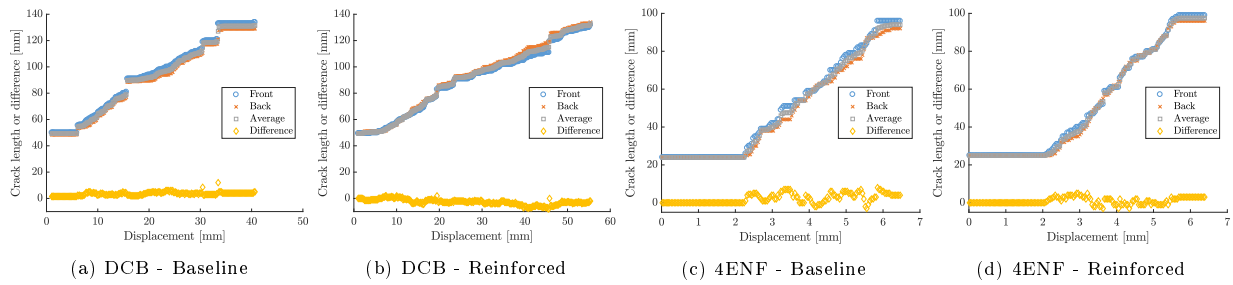


Figure A.1: Crack length as measured on both the front and the back of various representative specimens, as well as average crack length and the difference (front - back).

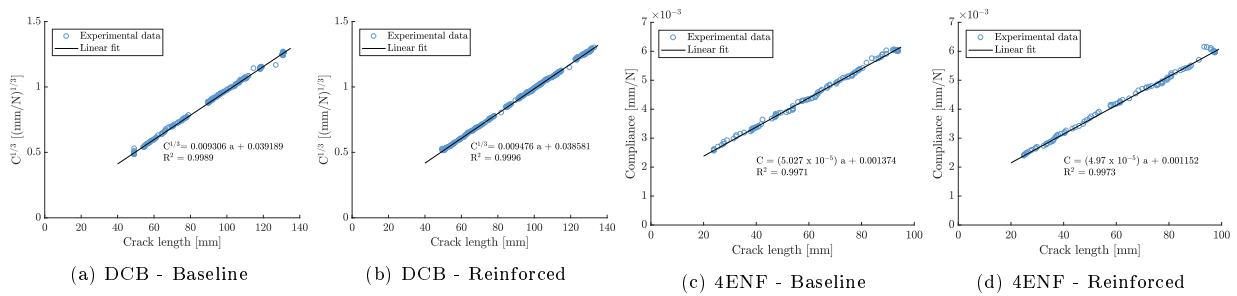


Figure A.2: Correlation between compliance and crack length for various representative specimens. Both experimental data and linear fits through those points are shown.

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