Thickness-dependence of the translaminar fracture toughness: experimental study using thin-ply composites

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Abstract

The concept of translaminar fracture toughness of 0° plies has enabled the development of a considerable number of ply-level numerical models for structural failure of laminated composites. Using thin-ply pre-pregs, this paper demonstrates that this translaminar toughness is not an absolute, but rather in-situ, property and depends strongly on the 0° ply-block thickness, even in situations where delamination and diffuse damage are inhibited. We used two different grades of a thin-ply carbon-epoxy system to produce four different 0° ply-block thicknesses ranging from 0.03 mm to 0.12 mm, and measured the respective translaminar fracture toughness using compact tension tests. SEM and X-ray analysis showed no delamination nor diffuse damage. Yet, the translaminar fracture toughness increased from 46 to 104 kJ/m² (initiation), and from 49 to 160 kJ/m² (propagation), for the thickness range above. This finding has significant implications for the development and use of ply-level numerical failure models, for structural design with thin-ply composites, and for the development of thin-ply material systems.

Keywords: Thin-ply prepreg, translaminar fracture toughness, size effects, ply-blocking, SEM, X-ray.

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1. Introduction

The ply-block thickness effect on the onset of micro-cracking and delamination has been extensively analysed [1–6]. Kim and Soni [7] investigated several quasi-isotropic layups, with different layups sequences while keeping the same ratio of each constituent ply; the authors showed that the delamination threshold decreased with increasing ply-block thickness. Similarly, Wisnom et al. [8] observed significant scaling effects when changing the ply-blocks thickness in quasi-isotropic laminates. The laminates with larger ply-blocks failed by complete delamination, before fibre failure could take place. Therefore, ply-blocking has been seen to result in extensive damage zones in multidirectional laminates. This creates a substantial challenge when attempting to characterize the translaminar fracture of 0° plies for different 0° ply-block thicknesses, using cross-ply specimens [6, 9, 10].

Regarding the measurement of the translaminar fracture toughness of 0° ply-blocks, most of the work found in the literature has been bounded by a minimum ply thickness of 0.125 mm. Published work in the literature [4, 6, 9–11] suggest that the translaminar fracture toughness of cross-ply laminates and of 0° ply-block depends on the thickness of that ply-block. While it can be speculated that delamination may play a meaningful role in this (the extent of delamination in thick ply-block laminates is larger [10]), the analysis of the translaminar fracture surfaces of 0° plies of different thicknesses reveals significant differences [10]. Additionally, an analytical model [12] which takes into account the energy dissipated by debonding and by pull-out within the ply, but neglects delamination, succeeded in predicting size effects observed by Laffan et al. [6] and Teixeira et al. [10]. Furthermore, by considering the likely thickness-dependence of the translaminar fracture toughness, Chen et al. [13] were recently able to predict size effects observed by Green et al. [14] in ply-level blocked open hole tension specimens.

Current ply-level numerical models of material failure, either based on a smeared-crack approach [15], or on partition of unity [16], rely on the translam-

inlar fracture toughness for predicting damage accumulation prior to ultimate failure. The implications of the likely dependence of the translaminar fracture toughness on the 0° ply-block-thickness has therefore profound implications for the use of current numerical models.

35 The challenge in establishing firmly whether the translaminar fracture toughness of a 0° ply-block depends on the ply-block thickness lies in that most specimen geometries (such a compact tension) cease to promote the desired failure mode when the ply thicknesses become larger than about 0.25 mm [10], depending on the exact material system.

40 Until recently, there had been little effort into reducing the ply thickness of CRFPs. Nowadays, new process methods have been developed and composite plies are now being produced with areal weights as low as 25 g/m^2 , i.e., with a uncured ply thickness of, approximately, 0.02 mm. From an engineering point of view, the access to thin-ply laminates has enlarged the design space, improving
45 homogenization and increasing the stacking sequences possible for a predefined laminate thickness [17–19].

Recent research on thin-ply composites [17, 18, 20–24] has shown some enhanced mechanical properties as well as size effects directly related to decreasing ply thickness. Sih et al. [20] and Yokozeki et al. [21, 22] observed a significant
50 reduction, and even suppression, of matrix cracking, delamination and splitting in thin-ply laminates under static, dynamic and impact loading; while standard ply thickness laminates presented considerable damage prior to failure, thin-ply laminates behaved mainly linearly. The onset of damage was delayed to close to the ultimate load in the load-bearing plies, leading to a quasi-brittle failure
55 [17, 20]. Thus, the span between first ply failure and collapse has been drastically reduced. The analysis and understandings of translaminar fracture toughness in thin-ply composites is, therefore, even more critical than for standard ply thicknesses.

To the knowledge of the authors, no work has been published on the measurement of the translaminar fracture toughness of thin UD ply composites.
60 Equally, there are no experimental studies on the thickness dependence of the

translaminar fracture toughness for thicknesses lower than 0.125 mm. The objective of this paper is to provide these first studies and the measurements mentioned.

65 This paper starts by introducing the thin-ply material used, the experimental method (section 2) and data reduction method (section 3). The results from X-ray imaging and microscopy are showed in section 4 and discussed in section 5. The main conclusions are drawn in section 6.

2. Experimental method

70 2.1. Material System

The material system used in this work was the unidirectional (UD) prepreg TR50s/K51, 6K Pyrofil[®] standard modulus carbon fibre and toughened epoxy system, supplied by SkyFlex [25]. Two prepreg grades were used:

- 30 g/m² (USN 030A), low grade, with a nominal ply thickness $t^0 =$
75 0.03 mm;
- 55 g/m² (USN 050A), high grade, with a nominal ply thickness $t^0 =$
0.055 mm.

Table 1 presents the relevant material properties, where subscripts 1 and 2 denote longitudinal and transverse direction in the plane of the laminae.

80 2.2. Specimen and layup configuration

Compact tension (CT) specimens [9, 10, 26], with layups shown in Table 2 and dimensions shown in Figure 1, were manufactured. While layup ‘90’ (see Table 2) aimed at measuring the intralaminar fracture toughness, layups A, B, C and D aimed at measuring the translaminar fracture toughness for 0° ply-blocks
85 with overall thicknesses of 0.03, 0.055, 0.06 and 0.11 mm respectively. The CT configuration was chosen as it allows a stable crack growth and the specimens are wide enough so that steady-state crack growth can be reached [9, 26, 27].

The ratio of $0^\circ/90^\circ$ plies in each layup was carefully chosen to keep it as constant as possible, so that the effects of ply-blocking were isolated. The mechanical properties of each layup were calculated from Table 1 using lamination theory and can be found in Table 3.

All laminates were manufactured using hand lay-up and cured in an autoclave according to the supplier's recommendations, as specified for the K51 resin system [25]. Once cured, a wet saw was used to cut the rectangular plates into the specimen's geometry (Figure 1). Two 8 mm holes were drilled using a carbide tipped drill. The specimens' notches were machined using a diamond coated disk-saw to guarantee an accurate and sharp crack tip [28]. The morphology of the crack tip, that can be typically obtained with this process, is shown in Figure 2.

2.3. Testing and post-mortem

At least six CT specimens for each layup (90, A, B, C and D) indicated in Table 2 were tested using an Instron machine with a 10 kN load cell. Each specimen was loaded under displacement control, at a constant rate of 0.2 mm/min to obtain quasi-static conditions. For each layup, the loading for one additional specimen was interrupted at approximately 90% of the respective average peak load for that layup, in order to evaluate the extension of damage at this stage.

All the inspected specimens were wedged before unloading in order to keep the fracture surfaces intact. *Post-mortem* analyses, such as X-ray and optical and scanning electron microscopy (SEM), enabled the identification of the damage zone, of the different damage modes, of the failure sequence, and confirmed that the crack propagated in the same plane defined by the initial notch.

X-ray analysis was used to examine the failure modes and damage extension for the different laminates. An organic penetrant (dibromomethane) was used to highlight the damage within the specimens. The specimens were immersed in dibromomethane for 5 minutes and then dwelled for another 20. The specimens were then exposed for 140 seconds to the X-Ray tube voltage which was carefully chosen accordingly to the specimens thickness: from 18 kV to 24 kV, as the

thickness increased.

The crack propagation path was investigated through optical microscopy in the through-the-thickness section. For this, each ply was polished away until the reaching the ply of interest. The specimen was then placed under the microscope and thoroughly analysed.

The failure mechanisms, at the level of the ply, were characterized using a Hitachi S-3400N SEM, operating at an acceleration voltage of 5-15 kV. For this, two representative specimens of each layup were cut and attached onto aluminium stubs. Compressed air was sprayed over each specimen to remove any dust or debris traces. The specimens were sputter-coated with gold and painted on the side with silver dag to ensure electrical conductivity.

3. Data reduction

3.1. Laminate fracture toughness

The modified compliance calibration method [26, 29] was used to obtain the laminate translaminar fracture toughness from the raw test data. For each layup in Table 2, a half CT specimen was modelled using the finite element (FE) Abaqus package. A 1 N load was applied at the position of the loading pin. The compliance calibration curve was obtained in 1 mm increments of the notch length, to capture the full compliance versus crack length response, for each layup type (the elastic properties for each layup were shown in Table 3). The compliance C vs. crack length a data were plotted and fitted according to [30]

$$C(a) = (\alpha a + \beta)^\chi, \quad (1)$$

where α , β , and χ were calculated to best fit the experimental data for each layup. Further details on the finite element model can be found in [31]. The parameters α , β and χ for each layup are listed in Table 4.

For the fracture toughness tests, an effective crack length, a_{eff} , could be determined using the elastic compliance measured from the load vs. displacement

145 curve of the test specimens, and the α , β and χ constants obtained numerically:

$$a_{\text{eff}} = \frac{C^{\frac{1}{\chi}} - \beta}{\alpha}. \quad (2)$$

The translaminar fracture toughness for each laminate was then be calculated as:

$$G_{\text{Ic}}^{\text{Lam}} = \frac{P_c^2}{2t} \frac{dC}{da} \quad (3)$$

where P_c is the measured load that initiates or propagates fracture and t is the specimen's thickness.

150 One of the main advantages of this data reduction method is that it does not rely on the observation of the surface of the specimen [29]. This is important as the external plies of the specimen do not necessarily reflect the actual crack front inside the specimen during crack growth; the crack front is not necessarily uniform through the thickness of the specimen, and delamination (as well as
155 other damage) near the crack front may influence the strain field at the surface.

Three different toughnesses were measured in this work: non-linearity onset, initiation and propagation. The non-linearity onset was defined at the point where the load-displacement curve ceases being perfectly linear. An initiation value was calculated through a linear regression of toughness values between
160 the non-linearity onset and propagation (see Section 4.3). The propagation toughness was defined as the average of the toughness values, once the R -curve had levelled out (steady-state).

3.2. Ply fracture toughness

For the 90° laminate (layup '90' in Table 2), the laminate toughness obtained
165 from Equation 3 corresponds immediately to the 90° ply intralaminar toughness, G_{Ic}^{90} . For the other layups (layups A, B, C and D in Table 2), the fracture toughness of the 0° plies was obtained from the rule of mixtures as

$$G_{\text{Ic}}^0 = \frac{G_{\text{Ic}}^{\text{Lam}} t^{\text{Lam}} - G_{\text{Ic}}^{90} t_{\text{T}}^{90}}{t_{\text{T}}^0} \quad (4)$$

where t^{Lam} is the thickness of the laminate, t_{T}^0 is the total thickness of all the 0° plies of the laminate, and t_{T}^{90} is the total thickness of the 90° plies in the laminate (note $t^{\text{Lam}} = t_{\text{T}}^0 + t_{\text{T}}^{90}$).
170

4. Results

4.1. Load-displacement curves

Except for the UD layup ('90' in Table 2), all laminates exhibited a stick-slip crack growth, typical of cross-ply laminates (see Figure 3, where d is the displacement). Despite the fact that all cross-ply layups (A, B, C and D) have
175 a very similar $0^\circ/90^\circ$ ply ratio, the size of the load-drops visible in the load-displacement curves was significantly dependent on the thickness of the 0° ply-block (t^0). The crack propagated more smoothly (higher number of smaller load-drops) in the blocked configurations. Both for the low graded (layups A
180 and C) and the high graded material (layups B and D), the peak load can be observed to increase with ply-block thickness (see Figure 3).

4.2. Post-mortem

4.2.1. X-ray

The damage extension was investigated via X-ray imaging, as shown in Figures 4 and 5. The X-ray images in Figure 4 were taken from layups where
185 specimens were loaded until, approximately, 90% of the average peak load had been reached, whilst those in Figure 5 were taken from fully tested specimens.

The height of the damaged zone is very small in all cases, but it is larger for layup D, for which the ply-block thickness is relatively similar to that of
190 classical thickness prepregs.

4.2.2. Optical microscopy

One representative micrograph for each cross-ply layup is presented in Figure 6. It can be seen that the crack path remained coplanar with the initial notch tip plane.

195 4.2.3. Scanning electron microscopy

A more detailed analysis of the failure process was done via SEM imaging of the fracture surfaces, as shown in Figures 7 to 10. The crack front corresponding to each load-drop was easily observable, even to the naked eye, from the fractured surfaces in all four CP layups (Figure 7). The pull-out height is visible in
200 Figures 8 and 9, while the top view in Figure 10 provides greater insight into the translaminar fracture surface across the thickness of the ply. The fibre/matrix interface and the resin rich-region between plies can be gleaned from Figure 9.

4.3. Laminate and ply fracture toughnesses

4.3.1. Intralaminar fracture toughness

205 The initiation intralaminar fracture toughness (layup ‘90’ in Table 2) was determined from the R -curves shown in Figure 11a and then used to calculate the toughness of the 0° plies (see section 3). A propagation value could not be measured as the CT specimens were not wide enough for the toughness to reach steady-state.

210 4.3.2. Translaminar fracture toughnesses

For each CP specimen (layups A, B, C and D in Table 2), three toughness values were measured: non-linearity onset, initiation and propagation. All three toughnesses are presented in Table 5 for the laminate level, and in Table 6 at level of the ply-block. Figure 11 presents the full R -curves for all CP laminates. The
215 ply-level toughnesses measured, for all four layups, were overlapped in Figure 12 and are presented as a function of the ply thickness in Figure 13. When using Equation (4), the initiation value G_{Ic}^{90} was used. It should be noted that the term G_{Ic}^{90} could even be omitted without loss of accuracy, since $G_{Ic}^{90} \ll G_{Ic}^0$.

5. Discussion

220 Fully-tested specimens revealed a thin crack path, well aligned with the notch tip, and reduced splitting (Figures 5 and 6).

The thickness of 0° ply-blocks was seen to influence the size of the load-drops and, therefore, crack growth stability. Specimens with a thicker 0° ply-block typically exhibited more populated load-displacement curves and, consequently, *R*-curves (Figures 3 and 11).

The *R*-curves for layup A (Figure 11b) were found to be essentially flat which indicated that steady-state had been reached within a small crack growth length (< 1 mm). The *R*-curve effect become more evident with increasing 0° ply thickness (see Figure 11). The difference between non-linearity onset and initiation toughness values indicates that there is some subcritical damage taking place prior to macroscopic crack growth.

A considerable increase was seen in both initiation and propagation toughnesses by increasing the ply-block thickness t^0 (see Figures 12 and 13, and Table 6). Since the non-linearity onset toughnesses are dominated by the microscopic damage mechanisms prior to macro-scale propagation in the 0° ply-blocks, the latter trend was not reflected as clearly in this toughness measure.

Despite a slight increase of non-linearity in specimens with increased t^0 , no extensive damage was observed in any of the layups. X-ray imaging showed limited signs of damage during ‘elastic’ loading (Figure 4), with one single split location standing out for laminates with the thickest 0° ply-block. This suggested that the extent of energy-dissipating mechanisms, such as fibre/matrix debonding and pull-out, increased with t^0 .

The height of pulled-out fibres (Figure 8) was observed to increase with increasing 0° ply-block thickness, which implies more energy being dissipated during crack growth (Figure 10). A high magnification of the $90^\circ/0^\circ$ interface shows riverlines (Figure 10), thus indicating that fracture initiates from the 90° plies, and propagates towards the mid-thickness of the 0° plies, as noted in previous works [6, 9, 32].

In addition to several observations suggesting there is no delamination (e.g. it is not visible in the X-rays in Figure 5 or in the SEMs in Figure 8), both the SEMs in Figures 9 and 10 show very clearly that delamination was successfully inhibited, and that, therefore, the ply-block thickness effect measured is not due

to delamination.

The width of the damage zone increases slightly but visibly with the ply
255 block thickness (Figure 5). In fact, this is why the use of thin-ply material was
fundamental to enable this study. For the thickest ply block, the width of the
damage region is therefore the largest, even if, in comparison to the inplane
dimensions of the specimen, it is still very small. By using an experimental
260 compliance calibration method to infer an equivalent crack length (Equation
(2) instead of simply measuring optically the length of the crack on the surface
90° ply), we are in effect including the contribution that this damage has on the
stated measures of fracture toughness. Therefore, the measures of toughness
quoted include the several local damage mechanisms that take place during
failure of the 0° ply. In addition to fibre fracture, these damage mechanisms
265 include the formation of splits and the subsequent pullout. In fact, the formation
of splits and the energy dissipated by friction during pullout account for the bulk
of the energy dissipated during translaminar fracture of carbon-fibre reinforced
composites [?]. If the translaminar fracture toughness were to represent only
the energy dissipated by fibre failure, then the values would be in comparison
270 negligible, and of no interest for ply-level numerical simulation of failure, nor
for material characterization.

There was a clear increase in toughness with t^0 , even tough layup B ($t^0 = 0.06$ mm)
showed a slightly lower toughness than layup C ($t^0 = 0.055$ mm). The latter may
eventually be related to some minor differences in the microstructure of materi-
275 als of different grades motivated by the fibre spreading technology. In any case,
for both grades, there was a clear increase of toughness with thickness (see Fig-
ure 14). The difference between initiation and propagation values corresponding
to a given ply-blocking t^0 , as well as the scatter, can also be seen to increase
with t^0 .

280 This work therefore confirms the dependence of the translaminar fracture
toughness with 0° ply-block thickness, with the concomitant implications for
numerical modelling and development of thin-ply material systems.

6. Conclusions

Using compact tension tests on cross-ply thin-ply carbon-epoxy UD specimens, this work demonstrated that:

- the translaminar fracture toughness in fibre-reinforced laminated composites, as well as the R -curve effect, depend significantly on the thickness of the 0° ply blocks (it is therefore not an absolute, but rather *in-situ*, property);
- for the materials tested in this study (with 0° ply-block thicknesses ranging from 0.03 mm to 0.12 mm), the translaminar fracture toughness increased from 46 to 104 kJ/m² (initiation), and from 49 to 160 kJ/m² (propagation);
- for the materials tested in this study, these increases cannot be attributed to delamination nor diffuse damage;
- for the materials tested in this study, these increases can be attributed to the lengths of the several scales of pulled-out fibres and bundles of fibres, visible through-the-thickness of the plies, which increase with 0° ply-block thickness;
- while thin-ply composites may offer superior damage-onset strength (when compared to standard ply thicknesses), the brittleness that entails must be carefully considered when designing with these materials;
- analytical and numerical ply-level damage propagation models used for design and damage-tolerance analysis should either include 0° ply-block-thickness-dependent translaminar fracture toughness, or use directly a value of translaminar fracture toughness appropriate for the ply-block thickness being considered.

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Table 1. TR50s/K51 properties provided by Skyflex [25].

Single fibre diameter [μm]	6.82	
Nominal ply thickness [mm]	0.03	0.055
Fibre areal weight [g/m^2]	30	55
Fibre volume fraction [%]	55	55
Cured resin density [g/cm^3]	1.20	
Fibre density [g/cm^3]	1.82	
Nominal laminate density [g/cm^3]	1.535	
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Longitudinal modulus E_1 [GPa]	125.3	
Transverse modulus E_2 [GPa]	8.4	
Major Poisson's ratio ν_{12}	0.28	
Shear modulus G_{12} [GPa]	5.1	
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Table 2. Thin-ply layups investigated. 0° is aligned with the direction of the applied load.

ID	Material Grade	Layup	Purpose of layup	t^0 ^a [mm]	t^{Lam} ^b [mm]	Number of plies
90	H	$[90]_{54}$	G_{Ic}^{90}	-	3.00	54
A	L	$[90_3/(90/0)_{24}/90_2]_s$	G_{Ic}^0	0.0307	3.25	106
B	H	$[90_2/(90/0)_{16}/90]_s$	G_{Ic}^0	0.0544	3.81	70
C	L	$[90_3/(90_2/0_2)_{12}/90_2]_s$	G_{Ic}^0	$2 \times 0.0306 = 0.0612$	3.24	106
D	H	$[90_2/(90_2/0_2)_8/90]_s$	G_{Ic}^0	$2 \times 0.0547 = 0.1094$	3.83	70

^a Measured 0° ply block thickness; calculated from the averaged total thickness of all the respective specimens.

^b Measured laminate thickness; averaged from all respective specimens.

Table 3. Laminates' elastic properties calculated from lamination theory.

Layup ID	Layup	E_x [GPa]	E_y [GPa]	ν_{xy}	G_{xy} [GPa]
90	$[90_{54}]$	125.3	8.4	0.019	5.1
A	$[90_3/(90/0)_{24}/90_2]_s$	72.87	61.77	0.038	5.1
B	$[90_2/(90/0)_{16}/90]_s$	72.14	62.10	0.038	5.1
C	$[90_3/(90_2/0_2)_{12}/90_2]_s$	72.87	61.77	0.038	5.1
D	$[90_2/(90_2/0_2)_8/90]_s$	72.14	62.10	0.038	5.1

Table 4. Numerical fitting parameters used in the modified compliance method (units system: N; mm).

Layup ID	Layup	α	β	χ
90	$[90]_{54}$	-0.0366	1.9636	-0.3676
A	$[90_3 / (90/0)_{24} / 90_2]_s$	-0.0531	2.8230	-0.4390
B	$[90_2 / (90/0)_{16} / 90]_s$	-0.0570	3.0359	-0.4390
C	$[90_3 / (90_2/0_2)_{12} / 90_2]_s$	-0.0531	2.8230	-0.4390
D	$[90_2 / (90_2/0_2)_8 / 90]_s$	-0.0570	3.0359	-0.4390

Table 5. Average *laminate* level critical energy release rates.

Layup	t^0 [mm]	G_{Ic}^{Lam} Non-linearity onset [kJ/m ²] (CoV [%])	G_{Ic}^{Lam} Initiation [kJ/m ²] (CoV [%])	G_{Ic}^{Lam} Propagation [kJ/m ²] (CoV [%])
90	-	0.220	0.255	-
$[90]_{54}$	-	(7.45)	(11.92)	(-)
A	0.03	16.28	20.85	22.82
$[90_3 / (90/0)_{24} / 90_2]_s$	0.03	(7.40)	(8.50)	(10.64)
B	0.055	16.19	26.75	43.43
$[90_2 / (90/0)_{16} / 90]_s$	0.055	(7.3)	(2.0)	(4.0)
C	0.06	19.78	24.79	32.30
$[90_3 / (90_2/0_2)_{12} / 90_2]_s$	0.06	(9.47)	(8.86)	(12.07)
D	0.11	16.62	44.59	73.40
$[90_2 / (90_2/0_2)_8 / 90]_s$	0.11	(13.6)	(7.4)	(9.2)

Table 6. Average *ply-block* level values of critical energy release rates.

Layup	t^0 [mm]	G_{Ic}^0 Non-linearity onset [kJ/m ²] (CoV [%])	G_{Ic}^0 Initiation [kJ/m ²] (CoV [%])	G_{Ic}^0 Propagation [kJ/m ²] (CoV [%])
A	0.03	32.86	45.86	49.16
$[90_3 / (90/0)_{24} / 90_2]_s$	0.03	(7.48)	(8.54)	(10.91)
B	0.055	35.10	58.19	94.30
$[90_2 / (90/0)_{16} / 90]_s$	0.055	(7.39)	(2.00)	(3.58)
C	0.06	43.37	54.44	71.03
$[90_3 / (90_2/0_2)_{12} / 90_2]_s$	0.06	(9.54)	(8.91)	(12.12)
D	0.11	36.06	97.23	160.25
$[90_2 / (90_2/0_2)_8 / 90]_s$	0.11	(13.70)	(7.39)	(9.24)

Figure 1. CT specimens dimensions and fibre directions. All dimensions are in mm.

Figure 2. CT crack tip morphology obtained using an optical microscope.

(a) Layup 90

(b) Layup A: $t^0 = 0.03$ mm

(c) Layup B: $t^0 = 0.055$ mm

(d) Layup C: $t^0 = 2 \times 0.03 = 0.06$ mm

(e) Layup D: $t^0 = 2 \times 0.055 = 0.11$ mm

Figure 3. Typical experimental load-displacement curves for thin-ply laminates. The circles highlight points at which load-drops (even if very small) took place.

(a) Layup 90 at $P=0.15$ kN

(b) Layup A: $t^0 = 0.03$ mm, at $P=1.91$ kN

(c) Layup B: $t^0 = 0.055$ mm, at $P=2.40$ kN

(d) Layup C: $t^0 = 2 \times 0.03 = 0.06$ mm, at $P=1.72$ kN

(e) Layup D: $t^0 = 2 \times 0.055 = 0.11$ mm, at $P=3.06$ kN

Figure 4. X-ray imaging of thin-ply laminates shows none or minor damage prior to peak load $P_{\max}$. Inset: magnification near the notch tip.

(a) Layup 90

(b) Layup A: $t^0 = 0.03$ mm

(c) Layup B: $t^0 = 0.055$ mm

(d) Layup C: $t^0 = 2 \times 0.03 = 0.06$ mm

(e) Layup D: $t^0 = 2 \times 0.055 = 0.11$ mm

Figure 5. X-ray imaging shows the damage after testing. The blocking of 0° plies does not lead to considerable diffuse damage. Inset: magnification near the notch tip.

(a) Layup A: $t^0 = 0.03$ mm

(b) Layup B: $t^0 = 0.055$ mm

(c) Layup C: $t^0 = 2 \times 0.03 = 0.06$ mm

(d) Layup D: $t^0 = 2 \times 0.055 = 0.11$ mm

Figure 6. Micrographs of CP thin-ply laminates show a stepped crack path. The size of the steps increases when blocking 0° plies.

Figure 7. Fractured surface for layup A showing that the shape of the crack front is visible at each crack arrest location. Crack propagates from the bottom left corner to the right top corner.

(a) Layup A: $t^0 = 0.03$ mm

(b) Layup B: $t^0 = 0.055$ mm

(c) Layup C: $t^0 = 2 \times 0.03 = 0.06$ mm

(d) Layup D: $t^0 = 2 \times 0.055 = 0.11$ mm

Figure 8. SEM fracture surfaces of CP thin-ply laminates showing bundles of fibres pulled out. The pull-out height increases when blocking 0° plies together. Crack propagates from the bottom left corner to the right top corner.

(a) Layup A: $t^0 = 0.03$ mm

(b) Layup B: $t^0 = 0.055$ mm

(c) Layup C: $t^0 = 2 \times 0.03 = 0.06$ mm

(d) Layup D: $t^0 = 2 \times 0.055 = 0.11$ mm

Figure 9. High magnification SEM fracture surfaces of CP thin-ply laminates. The images were taken in the mid-thickness of the specimens. Crack propagates from the bottom left corner to the right top corner.

(a) Layup A: $t^0 = 0.03$ mm

(b) Layup B: $t^0 = 0.055$ mm

(c) Layup C: $t^0 = 2 \times 0.03 = 0.06$ mm

(d) Layup D: $t^0 = 2 \times 0.055 = 0.11$ mm

Figure 10. Top view of the SEM fracture surfaces of CP thin-ply laminates. in each micrograph, the crack propagates from bottom to top.

(a) Layup 90

(b) Layup A: $t^0 = 0.03$ mm

(c) Layup B: $t^0 = 0.055$ mm

(d) Layup C: $t^0 = 2 \times 0.03 = 0.06$ mm

(e) Layup D: $t^0 = 2 \times 0.055 = 0.11$ mm

Figure 11. R -curves for laminate-level translaminal fracture toughness for thin-ply CP laminates (A-D). The intersection between the dashed lines at an angle and the vertical axes defines the initiation toughness and is highlighted with a circle on the vertical axis of each graph. The horizontal dashed lines indicate the propagation toughness.

Figure 12. R -curves for ply-level translaminar fracture toughness for thin-ply CP laminates (A-D).

Figure 13. Initiation (Δ) and propagation ($\bullet$) toughness values in function of the 0° ply thickness.

Figure 14. Translaminar fracture toughness increases with 0° ply-block thickness, with slightly different trendlines for the two grades of the same material tested.