

1 **A study on the longitudinal compression strength of fibre reinforced**  
2 **composites under uniaxial and off-axis loads using cross-ply laminate**  
3 **specimens**

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10 **Abstract**

11 Longitudinal compression testing of unidirectional FRP laminates remains a challenge due to the  
12 difficulty in applying high compressive loads without stress concentrations and boundary effects  
13 leading to premature failure. This work aims to critically evaluate different specimen designs and  
14 laminate configurations, cross-ply in particular, for the determination of longitudinal compression  
15 properties of unidirectional plies.

16 To this end, a comprehensive experimental campaign has been carried out, comparing strength,  
17 stiffness, and failure modes across different specimen designs and laminate configurations. The  
18 investigated cross-ply specimens produced comparable results without many of the issues observed  
19 in the testing unidirectional material and, therefore, are strongly recommended for the determination  
20 of longitudinal compressive strength.

21 Finally, the cross-ply material was tested under off-axis compression to study the effects of shear on  
22 the longitudinal compression strength using a series of compression specimens cut at different angles  
23 between 0 and 15° to the direction of the laminate.

24 *Keywords:* Polymer matrix composites; Mechanical properties; Longitudinal compression; Buckling.

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## 25 **1 Introduction**

26 The compressive strength in fibre direction is of great interest to the design and analysis of laminated  
27 composite structures. The longitudinal compressive failure (so called fibre kinking failure) is  
28 triggered by inter-fibre damage, which results in local buckling of fibres causing catastrophic  
29 material failure. Much work has been done over the years to try to understand the underlying  
30 physical phenomena behind this type of failure and its main contributing factors so that it can be  
31 more accurately predicted and designed against [1–5]. However, without accurate or reliable  
32 experimental measurements, these theories cannot be properly evaluated. The accurate  
33 characterization of the critical load in this failure mode remains problematic because the strength in  
34 the fibre direction is much higher than that in the transverse direction, which, if the tests are not  
35 designed and carried out correctly, often causes matrix failure to occur before the fibre micro-  
36 buckling can occur [6,7].

37 Premature matrix splitting of this kind can be caused by the transverse stresses through the thickness  
38 of the laminate that arise due to the Poisson effect and stress concentrations at specimen boundaries.  
39 Commonly, the solution to mitigate the effect of boundary conditions has been to add clamping  
40 fixtures that strengthen the matrix at the loading ends of the specimen and help to distribute the  
41 applied load by transmitting some of the compression through shear in the clamped interfaces [6,8].  
42 However, this introduces the risk of new stress concentrations at the fixture boundaries and of over  
43 constraining the specimen, making the results highly sensitive to the test operator and set-up  
44 conditions, as reported in [6].

45 Another proposed solution has been the use of specimens with waisted cross-section area that  
46 prevent fracture from occurring close to the specimen boundaries. However, the change in cross-  
47 section along with the relative low strength of the matrix can also cause critical stress concentrations  
48 that may eventually lead to premature splitting.

49 In short, the determination of longitudinal compression strength properties using unidirectional (UD)  
50 material can be quite problematic and the high sensitivity to boundary conditions should be a cause  
51 for concern any time experiments of this kind are being considered. The large variation in reported  
52 compressive strength measurements in [6,7,9] for the UD HexPly® IM7-8552 material system serve  
53 as a good example.

54 Because of these issues, the extraction of longitudinal ply properties from multidirectional (MD) or  
55 cross-ply (CP) laminates, using classical lamination theory (CLT) has been suggested as a more  
56 viable alternative [6,10,11]. However, previous experimental studies have always shown significant  
57 differences between the strength measurements obtained from UD and MD laminates. For the IM7-  
58 8552 material, for example, Lee and Soutis [6] and Ploeckl et al. [7] reported strength measurements  
59 from quasi-isotropic (QI) around 20% higher than the UD material. The use of CP laminates was  
60 also explored in the 1990s [10] and higher strengths than the plain UD material were again observed.  
61 Based on this previous work, it remains unclear whether the behaviour of MD laminate  
62 configurations under longitudinal compression can be representative of UD material and vice versa.  
63 However, if this can be established, the use of MD configurations, which have been shown to solve  
64 many of the issues that have plagued longitudinal compression in UD specimens, may alleviate the  
65 need for complex fixtures and specimen designs and, in turn, simplify the testing process and  
66 increase the level of confidence in the results.

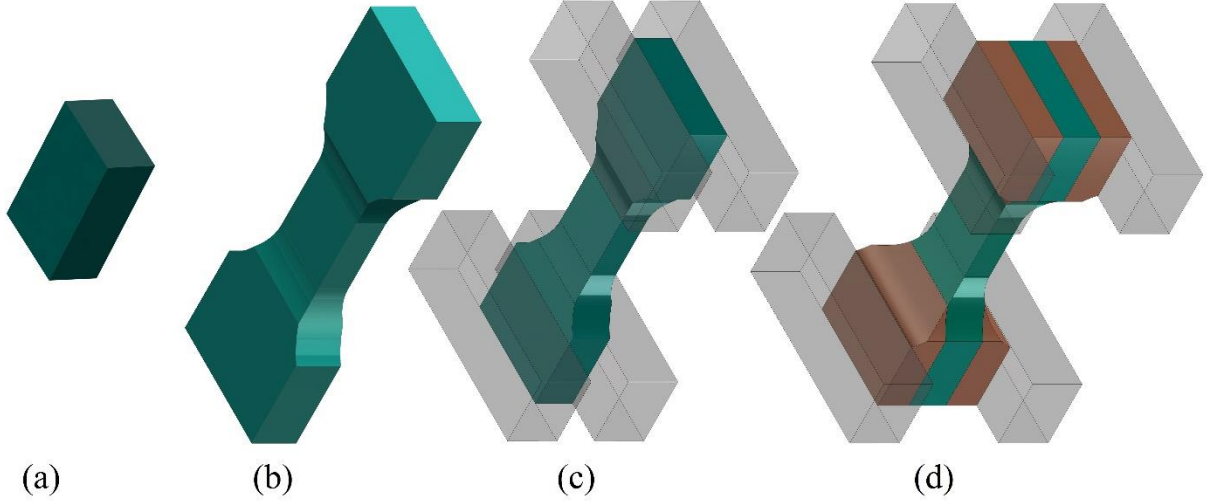
67 Therefore, in this study, a systematic experimental campaign has been carried out to: (i) determine  
68 the most suitable test and specimen configurations for the measurement of longitudinal compression  
69 strength; (ii) evaluate the equivalence between longitudinal compression properties obtained from  
70 UD and CP material, in particular; and (iii) investigate the applicability of CP material for the  
71 determination of UD failure envelope in combined loading cases (longitudinal compression and in-  
72 plane shear), which can be used to evaluate 3D fibre kinking failure theories and criteria.

## 73 **2 Methodology and experimental set-up**

### 74 **2.1 Specimen configuration**

75 The specimens for all experiments were cut from two different HexPly<sup>®</sup> IM7-8552 [12] composite  
76 plates with different ply lay-ups, UD ( $[0^\circ]_{26}$ ) and CP ( $[0^\circ/90^\circ]_{4s}$ ). Both laminates were manufactured  
77 together in the same facility to ensure similar quality levels between the two, while noting that local  
78 fibre architecture will naturally differ slightly between UD and MD laminates. In addition, all  
79 specimens were carefully ground and polished to ensure their two loading faces were parallel with  
80 adequate surface quality to a tolerance of  $\pm 0.05$  mm. This was done, in conjunction with the test set-  
81 up described in section 2.2, to minimise the possibility of bending in the specimens due to  
82 imperfections in the specimen, fixture or test procedure, which could otherwise affect the quality of  
83 the results [8].

84 The aim for the first set of experiments was to get an accurate measure of the longitudinal  
85 compressive strength of the unidirectional material as well as investigating different specimen  
86 designs and the effects of different boundary conditions. The different specimen configurations  
87 tested, shown in Figure 1, were (a) a simple unclamped cuboidal (rectangular) specimen (UD Cub),  
88 (b) an unclamped waisted, or dog-bone, design (UD DBU), (c) a waisted dog-bone specimen with  
89 clamping fixtures (UD DBC), and (d) a clamped dog-bone specimen with adhesively bonded GFRP  
90 end tabs (UD tabbed DBC) to relax the constraint of the clamping fixtures on the UD material. A  
91 gauge section of 5mm x 5mm was kept constant throughout all specimen designs, with a nominal  
92 thickness of 2mm.



93

94 Figure 1. *Unidirectional laminate specimen designs: (a) cuboid (UD Cub), (b) unclamped dog-bone*  
 95 *(UD DBU), (c) clamped dog-bone (UD DBC), and (d) clamped dog-bone with GFRP end tabs (UD*  
 96 *Tabbed DBC).*

97 Next, two different cross-ply specimens were tested to compare against the previous UD results and  
 98 study whether the effects of the boundary conditions were also as critical on the multi-directional  
 99 laminate. The specimen configurations, shown in Figure 2, were (a) a simple unclamped cuboid (CP  
 100 Cub) similar to the UD Cub design in Figure 1 (a), and (b) a clamped dog-bone specimen (CP DBC)  
 101 similar to the UD DBC design in Figure 1 (c). Longitudinal material, or ply properties were extracted  
 102 from the overall axial response using classical lamination theory (CLT) as described in [11].

103 First the **ABD** matrix,  $\begin{Bmatrix} \mathbf{N} \\ \mathbf{M} \end{Bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B} & \mathbf{D} \end{bmatrix} \begin{Bmatrix} \boldsymbol{\varepsilon}^0 \\ \mathbf{K} \end{Bmatrix}$ , which relates the deformation of the laminate given by  
 104 the in-plane strains  $\boldsymbol{\varepsilon}^0 = \{\varepsilon_{11}^0 \ \varepsilon_{22}^0 \ \varepsilon_{12}^0\}^T$  and the laminate curvatures  $\mathbf{K} = \{\kappa_{11} \ \kappa_{22} \ \kappa_{12}\}^T$  to the  
 105 resultant in-plane axial forces  $\mathbf{N} = \{N_{11} \ N_{22} \ N_{12}\}^T$  and moments  $\mathbf{M} = \{M_{11} \ M_{22} \ M_{12}\}^T$  per unit  
 106 width is computed as:

$$107 \quad A_{ij} = \sum_{k=1}^n \bar{Q}_{ij}^k (z_k - z_{k-1}) \quad (1)$$

$$108 \quad B_{ij} = \frac{1}{2} \sum_{k=1}^n \bar{Q}_{ij}^k (z_k^2 - z_{k-1}^2) \quad (2)$$

109 
$$D_{ij} = \frac{1}{3} \sum_{k=1}^n \bar{Q}_{ij}^k (z_k^3 - z_{k-1}^3) \quad (3)$$

110 where  $\bar{Q}_{ij}$  is the reduced stiffness of each ply,  $z$  is the position of the ply from the midplane and  $n$  is  
 111 the total plies in the laminate.

112 Then compound ABD matrix is inverted, which allows for the midplane strains,  $\boldsymbol{\varepsilon}^0$ , and curvatures,

113 
$$\begin{Bmatrix} \boldsymbol{\varepsilon}^0 \\ \mathbf{K} \end{Bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B} & \mathbf{D} \end{bmatrix}^{-1} \begin{Bmatrix} \mathbf{N} \\ \mathbf{M} \end{Bmatrix}.$$

114 By applying the measured normal compressive load,  $N_{11} < 0$ , the midplane strains for each  
 115 experiment can be obtained. Then, the stress state of a longitudinal ply can be determined with:

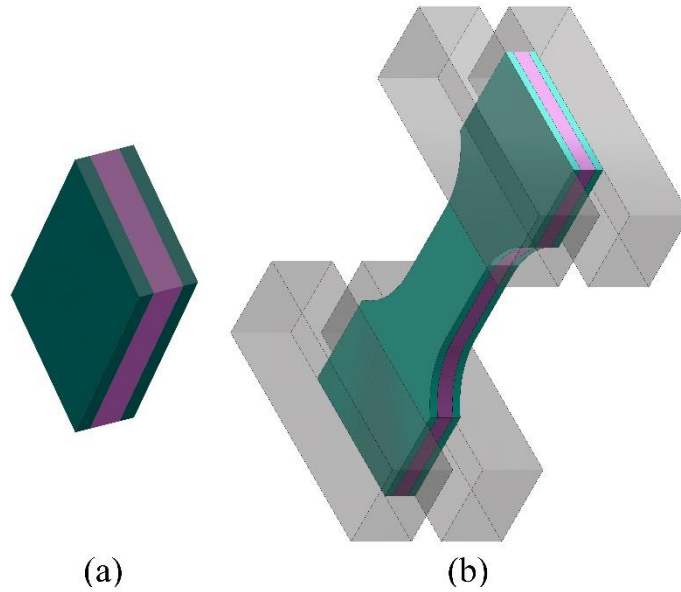
116 
$$\boldsymbol{\sigma}_{long} = \bar{\mathbf{Q}}_{long} \boldsymbol{\varepsilon}^0 \quad (4)$$

117 Finally, if the material orientation of the ply does not coincide with the global coordinate system, as

118 is the case of the off-axis compression tests in section 3.3, this stress state is then rotated by the off-

119 axis angle,  $\alpha$ , to give the local stresses in the material direction,  $\boldsymbol{\sigma}^\alpha = \{\sigma_{11} \ \sigma_{22} \ \tau_{12}\}^T$ .

120 
$$\boldsymbol{\sigma}^\alpha = \mathbf{R}[\alpha] \boldsymbol{\sigma}_{long} \quad \text{with} \quad \mathbf{R}[\alpha] = \begin{bmatrix} \cos[\alpha] & \sin[\alpha] & 0 \\ -\sin[\alpha] & \cos[\alpha] & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (5)$$



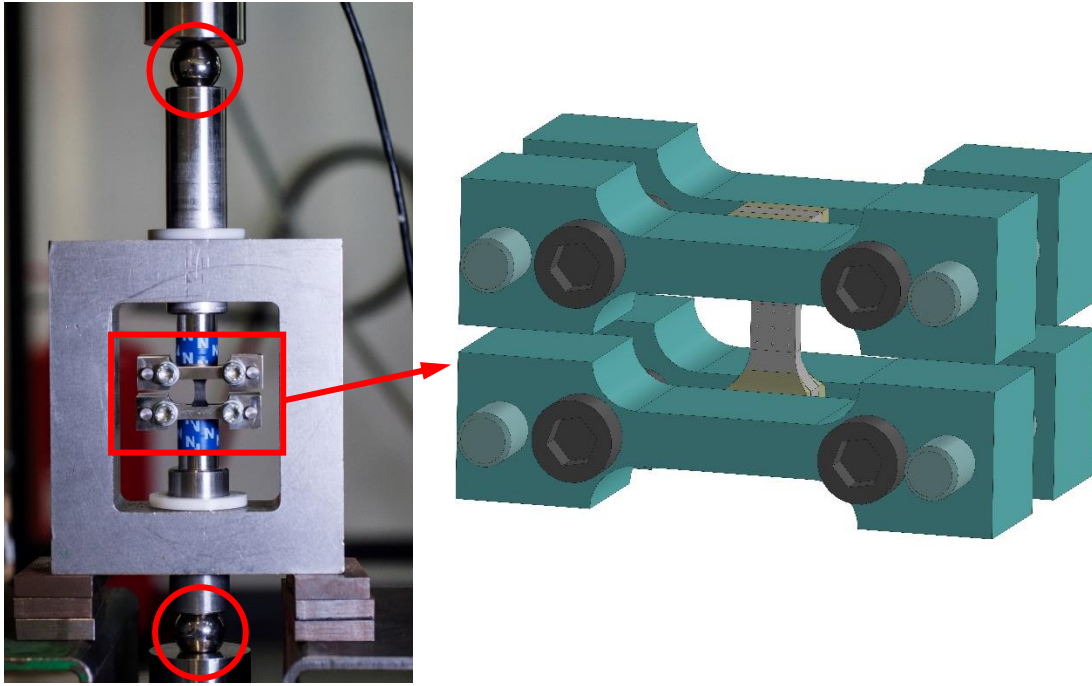
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122 Figure 2. *Cross-ply laminate specimen designs: (a) rectangular (CP Cub), (b) clamped dog-bone*  
123 *(CP DBC).*

124 Finally, a series of off-axis CP specimens were cut at orientations of 3, 6, 10 and 15°. These tests  
125 were used to study the effects of combined in-plane shear and longitudinal compression on the fibre  
126 strength and evaluate available fibre kinking failure theories. Similar to the standard  $\pm 45^\circ$  tension  
127 tests used to characterise the in-plane shear behaviour of composite laminates [13], the global  
128 response of the laminate can be considered as a superposition of its constituent plies following CLT  
129 only while there is no significant damage. The latter can cause considerable fibre rotation as well as  
130 inter and intra-laminar softening, making it difficult to decouple the behaviour of individual plies  
131 from the whole. Therefore, with these off-axis tests, a range of validity for the use of CP specimens  
132 in combined longitudinal compression and shear was determined. If the validity of this approach can  
133 be confirmed, the testing of compressive failure under combined loading would be greatly simplified  
134 in comparison to the  $\pm 5^\circ$ ,  $\pm 10^\circ$  laminates and tube specimens used in the past [14,15].

## 135 **2.2 Experimental setup and data process**

136 All the above experiments were conducted using a Zwick Roel 250 kN universal screw-driven  
137 testing machine under displacement control at a quasi-static loading rate of 0.01 mm/s. To ensure the  
138 alignment of the loading plates and avoid any eccentricity, the load was applied through two bearing  
139 balls an aligning frame, Figure 3, was installed. In addition, some cases required additional clamping  
140 fixtures, which are also shown in Figure 3.



(a) Alignment fixture

(b) Specimen clamping fixtures

141 Figure 3. Alignment and clamping fixtures used in fibre compression tests. (a) bearing balls (circled)  
 142 and alignment frame set-up, which ensures a strictly axial load is applied to the specimens, (b) close-  
 143 up view of the compact clamping fixtures is shown.

144 Throughout the duration of the tests, force-displacement data was extracted at a 400 KHz sampling  
 145 rate from the test rig. In order to capture the deformation of the specimens throughout the tests with  
 146 Digital Image Correlation (DIC) techniques, a digital camera was set to record one picture of  
 147 approximately 70x120mm at a 512x760px resolution every second. These images, along with finely  
 148 sprayed black and white speckle patterns on the surface of the specimens, allowed for the calculation  
 149 of full field strain histories, obtained by post-processing with the DIC analysis software GOM  
 150 Aramis.

151 Finally, in the case of CP specimens, as long as the assumptions of small strains and linear behaviour  
 152 were fulfilled, longitudinal compression strengths were extracted from the global laminate response  
 153 using CLT following the method described in section 2.1 [11].



154 In addition, following the experiments, a number of samples were selected for closer post-failure  
155 analysis using optical microscopy (OM) and scanning electron microscopy (SEM).

### 156 **3 Experimental results**

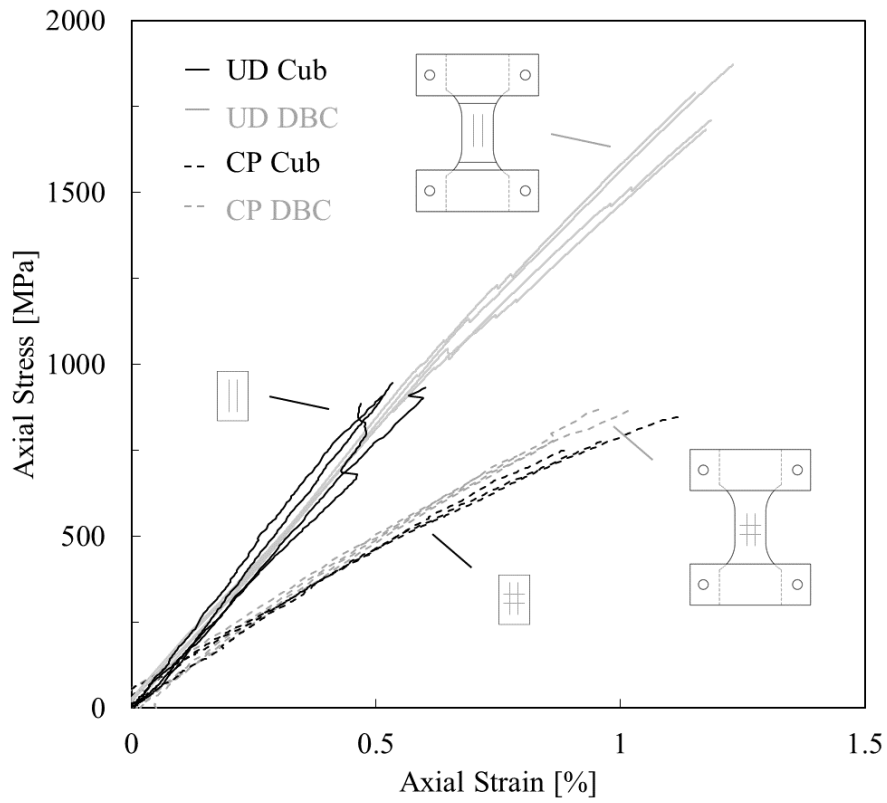
157 For each of the three sets of experiments described in the previous section, stress-strain curves and  
158 specimen strengths were extracted and are discussed below. The baseline strength measurements  
159 from the UD test results are reviewed and discussed in section 3.1. Next, the comparison of the CP  
160 results against the baseline UD measurements is shown to establish the equivalence between the two  
161 in section 3.2. Finally, in section 3.3, the off-axis CP test results are analysed to determine a range of  
162 validity of the CLT method for the determination of UD compression strength and the effects of  
163 shear on this mode of failure are investigated.

#### 164 **3.1 Unidirectional specimens**

165 Four different types of UD specimens were tested to study the effects of the boundary conditions and  
166 obtain the most accurate strength measurement for this particular IM7-8552 material system and give  
167 reference strength values for the rest of the study. These results are summarised in Figure 4 and  
168 Figure 5, which show the evolution of stress vs strain and a comparison of ultimate axial strengths  
169 between the different specimen designs, respectively. Since all specimens had the same stiffness, for  
170 the sake of clarity, only the rectangular and clamped dog-bone (DBC) specimens, which showed the  
171 minimum and maximum strength values, are shown in Figure 4. For the full comparison, the reader  
172 is referred to

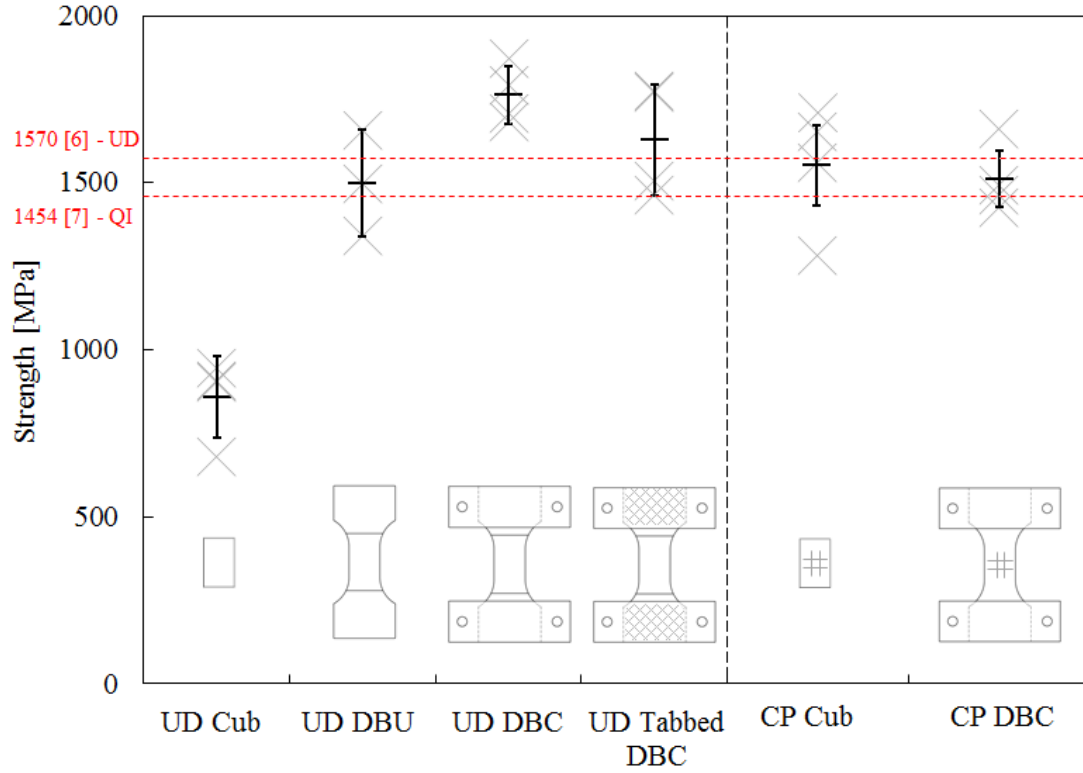
173 *Figure 5* and Table 1 where all the ultimate strength results of all four types of specimens can be  
174 found. Unfortunately, due to the shape of the fixtures and clamps, only the front, or in-plane surface  
175 was visible for all specimens so that there was no way to monitor out of plane bending in the tests.  
176 This may have been the cause for the significant scatter observed for some of the specimen designs

177 and should be recorded, when possible. However, it should be noted that the selected cross-ply  
178 designs showed good repeatability, as discussed in section 3.3.



179

180 Figure 4. Comparison between UD (DBC, Cub) and CP specimens (DBC, Cub) axial stress-strain  
181 curves.



182

183 Figure 5. Axial strength comparison between the four tested UD specimen designs (Cub, DBU, DBC  
 184 and Tabbed DBC) and two CP specimen designs (Cub and DBC) with literature data from IM7-8552  
 185 UD and QI specimens [6,7] added for reference. Black cross-marks in the figure represent the mean  
 186 and standard deviation for each specimen type.

187 Table 1. Summary of UD (Cub, DBU, DBC and Tabbed DBC) and CP (Cub, DBC) 0° compression  
 188 test results. The asterisk marks a specimen that may have failed early due to stress concentrations at  
 189 the boundary.

Axial Strength	UD Cub [MPa]	UD DBU [MPa]	UD DBC [MPa]	UD Tabbed DBC [MPa]	CP Cub [MPa]	CP DBC [MPa]
1	679	1499	1873	1773	1283*	1661
2	903	1340	1790	1506	1651	1423
3	945	1659	1710	1772	1558	1463
4	907		1683	1462	1710	1494
5				1381		
<b>AVG</b>	859	1499	1764	1579	1551	1510

<b>STDV</b>	121.2	159.5	85.6	182.6	189.2	104.6
<b>CV (%)</b>	14.1	10.6	4.9	11.6	12.8	6.9

190

191 As expected, the unclamped rectangular samples failed far below the expected fibre kinking strength  
 192 (1570 MPa) [6], at around 858 MPa on average. The specimens failed catastrophically due to matrix  
 193 splitting that originated at the loading boundaries before fibre failure could occur (see Figure 6 (a)).

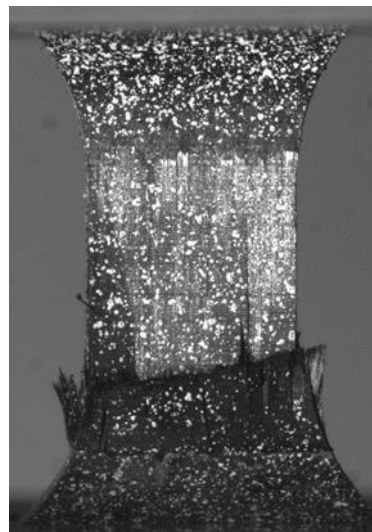
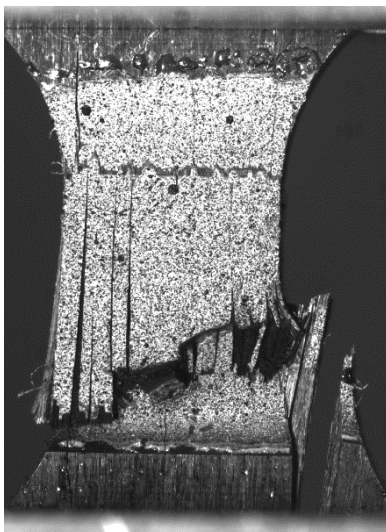
194 The unclamped dog-bone specimens (DBU), which tried to mitigate the effect of stress  
 195 concentrations at the loading edges, showed a considerable increase in strength, reaching 1499 MPa  
 196 on average, but still ultimately failed due to matrix splitting, as can be seen in Figure 6 (b).



(a) Cub



(b) DBU



(c) DBC

(c) Tabbed DBC

197 Figure 6. *Failed UD specimens showing different observed failure modes: (a) Cub, (b) DBU, (c)*  
198 *DBC and (d) Tabbed DBC.*

199 Therefore, it was necessary to resort to clamping fixtures, as used in [6–8], to apply combined  
200 loading compression (CLC, as described in ASTM D6641/D6641M) through combined end- and  
201 shear-loading at the clamps and strengthen the matrix in the transverse direction. However, the cited  
202 studies both reported kinking failure originating at the fixtures, likely caused by stress concentrations  
203 from the abrupt change in boundary conditions. The clamping fixtures were, therefore, used in  
204 combination with the dog-bone shaped specimens to reduce the effect of stress concentrations. Two  
205 different types of clamped specimen were tested, the simple dog-bone specimens (UD DBC), and the  
206 tabbed DBC specimens that included a layer of GFRP adhesively bonded to the composite below the  
207 clamped surface.

208 Even in the DBC specimens, some matrix cracking, as occurred in the DBU specimens, could not be  
209 completely prevented. However, in this case it only resulted in minor dips on the stress-strain curve,  
210 highlighted on the DBC curves in Figure 4, and did not significantly affect the stiffness, indicating  
211 that the load carrying ability was not affected. The DBC specimens continued to carry compressive  
212 loads far beyond this intermediate matrix splitting and eventually failed as desired in the form of  
213 kink bands within the gauge section, shown in Figure 6 (c), with an average strength of 1764 MPa.

214 On the other hand, the tabbed DBC specimen design was included to try and prevent the matrix  
215 splitting observed at the dog-bone radius in some of the DBC specimens. In addition, the direct

216 application of compressive fixtures could over-constrain the material and affect the fibre kinking  
217 strength, dominated by localised matrix damage, which itself is strongly pressure-dependent [16–18].  
218 Therefore, by relaxing the constraint on the UD material with the intermediate layer of GFRP  
219 between the fixtures, some insight could be gained into the effects of boundary conditions on this  
220 type of failure.

221 The tabbed DBC specimens failed at a much lower 1579 MPa on average but, interestingly, the  
222 results appeared to fall into two groups based on their failure stress and observed damage mode,  
223 although further testing would be required to verify this. One group of specimens failed below 1500  
224 MPa with most specimens failing by matrix splitting as in the unclamped specimens and a couple of  
225 cases of fibre kinking that initiated nearer to the boundary, possibly due to stress concentrations. The  
226 second group failed at stress above 1700MPa, by kinking within the gauge section with no noticeable  
227 matrix cracking (see Figure 6 (d)) and reached strengths very similar to the previous DBC specimen  
228 design.

229 From these results, it appears that there are possibly two different failure modes under longitudinal  
230 compression. For this specific IM7-8552 composite system, the combination of material properties  
231 and fibre waviness are enough to cause matrix failure resulting in splitting and fraying at an axial  
232 stress of around 1500 MPa, as observed in the unclamped DBU specimens and the first subgroup of  
233 tabbed DBC specimens. However, the formation of kink bands did not occur until axial stress levels  
234 between 1700-1800 MPa. It would seem that, for this fibre micro-buckling to occur, the material may  
235 have to be over constrained to some degree, preventing matrix damage from resulting in splitting or  
236 fraying, allowing the fibres to reach the higher buckling load.

### 237 **3.2 Cross-ply specimens**

238 In light of these issues with testing the thick UD specimens, a set of  $[0^\circ/90^\circ]_{4s}$  cross-ply specimens  
239 were tested following suggestions in the literature that multi-directional laminates may be better

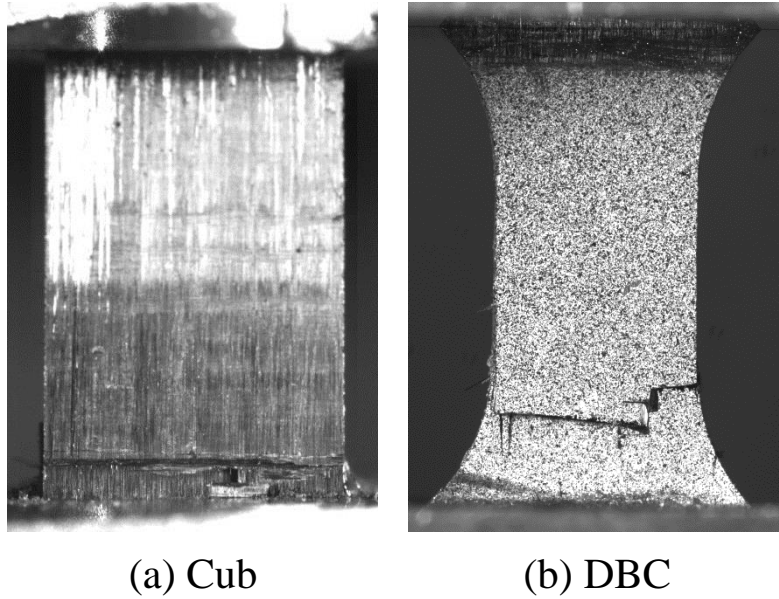
240 suited for the determination of fibre kinking strength [6,7,11,19] as the transverse plies help to  
241 reinforce the longitudinal fibres, allowing them to reach their buckling strength without the need for  
242 additional external constraints.

243 For the cross-ply material, only two specimen designs were tested, an unclamped rectangular  
244 specimen (CP Cub) and a clamped dog-bone specimen (CP DBC), shown in Figure 2. The results are  
245 summarised in Table 1 and the axial stress-strain curves for both specimen types are shown in Figure  
246 4 and

247 Figure 5. These also show the geometries and the extracted longitudinal compression strength next to  
248 the UD specimen results. Since the stress-strain curves in Figure 4 showed no noticeable nonlinearity  
249 and there were no signs of damage or fibre rotation in the specimens before fracture was observed,  
250 the use of linear CLT for the extraction of longitudinal ply properties [11] was considered valid and  
251 the ply strength data given in Table 1 and

252 Figure 5 is used for the rest of the discussion below.

253 As expected, both (CP Cub and CP DBC) geometries presented similar axial stiffness and practically  
254 the same axial strength, with the Cub specimen showing slightly greater scatter. In addition, both  
255 specimens failed within the gauge section, see Figure 7, due to fibre kinking originating in the central  
256 plies and propagating outwards. Unfortunately, because of this, no particularly useful failure images  
257 were captured on the outer layers during the test. However, section 4 includes more detailed  
258 microscopy images of different off-axis specimens showing typical failure propagation through  
259 longitudinal and transversal plies in CP specimens.



260 Figure 7. Failed CP specimens showing failure on the outer plies after initiating and propagating  
261 outwards through the laminate. Left to right: (a) CP Cub and (b) CP DBC specimens.

262 At a first glance, these results show that the practical issues encountered in testing the UD material  
263 are in fact avoided when testing the CP laminates, as no complex specimen design or fixtures are  
264 required to produce the desired mode of failure. In addition, the clamping fixtures did not appear to  
265 affect the compressive strength, although they may have improved experimental scatter. As a side  
266 note, however, significant experimental scatter is typically expected in this type of experiment due to  
267 the nature of the failure mode, which is caused by local fibre misalignments that can vary from one  
268 specimen to another. For reference, both the UD tests and the data from clamped QI specimens in  
269 [6,7] showed a similar variation in strength measurements.

270 However, when compared to the UD results from section 3.1, there are noticeable differences. Both  
271 CP specimens (CP Cub at 1551 MPa and CP DBC at 1510 MPa) failed at similar equivalent  
272 longitudinal ply strengths to the unclamped DBU and the subset of tabbed DBC specimens that  
273 failed due to matrix splitting. The UD specimens that reached fibre kinking strength, on the other  
274 hand, failed at around 1700 to 1800 MPa.



275 Previous studies on the same material showed longitudinal strength in QI laminates similar to that  
276 obtained here in the CP material and UD strength 10-20% lower [6,7]. However, UD specimens in  
277 both were reported to fail at the clamp edges, indicating that they may have suffered from critical  
278 stress concentrations, causing local matrix damage and premature onset of fibre kinking failure.

279 As discussed in the previous section, for the UD material it can be assumed that the material  
280 properties and local fibre misalignment (typically up to  $3^\circ$  [20]) result in the onset of Inter Fibre  
281 Failure (IFF) damage at longitudinal compressive loads of around 1500 MPa and the fibre micro-  
282 buckling strength, between 1700 and 1800 MPa, is only reached with sufficient additional constraints  
283 on the longitudinal fibres to make up for the reduced matrix support.

284 If similar material properties and fibre waviness to the UD laminate are assumed, it would seem that  
285 multi-directional laminates tend to fail at the onset of matrix damage, similar to the unconstrained  
286 UD specimens, whereas the stronger constraints on clamped UD specimens allows further matrix  
287 damage evolution and greater compressive loads before the constrained fibre buckling strength is  
288 reached.

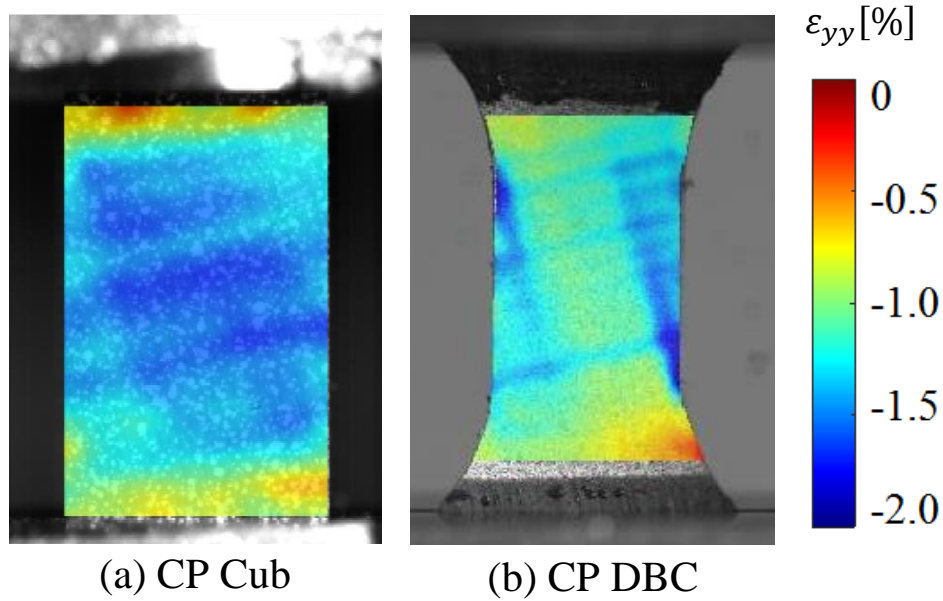
289 Therefore, CP or other multi-directional laminates can be used to measure the longitudinal  
290 compression strength more reliably than UD material and without the need for complicated fixtures.  
291 In addition, if the objective is to characterise the behaviour of UD plies in a multidirectional  
292 laminate, taking into consideration possible size effects and differences in local fibre architecture  
293 such as those noted by Lee and Soutis [6], it may be argued that CP specimens will give a more  
294 representative measurement of the expected compressive strength. In fact, unidirectional material  
295 should be used with extreme caution as the material strength can very easily be under- or  
296 overestimated. Without the use of clamping fixtures, stress concentrations and edge effects can  
297 prematurely initiate matrix cracking and even fibre kinking as observed in the unclamped specimens  
298 in section 3.1 and in [6,7]. At the same time, the clamping fixtures can over constrain the material

299 and delay the onset of fibre buckling, resulting in greater observed ultimate strength than would be  
300 possible otherwise.

### 301 **3.3 Off-axis compression specimens**

302 Having established the use of CP specimens for the measurement of the UD ply longitudinal  
303 compression strength, a set of off-axis compression tests were carried out to determine range of  
304 validity in combined loading, which is critical for the evaluation of 3D failure kinking theories. A  
305 series of CP Cub samples cut at 0, 3, 6, 10 and 15° with respect to surface fibre direction were tested  
306 in the same manner as the uniaxial compression test in section 3.2.

307 While the same was attempted for UD DBC and CP DBC specimen designs, these presented several  
308 issues that made the data unreliable. In both cases, the waisted design of the specimens in  
309 combination with the slight misalignment of the fibres, resulted in a non-uniform strain distribution  
310 through the gauge section and stress concentrations at the change in section were greatly exaggerated  
311 in the off-axis specimens, see Figure 8 (b). Because of this, it was difficult to accurately determine  
312 the stress state at the point of failure and, therefore, directly extract a material property from the axial  
313 measurements. In addition, in UD specimens, the same off-axis angles resulted in much greater shear  
314 stresses, producing significant fibre rotation and changes in the failure mode from fibre buckling to  
315 matrix dominated shear banding.



316 Figure 8. DIC longitudinal strain ( $\epsilon_{yy}$ ) overlay on two specimens showing non-uniform distribution in  
 317 a 15° off-axis CP DBC (b) compared to a 15° Cub specimen (a).

318 In contrast, the rectangular CP specimens (see Figure 8 (a)) showed a much more uniform strain  
 319 distribution throughout the gauge section, which allowed for average axial stresses to be used more  
 320 reliably to extract individual ply stress states and ultimate strength measurements. Therefore, only  
 321 these were used in the off-axis compression study.

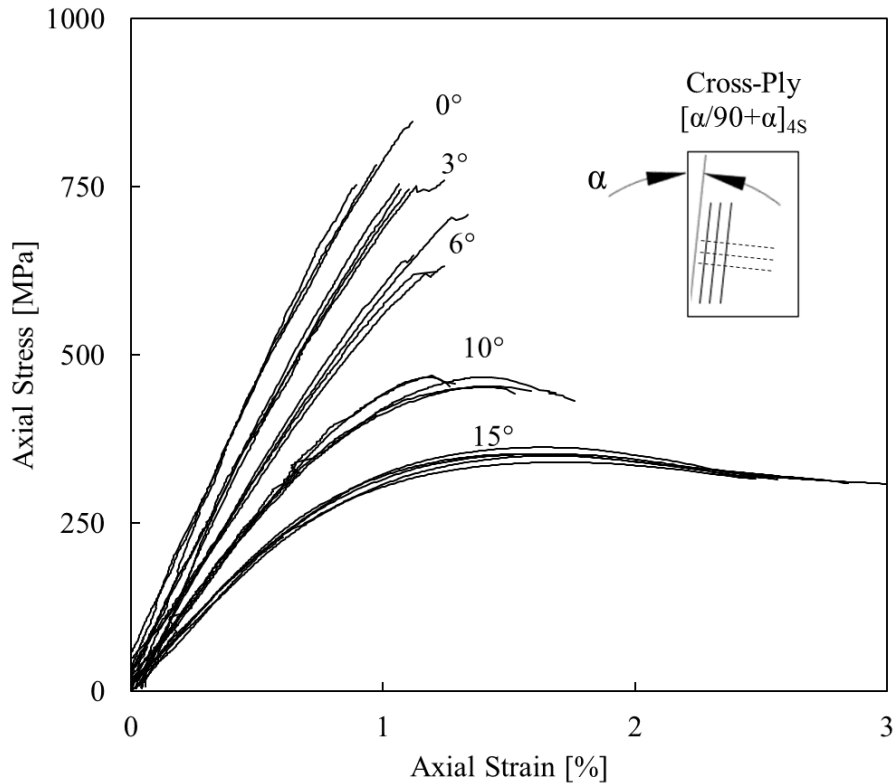
322 The axial data obtained for the off-axis CP Cub specimens is summarized in Table 2 and Figure 9,  
 323 which give the axial strength data and stress strain curves, respectively. A decrease in strength can be  
 324 observed as the off-axis angle increases, with noticeable nonlinearity in all specimens beyond 6°,  
 325 which also showed significant fibre rotation as the experiments progressed.

326 Table 2. Summary of off-axis (0, 3, 6, 10 and 15°) CP Cub axial strength results.

Axial Strength	CP Cub 0° [MPa]	CP Cub 3° [MPa]	CP Cub 6° [MPa]	CP Cub 10° [MPa]	CP Cub 15° [MPa]
1	747	744	623	467	341
2	783	746	643	468	353
3	847	741	706	452	353
4			630	451	350

<b>5</b>				466	363
<b>AVG</b>	792	744	651	461	352
<b>STDV</b>	50.6	2.1	37.9	8.5	7.9
<b>CV (%)</b>	6.4	0.3	5.8	1.9	2.3

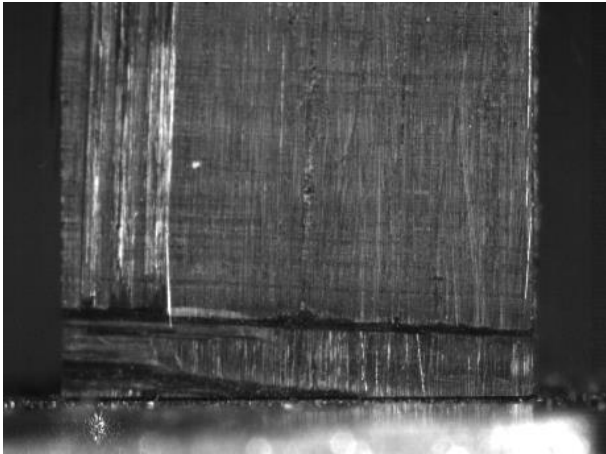
327



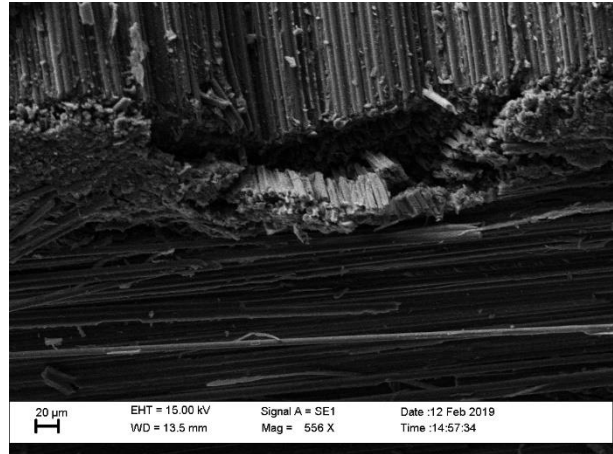
328

329 Figure 9. Comparison of axial stress-strain curves for CP specimens with misalignment angles of 0,  
330 3, 6, 10 and 15°.

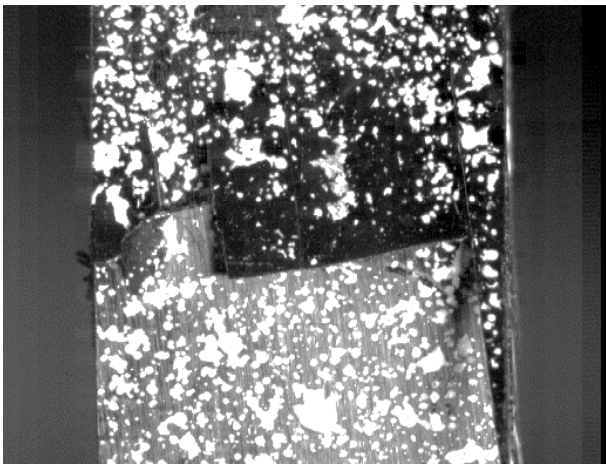
331 For a more in-depth look, macroscopic and SEM images in Figure 10 show the observed signs of  
332 fibre kinking failure in longitudinal plies and help to illustrate the differences in modes of failure  
333 between 3° , 6° and 10° specimens. For the lower off-axis specimens, from 0 to 6°, failure appeared  
334 to originate in the central longitudinal plies and propagate outwards, with the fibres tending to buckle  
335 in the out-of-plane direction. Conversely, for the 10 and 15° specimens, ultimate failure was  
336 preceded by significant shear non-linearity, which seemed to promote buckling in the same direction,  
337 keeping it more contained within the plane.



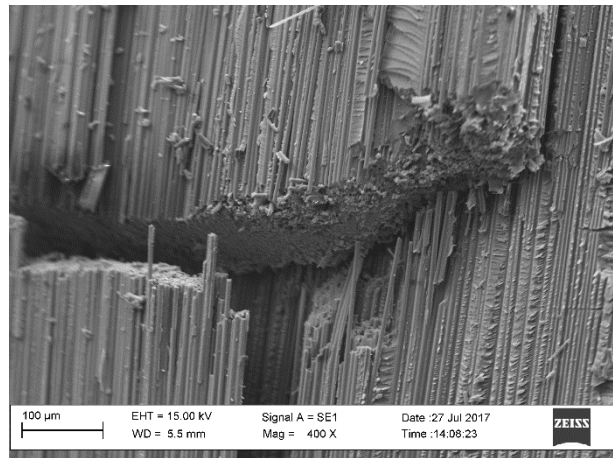
(a) 3° CP - failure surface



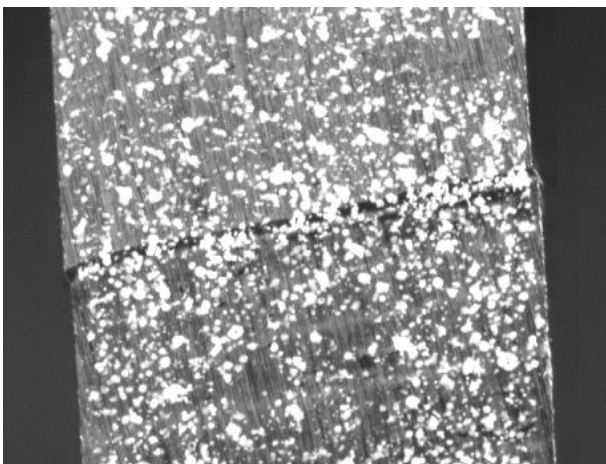
(b) 3° CP - through thickness SEM



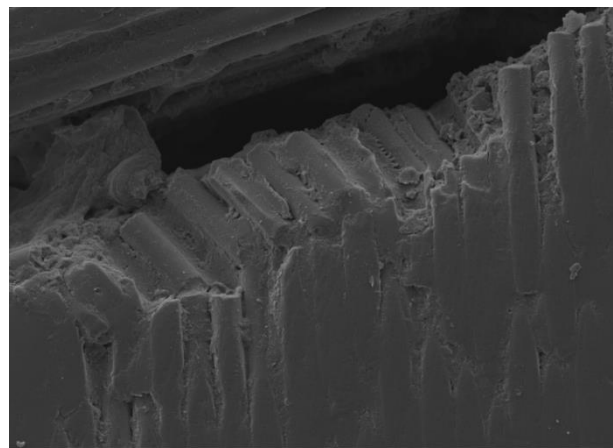
(c) 6° CP - failure surface



(d) 6° CP - through thickness SEM



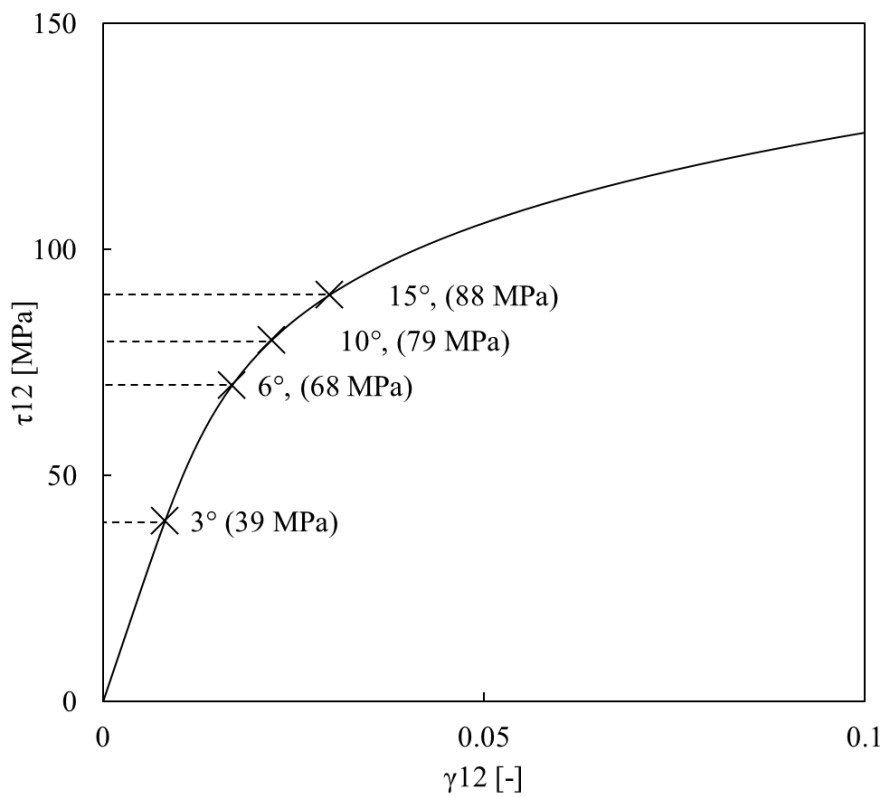
(e) 10° CP - failure surface



(f) 10° CP - through thickness SEM

338 Figure 10. Macroscopic (digital camera) and Scanning Electron Microscope (SEM) images of  
 339 different failed 3, 6 and 10° CP specimens showing signs of fibre kinking failure. Scale bars indicate  
 340 20 μm in (b), 100 μm in (d), and 25 μm in (f).

341 Up to  $6^\circ$ , however, there was no noticeable nonlinearity and no signs of damage or fibre rotation in  
342 the specimens before the point of failure. In addition, shear stress–strain curves for the same IM7-  
343 8552 material in [21,22] show significant nonlinearity starting only after shear stresses of around 60-  
344 70 MPa and both the 3 and  $6^\circ$  tests fall below that limit (see Figure 11). Therefore, for these  
345 specimens, an accurate estimate of the internal stress state in the longitudinal plies can be obtained  
346 using linear CLT, as was done for the uniaxial compression tests in section 3.2, and the use of CP  
347 material instead of UD can be considered valid.



348  
349 Figure 11. Average shear stresses from the 3 and  $6^\circ$  off-axis compression tests overlaid on the  
350 experimental shear stress–strain curve for an IM7-8552 composite, reproduced from [22].

#### 351 **4 Discussion and analysis**

352 Based on all the results gathered above, simple CP specimens can be used to determine the  
353 longitudinal compression strength of unidirectional composite material in both uniaxial and off-axis

354 compression tests, without the need for complex fixtures, for as long as the stress-strain curves  
355 remain linear. In this case, for the IM7-8552 composite, this limit was found at around  $6^\circ$  when the  
356 shear stresses in the laminate reached around 60-70 MPa. For greater off-axis angles, useful data  
357 cannot be simply extracted using linear CLT and a more rigorous analysis would be required, giving  
358 consideration to the nonlinear behaviour of the material, possible interlaminar damage, and fibre or  
359 specimen rotation.

360 For the uniaxial compression case, various different UD specimen designs were tested to obtain a  
361 reliable reference measure of the material's compressive strength. From these tests a serious  
362 difficulty in reaching the desired fibre micro-buckling failure mode was noted. Firstly, waisted, or  
363 dog-bone, specimen designs were necessary to avoid stress concentrations at the edges causing  
364 premature failure.

365 However, even then, there appear to be two different mechanisms dictating the compressive strength  
366 of the material depending on the boundary conditions of the experiment. For tests with more relaxed  
367 lateral constraints, including completely unclamped and clamped specimens with GFRP end tabs  
368 between the clamping fixtures, the material tended to fail due to matrix cracking and fibre kinking  
369 was rarely produced. On the other hand, fibre kinking, or micro-buckling, failure was only  
370 consistently achieved when the specimens were over-constrained, with the clamping fixtures  
371 possibly maintaining alignment of the fibres beyond the IFF failure of the matrix. Between these two  
372 different scenarios, matrix failure measured at around 1500 MPa, while the over-constrained fibre  
373 kinking mode was measured at over 1700 to 1800 MPa.

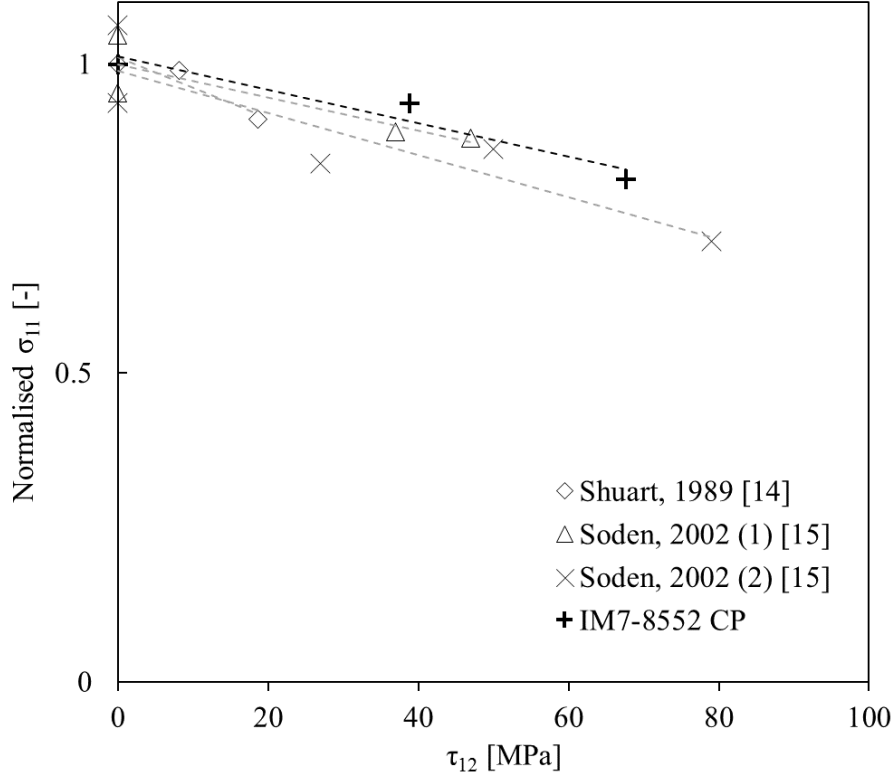
374 From this it was concluded that: (i) reliable compression strength measurements were extremely  
375 difficult to achieve with UD material; and (ii) the compressive failure of the laminate was caused by  
376 failure of the supporting matrix, at around 1500 MPa.

377 In second place, two different CP specimen designs were tested to compare against the UD results, a  
378 rectangular unclamped specimen and a clamped dog-bone design. The two different specimens  
379 showed no significant differences between them, regardless of shape or the use of clamping fixtures,  
380 indicating reliable material and test design. Not only that, but the extracted longitudinal compression  
381 strength using CLT [11] coincided with the measured UD results at 1500 MPa. Therefore, CP  
382 laminates have been shown to produce accurate results for longitudinal compressive strength and,  
383 due to greater reliability and lower sensitivity to boundary conditions, it is strongly recommended to  
384 use this type of material over UD laminates. In addition, fibre kinking strength is dependent on local  
385 fibre architecture and, therefore, a cross-ply, or quasi-isotropic, layup will better characterize the  
386 behaviour of multi-directional laminates, which are more typically used in engineering applications.

387 Finally, for the case of off-axis compression, the same CP material was used to prepare angled  
388 specimens cut at 0, 3, 6, 10 and 15° from the fibre direction. These showed that, as long as the  
389 resultant stress-strain curves remained linear, the assumptions of CLT remained valid and the effects  
390 of combined loading on the compressive strength could be measured the same specimen/test design  
391 as the previous uniaxial compression tests.

392 Shuart et al. in 1989 and Soden et al. in 2002 used  $\pm 5$  and  $\pm 10^\circ$  angle-ply specimens and  
393 unidirectional tubes, respectively, to study the longitudinal compressive strength of fibre composites  
394 under combined loading [14,15]. The effects of shear on longitudinal compression strength observed  
395 in the present study follow a similar trend to the results from [14,15], shown normalised against the  
396 uniaxial compression strength for each material in Figure 12 for a clearer comparison, which adds  
397 confidence in the validity of the proposed specimen design. In addition, the CP specimen presents  
398 several advantages over previous approaches: the CP material is more readily available and multiple  
399 different orientations can be obtained from a single laminate, making it a more versatile, cost-  
400 effective and convenient method to test different shear–longitudinal compression ratios.





401

402 Figure 12. Comparison of combined longitudinal compression and in-plane shear test results  
 403 between different materials and test methods in the literature [14,15] and the new results presented  
 404 in this article. Two different data sets from [15] are included. Results are shown normalised with the  
 405 uniaxial compression strength for each material.

406 Finally, the obtained results were used to evaluate the fibre kinking theory proposed by Pinho in [5],  
 407 which is one of the few criteria for this type of failure with a sound physical explanation  
 408 implemented in three dimensions and has been shown to produce good results in the uniaxial  
 409 compression case [23]. This theory consists in rotating the macroscopic stress state to an internal  
 410 misalignment frame, Figure 13 (a), obtained by adding the local shear strain to the initial fibre  
 411 waviness.

$$412 \quad \sigma^m = \mathbf{R}[\varphi] \sigma^\psi \quad (6)$$

$$413 \quad \varphi = \text{sign}[\tau_{12}^\psi] \varphi^0 + \gamma_m \quad (7)$$

414 Where  $\varphi$  is the misalignment angle,  $\varphi^0$  is the initial misalignment, and  $\gamma_m$  is the shear strain in the  
 415 misalignment frame. The kink-band stress,  $\boldsymbol{\sigma}^\psi = \mathbf{R}[\psi]\boldsymbol{\sigma}$ , is obtained in a similar manner by rotating  
 416 the Cauchy stress vector,  $\boldsymbol{\sigma}$ , to the kink-band plane with the angle,  $\psi$ , found numerically.

417 The local misalignment frame stresses are then used to evaluate the fibre finking criterion, where  
 418 failure can occur by instability of the additional fibre rotation, if  $\gamma_m$ , which is solved iteratively, does  
 419 not have a stable solution, or by matrix fracture, if  $\gamma_m$  is stable and:

$$420 \quad f_{\text{kink}} = f_{\text{IFF}}[\boldsymbol{\sigma}^m] = 1 \quad (8)$$

421 Where the kinking criterion,  $f_{\text{kink}}$ , is evaluated as an IFF criterion of the type described in [4,5,24]  
 422 on the misalignment frame,  $f_{\text{IFF}}[\boldsymbol{\sigma}^m]$ . A more detailed explanation and subsequent simplifications  
 423 made over the years to avoid iteration can be found in [3–5], however only the original, numerically  
 424 intensive, implementation has been used here to prevent any possible loss of accuracy.

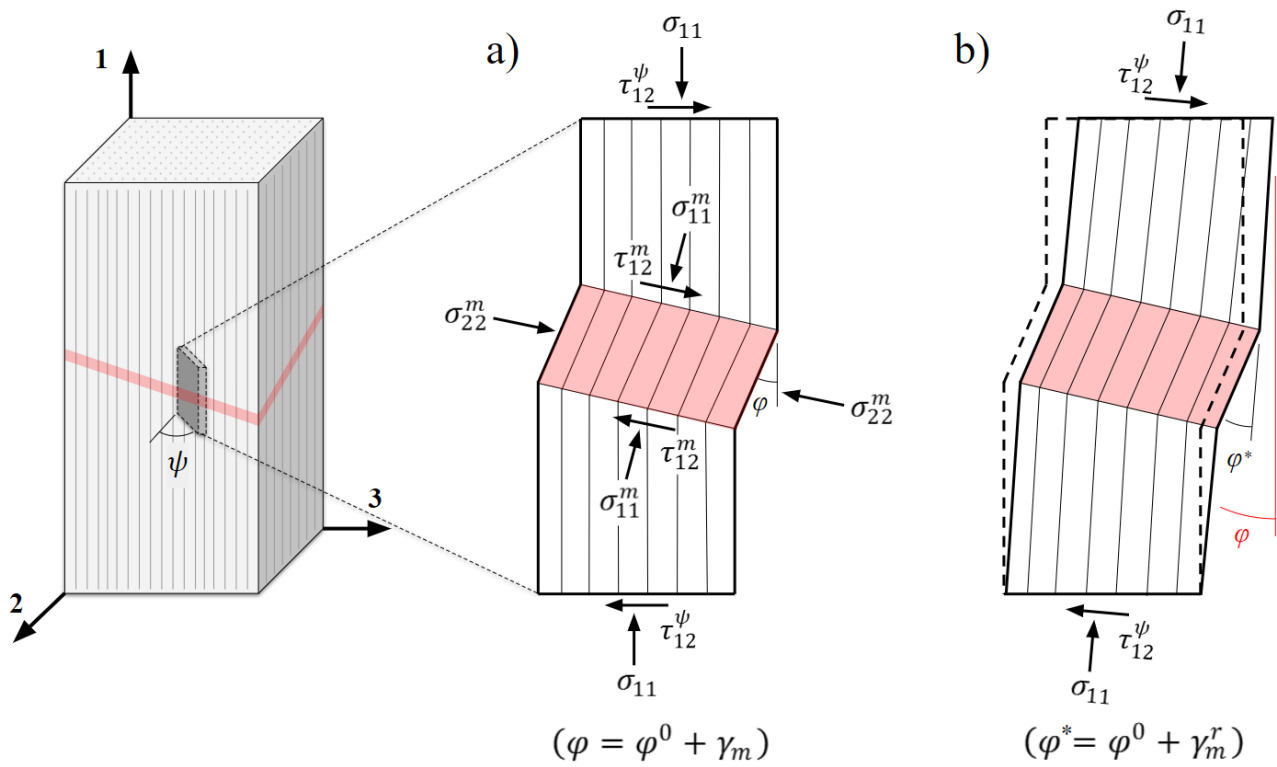
425 When used to study the present off-axis CP experiments, however, this theory, as originally  
 426 described in [25], appears to over predict the effect of shear. Predictions are shown next to  
 427 experimental results in terms of longitudinal ( $\sigma_{11}$ ) vs shear ( $\tau_{12}$ ) stress at failure in Figure 14.

428 However, with a minor modification, predictions can be greatly improved for cases with combined  
 429 shear. The proposed modification consists in replacing the misalignment frame shear strain,  $\gamma_m$ , from  
 430 (7) with a relative shear strain measure,  $\gamma_m^r$ , shown below.

$$431 \quad \gamma_m^r = f_{\text{CL}}[\tau_{12}^r] = f_{\text{CL}}[\tau_{12}^m - \tau_{12}^\psi] \quad (9)$$

432 In an analogous way,  $\gamma_m^r$  is obtained from the very same constitutive law ( $f_{\text{CL}}[\tau_{12}^r]$ ) employed  
 433 previously to calculate  $\gamma_m$ . However, now a relative shear stress,  $\tau_{12}^r$ , is used instead of  $\tau_{12}^m$ . In this  
 434 way, as the global fibre direction rotates with  $\tau_{12}^\psi$ , only the shear strain relative to the current material  
 435 orientation is considered for the misalignment angle calculation. Otherwise, the local fibre rotation is

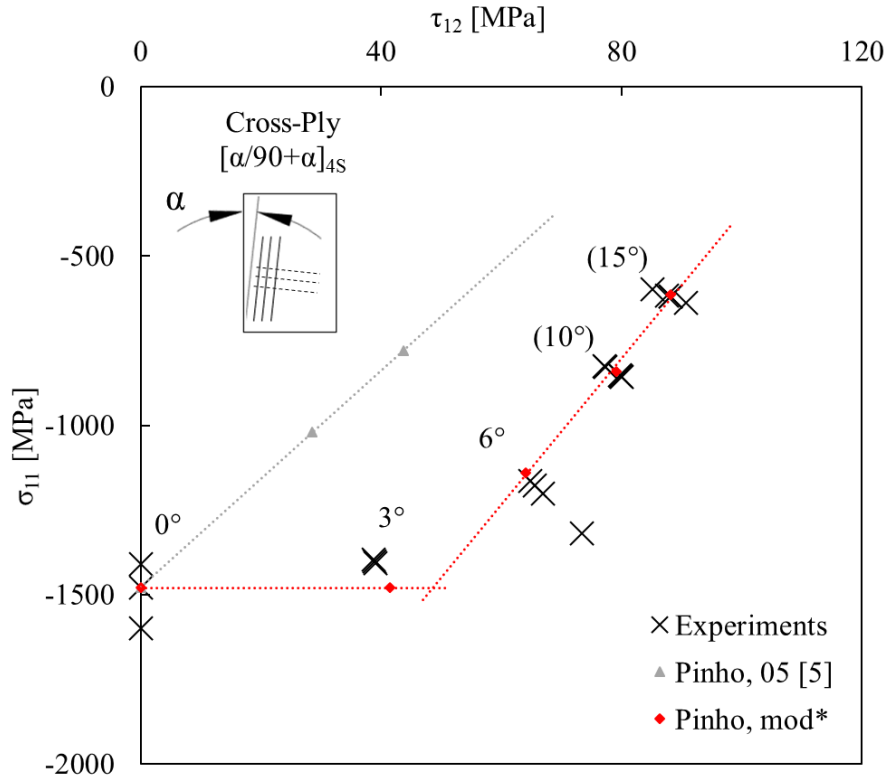
436 overestimated as illustrated in Figure 13 (b), where  $\varphi$  is the misalignment angle computed per  
 437 Pinho's original implementation, while  $\varphi^*$  is the angle corresponding to the proposed modification.



438

439 Figure 13. a) *Kink-band and misalignment planes according to fibre kinking theory [1,2,5] and b)*  
 440 *effect of considering the proposed relative shear vs the global shear for the misalignment angle,  $\varphi$ .*

441 Both models were calibrated with the average uniaxial compression strength and shear stress–strain  
 442 behaviour from [14,15] and gave an initial misalignment angle of 1.85°, which falls within typical  
 443 expected values and matches the analytical solution for the uniaxial compression case as described in  
 444 [26]. With the proposed modification, the solution remains unchanged for the pure compression case  
 445 but, for off-axis compression cases, there are some noticeable improvements. In the 0° and 3° tests,  
 446 the longitudinal compression strength ( $\sigma_{11}$ ) remains constant as the local shear stress in the  
 447 misalignment frame remains in the linear elastic region and buckling occurs purely due to  
 448 mechanical instability of the misaligned fibres. Beyond this point, the greater shear stresses cause  
 449 matrix failure in the local misalignment frame before the instability condition is met, with  
 450 subsequent micro-buckling occurring because of this.



451

452 Figure 14. Longitudinal ( $\sigma_{11}$ ) vs shear ( $\tau_{12}$ ) stress at failure for the  $0^\circ, 3^\circ, 6^\circ, 10^\circ$  and  $15^\circ$  CP Cub  
 453 specimens, extracted using CLT. Brackets on  $10^\circ$  and  $15^\circ$  results indicate that a correcting factor  
 454 has been applied to correct for fibre rotation. Grey markers indicate predicted failure stresses for  
 455 each case using the fibre kinking theory proposed by Pinho [5] and red markers indicate predictions  
 456 using the proposed modification. Numerical predictions were only calculated for the five off-axis  
 457 loading cases, dotted trend lines are extrapolated from these results.

458 This change in predicted cause of failure, from mechanical instability to IFF failure of the supporting  
 459 matrix, seems to agree well with the experimental results, which show little effect of the shear stress  
 460 between the  $0^\circ$  and  $3^\circ$  tests followed by a significant drop as the off-axis angle increases. In addition,  
 461 it would also help to explain the differences observed in the experiments (Figure 10), as the failure  
 462 mode appears to become more stable and matrix dominated with greater off-axis angles.

463 Overall, however, these results show that there is still work to be done on the prediction of fibre  
 464 kinking failure under combined, or off-axis, loads. Complex physically-based criteria like Pinho's,

465 appear unable to capture the effects of shear, indicating that some of the driving failure mechanisms  
466 may not yet be fully understood. The proposed modification to Pinho's criteria suggests one potential  
467 explanation but may still be a pragmatic simplification of the micro-scale fibre rotation and matrix  
468 damage mechanisms. Therefore, while the initial results appear to show good agreement, further  
469 research is needed on the micro-mechanical behaviour of fibre composites under combined  
470 compression and shear.

## 471 **5 Conclusions**

472 A series of longitudinal compression tests have been carried out on unidirectional and cross-ply  
473 IM7/8552 composite laminates, with the aim of finding an optimal test method for the determination  
474 of fibre compression strength.

475 For the UD samples, it resulted extremely challenging to produce reliable measurements, as the  
476 material proved highly sensitive to specimen geometry and boundary conditions. The CP specimens,  
477 on the other hand, produced much more reliable results, which were not noticeably affected by either  
478 specimen geometry or boundary conditions.

479 Therefore, considering the fact that the CP samples are also better than UD ones in representing  
480 practical multi-directional structures, the cubic CP sample is recommended throughout this work for  
481 characterizing fibre kinking strength.

482 In addition, the same CP specimen design was used with fibre orientations of 0, 3, 6, 10 and 15  
483 degrees to the loading axis to study the effect of shear on the fibre compression strength. This proved  
484 to be a reliable and much simpler approach to obtaining this type of data compared to previous  
485 experiments in the literature and provided additional data points for the evaluation of fibre  
486 compression failure criteria.

487 Finally, this data was used to evaluate the fibre kinking theory proposed by Pinho in [5] and a minor  
488 modification is proposed, which improves predictions in cases with combined longitudinal  
489 compression ( $\sigma_{11}$ ) and in-plane shear ( $\tau_{12}$ ).

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# A study on the longitudinal compression strength of fibre reinforced composites under uniaxial and off-axis loads using cross-ply laminate specimens.

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