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Arteiro, A., Catalanotti, G., Xavier, J., Linde, P., & Camanho, P. P. (2017). Effect of tow thickness on the structural response of aerospace-grade spread-tow fabrics. *Composite Structures*, 179, 208-223.
<https://doi.org/10.1016/j.compstruct.2017.06.047>

Published in:
Composite Structures

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
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Effect of tow thickness on the structural response of aerospace-grade spread-tow fabrics

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Abstract

The effect of ply thickness on the onset of intralaminar and interlaminar damage is extremely important for the structural response of laminated composite structures. This subject has gained particular interest in recent years due to the introduction in the market of spread-tow, ultra-thin carbon-fibre reinforcements with different configurations. In the present paper, an experimental test campaign was carried out to study the structural response of aerospace-grade plain weave spread-tow fabrics (STFs) of different areal weights. The results showed that, in spite of an apparent superior longitudinal tensile strength of the thick STF, the multidirectional thin-STF laminate exhibited an improved tensile unnotched strength over the thick-STF laminate, attributed to its damage suppression capability. However, damage suppression was also responsible for similar tensile notched strengths. In compression, the thin-STF laminate performed substantially better than the thick-STF laminate in both unnotched and notched configurations. Finally, a similar bearing response was obtained in both STF laminates, in spite of a slightly higher resistance of the thin-STF laminate to the propagation of subcritical damage mechanisms.

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Keywords: Polymer-matrix composites (PMCs), Spread-tow fabrics, Mechanical properties, Mechanical testing

1. Introduction

The thinner and wider tows obtained with tow spreading show unique benefits that open a broad range of new possibilities in terms of design and manufacturing of composite structures. For example, spread-tow fabrics (STFs) can be obtained using spread tapes in the weaving process instead of conventional yarns. Using spread tapes, fibre bundles are not only thinner, but they are also wider, resulting in flatter fabrics, with fewer interlacing points and better surface finish than conventional ones. Such fabric configurations are also characterised by minimal fibre waviness, and therefore lower crimp frequency and smaller crimp angles [1, 2], allowing the filaments to immediately carry tensile or compressive loads without first having to straighten.

Due to the thinner and wider spread tows, the amount of matrix between the tows of thin-ply fabrics is also very small, resulting in overall composite fibre volume fractions very close to the local fibre volume fraction of the spread tows [3, 4]. As a result, the performance of thin-ply fabrics can approach that of laminates made of unidirectional (UD) tapes.

In the present work, the effect of tow thickness on the structural response of aerospace-grade spread-tow fabrics was investigated. An experimental test campaign was carried out to study the structural response of aerospace-grade plain weave STFs with different areal weights. The test campaign included characterisation tests of the STFs, performed on simple UD STF laminates, and the detailed assessment of the structural response of multidirectional STF laminates defined based on a baseline of the aeronautical industry.

2. Material selection and manufacturing

T700SC TeXtreme® STFs from Oxeon AB pre-impregnated with HexPly® M21 toughened epoxy resin from Hexcel (with a nominal 35% resin content)

27 were selected for this study. Two plain weave configurations with different areal
28 weights were used: 160 g/m² and 240 g/m² STFs, with nominal fabric layer
29 thicknesses around 0.16 mm and 0.24 mm respectively.

30 The characterisation of the 160 g/m² and 240 g/m² STFs was performed on
31 UD textile laminates with a plain weave (cross-ply) configuration. Two multidirectional
32 textile laminates, one of each STF grade, were also designed based on
33 a damage tolerance optimised baseline laminate for aeronautical applications.

34 Table 1 shows the stacking sequences definition. The 0° orientation is coincident
35 with the loading direction. All selected laminates are balanced and symmetric
36 (due to the plain weave configuration). The multidirectional structural
37 laminates are orthotropic. These laminates were designed to match as possible
38 the thickness and stiffness of the baseline multidirectional laminate. However,
39 due to constraints in the stacking sequence imposed by the different thickness
40 of the *prepreg* weaves, laminates with different elastic properties (expectably in
41 the range of 3% for the Young's moduli, 4% for the shear modulus, and 5% for
42 the Poisson's ratio) and different thickness (Table 1) had to be considered.

43 All laminates were prepared for curing in a vacuum bag and cured using an
44 autoclave. The autoclave cure cycle was defined by setting a heat-up rate of
45 2°C/min from room temperature to 180°C, holding at 180°C for 120 minutes
46 and cooling down at a rate of 2°C/min. A gauge autoclave pressure of 4 bar
47 was applied throughout the cure cycle. After curing, each plate was cut to the
48 nominal dimensions of the specimens using a diamond-coated disk.

49 3. Experimental test programme

50 3.1. *Strength characterisation tests*

51 Unnotched tension and compression tests were performed on UD specimens,
52 including off-axis compression tests. All tests were performed under displacement
53 control. The tension tests were conducted at a speed of 1.0 mm/min in
54 an MTS 810 servo-hydraulic testing machine with a load capacity of 250 kN,
55 equipped with a 250 kN load cell. The specimens were fixed to the load frame

56 using a bolted clamping rig, and sandpaper was inserted between the specimen
57 surfaces and the grips to improve the load transfer capability and prevent sliding.
58 The compression tests were performed in an Instron 4208 electro-mechanical
59 universal testing machine (load capacity of 300 kN) equipped with a 100 kN
60 load cell at a controlled speed of 0.1 mm/min.

61 3.1.1. Fabric tensile unnotched strength

62 Plain weave unnotched specimens with a nominal width (W) of 25 mm
63 and a nominal length (L_s) of 300 mm were tested in tension, following the
64 ASTM D3039/D3039M – 14 test standard [5]. The tests were performed on
65 laminates *UDA240* and *UDA160* (Table 1). The gauge length (L) of the speci-
66 mens was set to 150 mm.

67 3.1.2. Fabric compressive unnotched strength

68 Unnotched compression tests were performed on laminates *UDB240* and
69 *UDB160* (Table 1). Following Koerber et al. [6], specimens with a nominal
70 width (W) of 10 mm and a nominal length (L) of 20 mm were tested using
71 an end-loading test rig with a self-alignment system. Polished tungsten-carbide
72 (TC) inserts were used to avoid damage on the contact surfaces of the test
73 fixture caused by the endings of the stiff carbon fibres [6, 7]. In addition, a
74 thin layer of molybdenum disulphide (MoS_2) was used between the specimen
75 end-surfaces and the surfaces of the rig to minimise friction [6].

76 3.1.3. Fabric off-axis compression tests

77 Off-axis specimens provide a simple way of studying the mechanical be-
78 haviour of UD composites and laminates under combined stresses, useful to
79 derive experimental yield and failure envelopes. In the present work, 15° and
80 30° off-axis compression tests were performed. These tests were carried out on
81 laminates *UDB240* and *UDB160*.

82 Following Koerber et al. [6], unnotched specimens with a nominal width (W)
83 of 10 mm and a nominal length (L) of 20 mm were tested using the same end-
84 loading test rig used in the UD unnotched compression tests (Sect. 3.1.2). To

85 determine the strength components of the off-axis tests, $\bar{\sigma}_{11}$, $\bar{\sigma}_{22}$ and $\bar{\sigma}_{12}$, the
 86 measured axial compressive strength in the loading coordinate system, $\bar{\sigma}_x$, needs
 87 to be transformed into the material coordinate system. This can be performed
 88 employing a simple coordinate transformation [6]:

$$\bar{\sigma}_{11} = \bar{\sigma}_x \cos^2 \theta \quad (1)$$

$$\bar{\sigma}_{22} = \bar{\sigma}_x \sin^2 \theta \quad (2)$$

$$\bar{\sigma}_{12} = -\bar{\sigma}_x \sin \theta \cos \theta \quad (3)$$

89 where the transformation angle $\theta = \theta_0 + \Delta\theta$ consists of the initial off-axis angle,
 90 θ_0 , and the additional fibre rotation, $\Delta\theta$, occurring due to the extension-shear
 91 coupling effect [6]. The additional fibre rotation $\Delta\theta$ can be measured via post-
 92 processing of full-field measurements obtained using, for example, the digital
 93 image correlation (DIC) technique (Sect. 4). It is important to note that the
 94 strength components of the off-axis tests, $\bar{\sigma}_{11}$, $\bar{\sigma}_{22}$ and $\bar{\sigma}_{12}$, expressed in the
 95 material coordinate system, are not the ply strengths for uniaxial loading along
 96 the main material directions.

97 According to Koerber et al. [6], the off-axis specimens with the proposed
 98 geometry are characterised by a large barreling deformation at high axial com-
 99 pressive strains. To avoid overpredicting the actual axial compressive strength,
 100 the true specimen cross section should be used in the calculation of the applied
 101 axial stress. Following Koerber et al. [6], the true specimen cross section can be
 102 estimated applying a volume consistency condition:

$$S = S_0 \frac{L_0}{L} = S_0 \left(1 - \frac{\Delta L}{L_0} \right)^{-1} \quad (4)$$

103 where $S_0 = W \times t$ is the initial cross-section area, L_0 and L are respectively
 104 the initial and current specimen length, and ΔL is the specimen length change
 105 given by the relative displacement, in the loading direction, between two points
 106 near the top and bottom loading surfaces. This relative displacement can be
 107 obtained, for example, from the in-plane displacement field measured using the

108 DIC technique (Sect. 4).

109 3.2. Structural tests

110 To assess the effect of the grade of the STFs on the mechanical response of
111 structural laminates, tension, compression and bearing tests were performed on
112 the multidirectional STF laminates *DTO240* and *DTO160* (Table 1). The ten-
113 sion tests were performed in an MTS 810 servo-hydraulic testing machine with
114 a load capacity of 250 kN, equipped with a 250 kN load cell. The compression
115 and bearing tests were performed in an MTS 810 testing machine with a load
116 capacity of 100 kN, equipped with a 100 kN load cell. All tests were performed
117 at a controlled speed of 1.0 mm/min.

118 Following the ASTM D6484/D6484M – 14 test standard [8], a special test rig
119 designed to prevent buckling was used in the compression tests. The alignment
120 of the clamping system with the axis of the testing machine was performed using
121 two guiding pins with a diameter of 6 mm in the ends of the specimens.

122 The guiding holes in the compression specimens [8] and the open holes and
123 notches machined to assess the notched response of laminates *DTO240* and
124 *DTO160* were obtained using a drilling or a milling machine, respectively.
125 Carbon-epoxy sacrificial plates were used at the insertion and exit points of
126 the drill bit to avoid damage during the machining process. A 1 mm drill bit
127 was used to machine the sharp notches, ensuring a distance of 1 mm between
128 the notch faces. A constant width-to-notch length ratio ($W/2a$) equal to 6 was
129 considered.

130 3.2.1. Laminate tensile and compressive unnotched strengths

131 In this work, unnotched specimens with a nominal width (W) of 25 mm
132 and a nominal length (L_s) of 300 mm were tested in tension following the
133 ASTM D3039/D3039M – 14 test standard [5]. The gauge length (L) was set
134 to 150 mm. Unnotched compression tests were conducted on specimens with a
135 nominal width of 25 mm and a nominal length of 305 mm.

136 *3.2.2. Laminate tensile centre-notched strength*

137 To understand the mechanical performance and structural integrity of the
138 STF laminates in the presence of high stress concentrations, Centre-Notched
139 Tension (CNT) tests were carried out in the present work. CNT specimens
140 with a nominal width (W) of 30 mm and a nominal length (L_s) of 300 mm were
141 tested. The gauge length (L) was set to 150 mm. A centre notch with a nominal
142 length ($2a$) of 5 mm was used.

143 *3.2.3. Laminate compressive centre-notched strength*

144 In the present work, Centre-Notched Compression (CNC) tests were con-
145 ducted on specimens with a nominal width (W) of 30 mm and a nominal length
146 (L_s) of 305 mm. The centre notch had a nominal length ($2a$) of 5 mm. The sep-
147 aration of 1 mm between the crack faces was sufficient to avoid contact between
148 the crack faces after compressive failure.

149 *3.2.4. Open-Hole Tension (OHT) tests*

150 In the present work, Open-Hole Tension (OHT) tests were carried out to eval-
151 uate the mechanical behaviour in the presence of stress concentrations, based on
152 the ASTM D5766/D5766M – 11 test standard [9]. OHT specimens of different
153 sizes were tested. Table 2 shows the OHT test matrix, where W is the nominal
154 specimen width, L_s is the nominal specimen length, L is the gauge length (free
155 length between grips), and d is the hole diameter. The width-to-hole diameter
156 ratio (W/d) was constant and equal to 6.

157 *3.2.5. Open-Hole Compression (OHC) tests*

158 Open-Hole Compression (OHC) tests were conducted on specimens with a
159 nominal width (W) of 30 mm and a nominal length (L_s) of 305 mm. The
160 nominal hole diameter (d) was 5 mm, resulting in a width-to-hole diameter
161 ratio (W/d) equal to 6.

162 3.2.6. Bearing tests

163 Mechanically fastened joints are generally the critical part of a composite
164 structure, as they are a source of weakness and compliance. Following the
165 ASTM D5961/D5961M – 13 test standard [10], bolt-bearing tests were per-
166 formed in the present study. Specimens with a nominal hole diameter (d) of
167 6 mm, end distance-to-hole diameter ratio $e/d = 6$, width-to-hole diameter ra-
168 tio $W/d = 6$, and nominal length (L_s) of 215 mm were tested. A bolt M6 was
169 used with a washer subjected to a “finger-tight” clamping pressure, correspond-
170 ing to a torque $T = 2.2$ Nm. The end of the specimen far from the bearing hole
171 was clamped using a bolted clamping rig. The alignment of the longitudinal axis
172 of the gripped specimen with the test direction was performed using a guiding
173 pin with a diameter of 4 mm.

174 4. Instrumentation

175 The experimental monitoring of damage and fracture phenomena in com-
176 posite materials using optical full-field techniques can be extremely useful to
177 identify and understand the complex failure behaviour of these materials [11–
178 15]. In this experimental programme, full-field measurements were performed
179 using the DIC technique to obtain the surface in-plane displacement and strain
180 fields of the outer (0/90) STF layer. Measurements were performed in at least
181 one representative specimen of each laminate and test configuration. These
182 results were used to assist in the assessment of strain concentrations and to
183 monitor the differences in damage formation and propagation in the different
184 STF laminates.

185 All measurements were performed by means of a single camera, using the
186 ARAMIS DIC-2D v6.0.2 system developed by GOM [16]. The optical system,
187 its characteristics and the adopted configuration are summarised in Table 3.

188 5. Experimental results and discussion

189 5.1. *Strength characterisation test results*

190 5.1.1. *Fabric tensile unnotched strength test results*

191 As expected, linear stress-strain relations up to the ultimate remote stress
192 were obtained in both STF layers (Fig. 1). Prior to ultimate failure, transverse matrix
193 cracking had not occurred (Fig. 2). Both STF layers were characterised by a catas-
194 trophic fibre-dominated failure mode, with evidence of transverse and longitudi-
195 nal split cracking of the spread-tow yarns (Fig. 3). The *UDA240* STF laminate
196 also exhibited gauge section delamination between the STF layers (Fig. 3a),
197 which was reduced in the *UDA160* STF laminate (Fig. 3b). It was also noted
198 that the 240 g/m² STF was more susceptible to fibre-matrix splitting than the
199 thinner 160 g/m² STF.

200 Table 4 shows the measured longitudinal Young's moduli E_{1T} , Poisson's ra-
201 tios ν_{12} and mean tensile unnotched strengths X_T of the 240 g/m² and 160 g/m²
202 STFs. Interestingly, the difference in the Young's moduli is negligible. However,
203 the tensile strength of the thinner 160 g/m² STF is 7.2% lower than the tensile
204 strength of the 240 g/m² STF, which is not in line with the results reported in
205 the literature for multidirectional¹ tape laminates [13, 17–19]. Apparently, due
206 to the woven reinforcement architecture, the susceptibility of the 240 g/m² STF
207 for earlier development of fibre-matrix splitting leads to some relaxation of the
208 highly stressed longitudinal yarns, which delays the laminate final fracture, an
209 effect not observed in unnotched multidirectional tape laminates.

210 5.1.2. *Fabric compressive unnotched strength test results*

211 In the unnotched compression tests, before ultimate failure, modest load
212 drops were observed in both STFs, with a negligible effect on the stiffness of
213 the tested specimens; in some cases, the first load drop was also the peak load.

¹Even though the results presented in Sect. 5.1.1 refer to UD textile laminates, these include both 0° and 90° tapes in their architecture, making them comparable to cross-ply tape laminates.

214 These load drops can be attributed to the development of compressive damage,
 215 in the form of kink bands or brittle, shear-driven compressive cracks, which
 216 could be observed in the failed specimens after testing (Fig. 4).

217 Final failure was catastrophic in all specimens, characterised by a total loss of
 218 load-carrying capacity (sudden load drop, down to practically zero). However,
 219 ultimate failure was not due to the propagation of compressive fibre failure
 220 through the thickness of the specimen, but it occurred due to layer splitting
 221 along the length of the specimen, induced by localised longitudinal compressive
 222 failure of thin sublaminae (see Fig. 4).

223 Table 4 shows the measured longitudinal Young's moduli E_{1C} and mean
 224 compressive unnotched strengths X_C of the 240 g/m² and 160 g/m² STFs. It
 225 is interesting to note that the difference in Young's moduli is not only small
 226 between *prepreg* weaves, but also between the tensile and compressive loading
 227 conditions (Table 4). It should be noted that this is often not the case in
 228 woven fabrics (e.g. Ref. [2]). On the other hand, the thinner 160 g/m² STF
 229 exhibits a compressive unnotched strength 16.2% higher than the 240 g/m²
 230 STF. This superior compressive unnotched response can be attributed not only
 231 to an improved uniformity of the microstructure of spread tows [19], but also
 232 to a better uniformity of the woven architecture, including lower fibre waviness
 233 and smaller crimp angles, which delay micro- and meso-instabilities in the fibre
 234 direction and, consequently, improve the longitudinal compressive strength.

235 5.1.3. Off-axis compression test results

236 As suggested by Koerber et al. [6], the axial stress, σ_x , and the axial com-
 237 pressive strength, $\bar{\sigma}_x$, were calculated dividing respectively the load signal and
 238 the peak load by the true specimen cross section (Eq. (4)), determined based
 239 on the relative displacement obtained from a representative specimen of each
 240 off-axis angle and STF grade.

241 In the 15° off-axis compression tests, a small nonlinearity before ultimate
 242 failure was observed. A single kink band penetrating completely through the
 243 thickness of the specimen, approximately perpendicular to the off-axis direction,

244 or a series of kink bands had formed along the length of the 15° off-axis spec-
 245 imens (Fig. 5). Surface crushing was observed on the failed specimens at the
 246 loaded ends. Small delaminations from the end surfaces were often observed.
 247 Some 15° off-axis specimens also exhibited a “brush”-like layer splitting failure
 248 mode, with no clear longitudinal compressive failure mode. Nevertheless, the
 249 different failure modes had no effect on the ultimate failure stress of the 15°
 250 off-axis compression tests.

251 The 30° off-axis compression tests exhibited a marked nonlinear response,
 252 attributed to high localised plastic deformation and to an accumulation of com-
 253 pressive damage. Ultimate failure generally occurred quickly, with a steep load
 254 drop. However, due to the large accumulation of damage, this sudden load drop
 255 was not catastrophic, but resulted from extensive material degradation. During
 256 damage accumulation, small buckling edge delaminations of thin outer sublam-
 257 inates were observed (Fig. 6), followed by crushing of one of the corners of the
 258 loaded ends. Finally, the load started dropping quickly. This was apparently
 259 due to compression stability failure of the fibres or due to severe out-of-plane
 260 layer splitting. Some specimens exhibited surface crushing, with a “brush”-like
 261 layer splitting failure mode (Fig. 6). Marked kink bands, approximately perpen-
 262 dicular to the off-axis direction, which penetrate partially through the thickness
 263 of the specimens, could also be observed (Fig. 6). In some cases, delaminations
 264 propagated from the kink bands towards one of the [ends of the specimen](#), which
 265 prevented the kink bands from extending completely through the thickness.

266 Table 5 shows the mean axial compressive strengths, $\bar{\sigma}_x$, of the 240 g/m² and
 267 160 g/m² STFs for the 15° and 30° off-axis tests, and the respective coefficients
 268 of variation. Interestingly, the axial compressive strength of the 15° off-axis
 269 specimens of both laminates is virtually the same; it differs by just 1.3%. In
 270 fact, no difference was observed between the mechanical response and failure
 271 modes of the 15° off-axis specimens of the 240 g/m² and 160 g/m² STFs. On the
 272 other hand, the thinner 160 g/m² STF exhibits a 30° off-axis axial compressive
 273 strength 16.9% higher than the 240 g/m² STF (a difference in the range of that
 274 observed for the unnotched compressive strengths in Sect. 5.1.2).

Figure 7 shows the failure envelopes of the 240 g/m² and 160 g/m² STFs for the combined compression/in-plane shear stress space σ_{11} – σ_{12} (in the material coordinate system), obtained from the measured axial compressive strength in the loading coordinate system, $\bar{\sigma}_x$, using Eqs. (1)–(3). The correct off-axis angle at failure, θ , was obtained from the DIC data of a representative specimen of each off-axis configuration and STF.

Due to the balanced amount of fibres in the warp- and weft-direction, it can be assumed that the corresponding compressive strengths are equal (i.e. $X_C = Y_C$), and the 15° and 30° off-axis data can be used to represent fictitious 75° and 60° off-axis specimens, respectively. By simply interchanging the warp and weft stress components, the data points for fictitious 75° and 60° off-axis specimens can be obtained. These data points are also plotted in the σ_{11} – σ_{12} stress diagram of Fig. 7.

As observed by Koerber et al. [6] for a 5-harness-satin textile carbon-epoxy composite, an approximately constant value of the in-plane shear stress at failure was obtained regardless of the applied multiaxial stress state. A maximum stress failure criterion seems therefore suitable to approximate the failure envelopes of the STFs studied in the present work (Fig. 7). Hence, the obtained off-axis data can be used to estimate the in-plane shear strengths (S_L) of the STFs investigated in the present study (see $\times$ data points in Fig. 7). The resulting in-plane shear strengths are respectively $S_L = 71$ MPa and $S_L = 75$ MPa for the 240 g/m² and 160 g/m² STFs, a difference of 5.6%. The meso-structure of the textile composites, which resembles a cross-ply laminate, apparently promotes a [thickness](#) effect on the in-plane shear strength. In fact, Fig. 7 shows that the thinner 160 g/m² STF not only exhibits a markedly superior behaviour in compression, attributed to the uniformity of the thinner reinforcement architecture of the 160 g/m² STFs (Sect. 5.1.2), but also a slightly higher in-plane shear strength, which can be attributed to the ability of the thinner spread-tow yarns to suppress microcracking caused by shear loading (*in situ* effect [20]). On the other hand, from the 30° off-axis specimens, for example, it is possible to estimate the shear modulus, G_{12} , of the plain weaves from the measured off-

axis stiffness and using Laminated Plate Theory [21]. A small difference, in the range of 5%, was obtained (Table 5). It is interesting to note that, despite the differences in the strengths of the STFs, the differences in the measured elastic properties are practically negligible.

5.2. Structural test results

5.2.1. Laminate tensile unnotched strength test results

Laminate *DTO160* was characterised by an approximately linear remote stress-strain relation up to ultimate failure (Fig. 8). Laminate *DTO240*, on the other hand, exhibited a minor nonlinear behaviour close to the ultimate load (Fig. 8), resulting in a slightly higher failure strain $\bar{\epsilon}_x$ (Table 6). However, laminate *DTO160* exhibits a tensile unnotched strength, X_T^L , 13.9% higher than laminate *DTO240*. This improved laminate unnotched response is attributed to the damage suppression capability of laminates made of thinner reinforcements [13, 17, 19]. On the other hand, the nonlinear response of laminate *DTO240* can be attributed to the development of subcritical damage, including matrix cracking of the transverse spread-tow yarns and longitudinal splitting along the 0° spread-tow yarns (Fig. 9), and to the nonlinear behaviour of the off-axis STFs.

At failure, both laminates exhibited a catastrophic fibre-dominated failure mode (Fig. 10). However, laminate *DTO240* (Fig. 10a) was characterised by extensive pull-out, with transverse and longitudinal split cracking along the transverse and longitudinal spread-tow yarns, respectively. A diffuse failure region was observed, without a clear fracture plane. Laminate *DTO160* (Fig. 10b), as expected, exhibited a more brittle net-section failure mode, with a fracture plane perpendicular to the loading direction. Matrix damage and fibre-matrix splitting was effectively precluded when reducing the yarns grade from 240 g/m² to 160 g/m², resulting in an improved unnotched response (see Table 6). Gauge section delamination was not observed in the tested multidirectional fabric laminates.

Table 6 also shows the measured Young’s modulus, E_x , of both laminates.

336 As can be observed, laminate *DTO160* is stiffer than laminate *DTO240*, which
337 partially explains the higher strength of the former. Nevertheless, the thickness
338 effect is expected to have the largest contribution for this improved strength.

339 It is also interesting to note that the apparent superior longitudinal strength
340 of the 240 g/m² STF reported in Sect. 5.1.1 did not translate into a superior
341 laminate strength. If, in the former, subcritical damage growth (mostly
342 longitudinal splitting — Fig. 2), apparently resulted in the relaxation of the
343 longitudinal yarns, delaying ultimate failure, in the latter, transverse cracking
344 and longitudinal splitting (Fig. 9) caused local stress redistributions that promoted
345 earlier laminate failure, reducing the laminate unnotched strength, as
346 observed elsewhere [13, 17–19].

347 5.2.2. Laminate compressive unnotched strength test results

348 Before compressive failure, small load drops were observed in some specimens
349 of both laminates, with a negligible effect on the stiffness of the tested
350 specimens. These can be attributed to the development of compressive damage
351 before ultimate failure, which was sudden and catastrophic, characterised by a
352 big load drop. After testing, all specimens exhibited a net-section failure mode,
353 characterised by a complex combination of damage mechanisms, including fibre
354 kinking, wedge transverse fracture, delamination and surface fibre/matrix
355 splitting caused by buckling of the outer STF layers (Fig. 11).

356 Laminate *DTO160* exhibited a slightly more brittle failure mode, with a
357 more clear through-the-thickness fracture plane, inclined with respect to the
358 mid-plane of the specimen (Fig. 11b). Delamination between STF layers was
359 absent. In laminate *DTO240*, on the other hand, a more diffuse fracture region
360 was observed, including free-edge delamination along the outer STF layers
361 (Fig. 11a).

362 Table 6 shows the mean laminate compressive unnotched strengths, X_C^L ,
363 of laminates *DTO240* and *DTO160*. Laminate *DTO160* exhibits a compressive
364 unnotched strength 17.7% higher than laminate *DTO240*, which can be
365 attributed to the uniformity of the thinner reinforcement architecture of the

160 g/m² STFs of laminate *DTO160*. In fact, the thinner 160 g/m² STF exhibits higher compressive strength than the 240 g/m² STF (Sect. 5.1.2), as the better uniformity of the spread-tow yarns, lower fibre waviness and smaller crimp angles of the former can delay micro-instabilities in the fibre direction, allowing the longitudinal yarns to carry higher loads.

It is noted that the variation in the test results of laminate *DTO240* is atypically high (Table 6). However, this can be attributed to the less uniform reinforcement configuration of laminate *DTO240*. In fact, a similar effect of the reduced uniformity of the microstructure was also observed by Amacher et al. [19], with thicker UD tapes showing not only lower strength but also higher variability in the test results of smooth coupons subjected to compressive failure.

5.2.3. *Laminate tensile centre-notched strength test results*

All CNT coupons of laminates *DTO240* and *DTO160* exhibited an approximately linear response, with small load drops observed close to the peak load, with no effect on the stiffness of the specimens. These small load drops can be attributed to internal damage growth from the notch tips, which blunted the strain concentration and modified the surface strain fields (Fig. 12). In laminate *DTO240* (Fig. 12a) transverse split cracks formed in the 90° spread-tow yarns, while longitudinal splitting at the vicinity of the notch tips blunted the strain concentration, preventing further intralaminar damage growth until catastrophic failure of the 0° spread-tow yarns. On the other hand, in laminate *DTO160* (Fig. 12b), intralaminar damage growth from the notch tips started close to the peak remote stress and propagated quickly across the width, along the off-axis directions. Longitudinal split cracking tangent to the notch tips was also observed, however without preventing the occurrence of intralaminar damage growth from the notch tips.

Both laminates exhibited a fibre-dominated pull-out failure mode. However, laminate *DTO240* exhibited a more diffuse failure zone; some specimens did not exhibit a clear fracture plane, whereas others exhibited diffuse fracture predominantly along the -45° direction, including pull-out and delamination

396 of large fibre bundles. Laminate *DTO160* exhibited fracture predominantly
397 along the -45° direction, with fibre bundle pull-out and delaminations with a
398 triangular shape due to intralaminar fracture along the 45° direction of some off-
399 axis STF layers. Longitudinal splitting of the 0° spread-tow yarns was observed
400 in the specimens of both laminates.

401 Table 7 shows the average results for the ultimate remote stress of the CNT
402 tests. It is interesting to note that the tensile centre-notched strengths of lam-
403 inates *DTO240* and *DTO160* differ by just 0.9%, in spite of the differences in
404 the morphology and extent of the failure mechanisms involved in the fracture
405 process. The similarity of the experimental results can be attributed to the
406 development of internal longitudinal split cracking tangent to the notch tips be-
407 fore ultimate failure of both laminates (Fig. 12). However, the susceptibility of
408 the thicker spread-tow yarns of laminate *DTO240* to develop early subcritical
409 damage results in a diffuse failure mode due to the propagation of transverse
410 and longitudinal split cracking.

411 5.2.4. Laminate compressive centre-notched strength test results

412 Centre-notched coupons of laminates *DTO240* and *DTO160* were also tested
413 to failure in compression. Interestingly, before ultimate failure, the morphology
414 and extent of damage was very similar in both laminates. Damage propagation
415 from the notch tips started early before ultimate failure, but substantial damage
416 growth did not occur until that point, remaining confined to the vicinity of the
417 notch tips.

418 Small load drops were observed in some specimens of laminate *DTO240*,
419 close to or after the peak load. These load drops, which had a negligible effect
420 on the stiffness of the tested specimens, were attributed to the development of
421 the damage process zone ahead of the notch tips. In laminate *DTO160*, no load
422 drops were observed, suggesting that the development of the damage process
423 zone had a much lower effect on the response of laminate *DTO160* than in
424 laminate *DTO240*.

425 Unstable propagation across the ligament width occurred just upon ultimate

failure. Both laminates exhibited a catastrophic failure mode, characterised by a steep load drop. All specimens exhibited a net-section failure mode (Fig. 13). However, failure of laminate *DTO240* was characterised by a complex combination of damage mechanisms, including fibre kinking, wedge transverse fracture and surface fibre/matrix splitting caused by buckling of the outer STF layers (Fig. 13a). On the other hand, failure of laminate *DTO160* was characterised predominantly by fibre kinking, which propagated across the ligament section ahead of the notch tips (Fig. 13b). Clear kink bands formed through the thickness of the laminate, along a plane inclined with respect to the loading direction. Small longitudinal split cracks at the lateral free edges were also observed in some specimens, due to buckling of the thin outer layers.

Table 7 shows the mean values of the ultimate remote stress of the CNC tests and corresponding coefficients of variation (C.V.). Following the trends observed for the compressive unnotched strength (Sect. 5.2.2), laminate *DTO160* is characterised by an improved compressive notched response, with a compressive centre-notched strength 10.3% higher than laminate *DTO240*. The more brittle failure mode of laminate *DTO160*, attributed to a better uniformity of the thin 160 g/m² spread-tow yarns that delays the onset of the micro-instabilities that lead to compressive failure, results in an improved compressive response either or not in the presence of stress concentrations, which can be relevant for a number of industrial applications, including in aerospace.

5.2.5. OHT test results

All OHT specimens exhibited an approximately linear response until ultimate failure. Small load drops were observed close to the peak load (clearer in the large OHT specimens, with a hole diameter of 5 mm), caused by damage growth at the vicinity of the open hole just before unstable catastrophic failure.

The small OHT specimens of both laminates exhibited longitudinal split cracking tangent to the hole boundary, resulting in an important blunting effect that precluded stable intralaminar cracking across the ligament section before catastrophic failure of the longitudinal spread-tow yarns (Fig. 14). In the large

OHT specimens (Fig. 15), intralaminar cracking perpendicular to the loading direction was observed in both laminates, which started propagating early before ultimate failure. After stable propagation, transverse intralaminar fracture eventually originated other damage mechanisms ahead of the crack tips, in particular longitudinal splitting. It was also noted that, in general, internal damage growth was delayed in laminate *DTO160*.

Both laminates exhibited a fibre-dominated pull-out failure mode, independently of the coupon geometry. Laminate *DTO240* exhibited a diffuse fracture plane either perpendicular or at 45° with the loading direction, dominated by fibre bundle pull-out and split cracking of the longitudinal and off-axis spread-tow yarns. Transverse split cracking and delamination of the outer STF layers were also observed. Laminate *DTO160* exhibited a [more brittle](#) failure mode, with the fracture plane predominantly at 45° with the loading direction. Fibre bundle pull-out and split cracking of the longitudinal and off-axis spread-tow yarns were also observed, but in lesser extent than in laminate *DTO240*. Laminate *DTO160* also exhibited delaminations with triangular shape across the ligament section. The damage morphology of each laminate was similar in both coupon geometries, even though the extent of diffuse damage increased with specimen size in both cases.

Table 7 shows the average results for the ultimate remote stress of the OHT tests, and corresponding coefficients of variation. Interestingly, for the specimens with a hole diameter of 2 mm, laminate *DTO160* exhibits an ultimate remote stress 4.9% higher than laminate *DTO240*. Because the ligament section is sufficiently small, the extent of diffuse damage observed in both laminates is enough to effectively blunt the notch (Fig. 14), while the stronger unnotched ligaments of laminate *DTO160* contribute for a slightly higher tensile notched strength. On the other hand, the ultimate remote stress of the specimens with a hole diameter of 5 mm is virtually the same, as it differs by just 1.4%. In this case, notch blunting in laminate *DTO160* is not so effective (Fig. 15b), [leading](#) to a notched strength reduction (in the range of 7.3%) with increasing hole diameter. In laminate *DTO240*, though, due to its higher susceptibility to develop

subcritical damage mechanisms with a significant blunting effect (Fig. 15a), the notched strength remains virtually unchanged with increasing hole diameter (for the hole diameter range studied in the present work); hence, it can be expected that, as the specimen size increases, the tensile notched strength of laminate *DTO240* will become higher than the tensile notched strength of laminate *DTO160*. Nevertheless, the difference is not remarkable, suggesting that thin STFs can be effectively used in notched structures subjected to tensile loads (see also Sect. 5.2.3), in particular if other criteria such as high unnotched strengths and/or improved compressive behaviour are also to be taken into account.

5.2.6. OHC test results

A linear response was obtained in all OHC specimens of both laminates, which exhibited a catastrophic failure mode, characterised by a steep load drop. Intralaminar compressive damage growth from the vicinity of the hole boundary started early in both laminates. Before ultimate failure, intralaminar compressive damage propagated stably but quickly across the ligament section in laminate *DTO240*, whereas in laminate *DTO160* it propagated unstably upon ultimate failure. The ability of laminate *DTO160* to delay through-the-width propagation of intralaminar damage resulted in an improved compressive notched response (Table 7).

After testing, all specimens exhibited a net-section failure mode (Fig. 16). However, failure of laminate *DTO240* was characterised by a complex combination of damage mechanisms, including fibre kinking, wedge transverse fracture and surface fibre/matrix splitting caused by buckling of the outer STF layers (Fig 16a). Failure of laminate *DTO160* was dominated by fibre kinking, which propagated across the ligament section ahead of the hole boundary (Fig. 16b). Clear kink bands formed through the thickness of the laminate, along a plane inclined with respect to the loading direction. Surface splitting due to intralaminar compressive fracture of the outer STF layers along the fracture plane was also observed.

Table 7 shows the average results for the ultimate remote stress of the OHC

517 tests and corresponding coefficients of variation. Following the trends of the
518 unnotched and centre-notched compression tests (Sects. 5.2.2 and 5.2.4, respec-
519 tively), laminate *DTO160* exhibits an improved compressive notched response,
520 with an open-hole compressive strength 7.4% higher than laminate *DTO240*.
521 Interestingly, it is noted that, whereas subcritical damage growth in notched
522 coupons acts as a blunting mechanism in tension (Sects. 5.2.3 and 5.2.5), in
523 compression it seems to contribute for early fracture of the longitudinal spread-
524 tow yarns, as observed in the unnotched configuration (Sect. 5.2.2). Precluding
525 the propagation of subcritical damage, as observed in laminate *DTO160*, can
526 delay longitudinal compressive failure, improving the compressive response.

527 5.2.7. Bearing test results

528 Bolt-bearing tests were performed on laminates *DTO240* and *DTO160* to
529 assess the effect of tow thickness on the performance of STF mechanically fas-
530 tened joints. As expected, all specimens exhibited a bearing failure mode, re-
531 sulting from local compressive damage in the bearing hole region. Besides local
532 compressive failure and crushing of the load-bearing surface, which is the typ-
533 ical failure mode observed in composite laminates subjected to bearing loads
534 [13, 22], split cracking of the longitudinal and transverse spread-tow yarns of
535 the outer layers was also observed in the region outside the washer, after perma-
536 nent deformation of the hole. No relevant difference between the failure modes
537 of laminates *DTO240* and *DTO160* was observed.

538 The bearing stress-bearing strain curves [10] of both laminates were linear up
539 to approximately 50% of the maximum bearing stress, exhibiting a small kink
540 before the response becomes nonlinear (a similar response was already reported
541 in previous work [13]). [Micrographs](#) taken from the bearing plane of interrupted
542 tests showed that the nonlinearity in the bearing stress-bearing strain curves was
543 caused by the propagation of fibre kinking and shear-driven matrix cracking, as
544 well as fibre crushing along the inner 0° spread-tow yarns (Figs. 17a and 18a).
545 It was also noted that the extent of matrix cracking in laminate *DTO160* was
546 noticeably lower than in laminate *DTO240*, indicating that compressive matrix-

547 dominated fracture was effectively delayed in the thinner STFs due to an *in situ*
548 effect in compression [23].

549 For bearing stresses greater than the initial peak bearing stress, extensive fi-
550 bre kinking and shear-driven matrix cracking were observed (Figs. 17b and 18b).
551 These damage mechanisms were not restricted to the vicinity of the hole edge,
552 occurring along the bearing plane far from the loading surface. Moreover, their
553 interaction led to the formation of through-the-thickness shear cracks, which
554 were responsible for the first load drops. It is also interesting to note that
555 laminate *DTO160* exhibited a “more brittle” longitudinal compressive failure
556 mode, with more pronounced kink bands along the 0° spread-tow yarns, as well
557 as shear-driven fibre fractures.

558 After the first load drop and formation of the first through-the-thickness
559 shear cracks, further loading lead to additional matrix cracking and fibre kink-
560 ing, promoting the formation and propagation of the shear cracks along the
561 bearing plane. Subsequent hole deformation also caused additional fibre and
562 matrix crushing at the hole edge.

563 Table 8 shows the average test results and respective coefficients of variation
564 for the bearing strengths of laminates *DTO240* and *DTO160* adopting some of
565 the most common bearing strength definitions used in the literature, namely the
566 average bearing stress at the onset of nonlinearity, the average bearing stress for
567 an offset bearing strain of 2%, the average bearing stress at the first load drop,
568 and the average maximum bearing stress. The bearing stress and the offset
569 bearing strain were determined following the ASTM D5961/D5961M – 13 test
570 standard [10].

571 As can be observed, because the governing failure mechanisms were essen-
572 tially the same, laminates *DTO240* and *DTO160* exhibit virtually the same
573 bearing response, independently of the bearing strength definition (Table 8).
574 The only exception is the average bearing stress for an offset bearing strain of
575 2%, which is 5% higher in laminate *DTO160*. This can be attributed to the
576 ability of the thinner STF to delay the propagation of compressive subcritical
577 damage mechanisms before severe hole deformation.

578 It is interesting to note that, whereas previous studies [13, 19] have shown
579 that the structural performance of mechanically fastened joints of thin-ply lami-
580 nates can be considerably better than laminates with thicker UD plies, the same
581 **thickness** effect was not observed in the present study, in spite of the improved
582 compressive response of the thinner 160 g/m² STF. This is perhaps due to the
583 less significant difference between the thickness of the yarns when compared
584 with previous studies [13, 19], and also due to the fact that the yarns of both
585 STFs were obtained by tow spreading, ensuring a good homogeneity of the mi-
586 crostructure in spite of the different tow thicknesses. Nevertheless, it can be
587 expected that, for a wider range of tow thicknesses, or for a comparison with
588 conventional textile composites with less uniform meso-structures, the damage
589 suppression capability of the thin yarns will play a positive role in improving
590 the bearing response of advanced textile composites.

591 6. Conclusions

592 With the aim to study the structural response of aerospace-grade plain weave
593 STFs of different tow thicknesses, an experimental test campaign was carried out
594 which included basic characterisation of the STFs and the detailed assessment
595 of the structural response of laminates based on a baseline of the aeronautical
596 industry.

597 Characterisation tests showed that the thin STF exhibited lower tensile
598 strength than the thick STF, attributed to the superior ability of the latter to de-
599 velop subcritical damage growth that apparently resulted in a stress relaxation of
600 the longitudinal yarns, consequently delaying ultimate failure. In compression,
601 though, the trend changes dramatically. The thin STF exhibited a compressive
602 unnotched strength 16.2% higher than the thick STF, in agreement with what
603 has been observed in UD tapes [19]. This improved behaviour can be attributed
604 to the uniformity of the thin spread-tow yarns, including lower fibre waviness
605 and smaller crimp angles, which delays micro-instabilities in the fibre direction
606 and, consequently, improves the longitudinal strength. Off-axis compression

607 tests also showed that, when subjected to combined compression/in-plane shear
608 loads, the thin STF is characterised by an improved overall compressive resistance. Using the obtained off-axis data, it was possible to estimate the in-plane
609 shear strengths of the STFs, showing that the thin STF also exhibits an improved in-plane shear response over the thick STF, attributed to an *in situ* effect
610 in shear [20].
611

612
613 At the laminate level, as expected, the thin-STF laminate exhibited a tensile
614 unnotched strength 13.9% higher than the thick-STF laminate. This improved
615 unnotched response, already observed in multidirectional tape laminates [13, 17–
616 19], was attributed to the damage suppression capability of laminates made
617 of thinner reinforcements. By precluding subcritical damage mechanisms, the
618 thin-STF laminate was able to sustain reasonably higher applied loads. It is
619 noted that the apparent superior longitudinal strength of the thick STF did
620 not translate into a superior laminate strength. In compression, following the
621 trend of the UD STF laminates, an improvement of the compressive unnotched
622 strength of 17.7% was observed for the thin-STF laminate when compared with
623 the thick-STF laminate.

624 Interestingly, the tensile notched strengths of the multidirectional STF lam-
625 inates did not differ substantially, in spite of some differences in the morphology
626 and extent of the failure mechanisms involved in the fracture process. The simi-
627 larity of the notched responses can be attributed to the development of internal
628 longitudinal split cracking tangent to the notch tips before ultimate failure of
629 both laminates. In compression, following the trends observed for the smooth
630 coupons, the thin-STF laminate exhibited an improved compressive notched re-
631 sponse. Finally, a similar bearing response was obtained for both STF laminates.
632 The thin-STF laminate exhibited a slightly higher resistance to the propagation
633 of subcritical damage mechanisms at the initial stages of permanent damage,
634 but the resistance to severe damage growth was virtually the same.

635 Acknowledgements

636 This work was funded by AIRBUS under project 2genComp — second gen-
637 eration Composites. The authors gratefully acknowledge the support provided
638 by AIRBUS.

639 The authors are also grateful to Oxeon AB (Borås, Sweden) for providing
640 the spread-tow fabrics used in the experimental test campaign reported in this
641 paper.

642 The first author would like to thank the financial support provided by FCT
643 – Fundação para a Ciência e a Tecnologia through National Funds in the scope
644 of project MITP-TB/PFM/0005/2013.

645 The last author gratefully acknowledges the funding of Project NORTE-01-
646 0145-FEDER-000022 – SciTech – Science and Technology for Competitive and
647 Sustainable Industries, co-financed by Programa Operacional Regional do Norte
648 (NORTE2020), Fundo Europeu de Desenvolvimento Regional (FEDER).

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Figure 1: Virtual strain gauges and remote stress-strain relations of representative UD plain weave unnotched tension test specimens obtained with the DIC technique. The loading direction is parallel to the horizontal axis of the specimens.

Figure 2: (Top) Coloured distributions of grey levels (0–255), (middle) longitudinal strain fields, ε_x , and (bottom) local longitudinal strain along the edges of the outer STF layer (red and black dashed lines) of representative UD unnotched tension test specimens of laminates (i) UDA_{240} and (ii) UDA_{160} obtained with the DIC technique at the stage prior to ultimate failure. The reference DIC coordinate system is shown in the top figures, where the x -axis is aligned with the loading direction.

(a) Thick STF *UDA240*.

(b) Thin STF *UDA160*.

Figure 3: Representative UD plain weave unnotched tension test specimens after testing.

“brush”-like layer splitting shear-driven fibre fracture kink band
(a) Thick STF *UDB240*.

shear-driven fibre fracture kink band “brush”-like layer splitting crushing
(b) Thin STF *UDB160*.

Figure 4: Representative UD plain weave unnotched compression test specimens after testing.

(a) Thick STF *UDB240*.

(b) Thin STF *UDB160*.

Figure 5: Representative 15° off-axis compression test specimens after testing.

(a) Thick STF *UDB240*.

(b) Thin STF *UDB160*.

Figure 6: Representative 30° off-axis compression test specimens after testing.

Figure 7: Failure envelopes for the combined compression/in-plane shear stress space.

Figure 8: Virtual strain gauges and remote stress-strain relations of representative unnotched tension test specimens obtained with the DIC technique. The loading direction is parallel to the horizontal axis of the specimens.

Figure 9: (Top) Coloured distributions of grey levels (0–255), (middle) longitudinal strain fields, ϵ_x , and (bottom) local longitudinal strain along the edges of the outer STF layer (red and black dashed lines) of representative unnotched tension test specimens of laminates (i) *DTO240* and (ii) *DTO160* obtained with the DIC technique at the stage prior to ultimate failure. The reference DIC coordinate system is shown in the top figures, where the x -axis is aligned with the loading direction.

(a) Thick-STF laminate *DTO240*.

(b) Thin-STF laminate *DTO160*.

Figure 10: Representative unnotched tension test specimens after testing.

(a) Thick-STF laminate *DTO240*.

(b) Thin-STF laminate *DTO160*.

Figure 11: Details of the laminate unnotched compression test specimens after testing.

(a) Thick-STF laminate *DTO240*.

(b) Thin-STF laminate *DTO160*.

Figure 12: Specimen surface and longitudinal strain fields, ε_y , of representative CNT test specimens of laminates *DTO240* and *DTO160* obtained with the DIC system before ultimate failure. The reference DIC coordinate systems are shown in the figures, where the y -axis is aligned with the loading direction.

(a) Thick-STF laminate *DTO240*.

(b) Thin-STF laminate *DTO160*.

Figure 13: Details of representative CNC test specimens after testing.

(a) Thick-STF laminate *DTO240*.

(b) Thin-STF laminate *DTO160*.

Figure 14: Specimen surface and longitudinal strain fields, ε_y , of representative OHT test specimens of laminates *DTO240* and *DTO160* with a hole diameter of 2 mm obtained with the DIC system before ultimate failure. The reference DIC coordinate systems are shown in the figures, where the y -axis is aligned with the loading direction.

(a) Thick-STF laminate *DTO240*.

(b) Thin-STF laminate *DTO160*.

Figure 15: Specimen surface and longitudinal strain fields, ε_y , of representative OHT test specimens of laminates *DTO240* and *DTO160* with a hole diameter of 5 mm obtained with the DIC system before ultimate failure. The reference DIC coordinate systems are shown in the figures, where the y -axis is aligned with the loading direction.

(a) Thick-STF laminate *DTO240*.

(b) Thin-STF laminate *DTO160*.

Figure 16: Details of the OHC test specimens after testing.

(a) Onset of nonlinearity.

(b) First load drop.

Figure 17: [Micrographs](#) of the bearing plane of representative bolt-bearing specimens of laminate *DT0240* after interrupted testing. Magnification factor of $5\times$.

(a) Onset of nonlinearity.

(b) First load drop.

Figure 18: [Micrographs](#) of the bearing plane of representative bolt-bearing specimens of laminate *DT0160* after interrupted testing. Magnification factor of $5\times$.

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Table 1: Stacking sequence definitions of the T700SC/M21 STF laminates.

Laminate ID	STF grade	STF stacking sequence	Nominal laminate thickness (mm)
Textile characterisation			
<i>UDA240</i>	240 g/m ²	[0] ₈	1.92
<i>UDB240</i>	240 g/m ²	[0] ₁₈	4.32
<i>UDA160</i>	160 g/m ²	[0] ₁₂	1.92
<i>UDB160</i>	160 g/m ²	[0] ₂₆	4.16
Structural characterisation			
<i>DTO240</i>	240 g/m ²	[0/45 ₂ /0/45 ₂ /0]	1.68
<i>DTO160</i>	160 g/m ²	[0/45/0/45 ₂ /0/45 ₂ /0/45/0]	1.76

Table 2: OHT test matrix.

Geometry	L_s (mm)	L (mm)	W (mm)	d (mm)
Large	300	150	30	5
Small	300	200	12	2

Table 3: Configuration of the DIC system.

Camera-lens optical system	
CCD camera	Baumer 138 Optronic FWX20 8-bit Resolution: 1624 × 1236 pixels ² Sensor format: 1/1.8"
Lens	Nikon AF Micro-Nikkor 200 mm $f/4D$ IF-ED
DIC measuring parameters	
Subset size	15 × 15 pixels ²
Subset step	13 × 13 pixels ²
Strain base length	5 subsets
Strain validity code	55.0%
Strain computation method	Total
DIC resolution	
Spatial resolution	2×10^{-2} pixels [24, 25]
Strain resolution	0.01-0.04% [24, 25]

Table 4: Unnotched tension and compression test results.

Results	240 g/m ² STF	160 g/m ² STF
Tension		
E_{1T} (MPa)	66909	66229
ν_{12} (-)	0.097	0.061
X_T (MPa)	1408 (4.4%) [†]	1307 (2.8%) [†]
Compression		
E_{1C} (MPa)	65089	63210
X_C (MPa)	456 (7.5%) [†]	530 (3.1%) [†]

[†] Coefficients of variation (C.V.).

Table 5: Off-axis compression test results.

Results	240 g/m ² STF	160 g/m ² STF
15° off-axis compression		
$\bar{\sigma}_x$ (MPa)	278 (5.3%) [†]	274 (6.4%) [†]
30° off-axis compression		
G_{12} (MPa)	8725	8317
$\bar{\sigma}_x$ (MPa)	151 (1.7%) [†]	176 (2.0%) [†]

[†] Coefficients of variation (C.V.).

Table 6: Laminate tensile and compressive unnotched test results.

Results	<i>DTO240</i>	<i>DTO160</i>
Tension		
E_x (MPa)	40732	49317
$\bar{\epsilon}_x$ (%)	1.94	1.84
X_T^L (MPa)	753 (1.3%) [†]	857 (2.9%) [†]
Compression		
X_C^L (MPa)	381 (12.1%) [†]	448 (5.4%) [†]

[†] Coefficients of variation (C.V.).

Table 7: Laminate tensile and compressive notched test results.

Results	Centre notch 2a = 5 mm		Open hole			
	<i>DTO240</i>	<i>DTO160</i>	<i>d</i> = 2 mm		<i>d</i> = 5 mm	
			<i>DTO240</i>	<i>DTO160</i>	<i>DTO240</i>	<i>DTO160</i>
Tension						
$\bar{\sigma}^\infty$ (MPa)	490	494	523	548	515	508
(C.V.)	(6.2%)	(3.9%)	(6.3%)	(4.9%)	(4.9%)	(3.4%)
Compression						
$\bar{\sigma}^\infty$ (MPa)	256	283	-	-	239	257
(C.V.)	(9.9%)	(2.1%)	-	-	(0.9%)	(0.2%)

Table 8: Bearing test results.

Results	<i>DTO240</i>	<i>DTO160</i>
<i>Average bearing stress at the onset of nonlinearity</i>		
$\sigma_{\text{nonlin}}^{br}$ (MPa)	628	629
(C.V.)	(5.0%)	(2.7%)
<i>Average bearing stress for an offset bearing strain of 2%</i>		
$\sigma_{2\% \text{offset}}^{br}$ (MPa)	884	925
(C.V.)	(1.3%)	(1.6%)
<i>Average bearing stress at the first load drop</i>		
$\sigma_{\text{drop}}^{br}$ (MPa)	1106	1093
(C.V.)	(9.5%)	(2.8%)
<i>Average maximum bearing stress</i>		
σ_{max}^{br} (MPa)	1171	1184
(C.V.)	(1.9%)	(3.9%)