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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: Link to publication record in 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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Preprint submitted to Compos Struct

June 16, 2017

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

1 1. Introduction

The thinner and wider tows obtained with tow spreading show unique ben-2 efits that open a broad range of new possibilities in terms of design and manu-3 facturing of composite structures. For example, spread-tow fabrics (STFs) can be obtained using spread tapes in the weaving process instead of conventional 5 yarns. Using spread tapes, fibre bundles are not only thinner, but they are 6 also wider, resulting in flatter fabrics, with fewer interlacing points and better 7 surface finish than conventional ones. Such fabric configurations are also char-8 acterised by minimal fibre waviness, and therefore lower crimp frequency and 9 smaller crimp angles [1, 2], allowing the filaments to immediately carry tensile 10 or compressive loads without first having to straighten. 11

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.

24 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)

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

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

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

All laminates were prepared for curing in a vacuum bag and cured using an autoclave. The autoclave cure cycle was defined by setting a heat-up rate of 2°C/min from room temperature to 180°C, holding at 180°C for 120 minutes and cooling down at a rate of 2°C/min. A gauge autoclave pressure of 4 bar was applied throughout the cure cycle. After curing, each plate was cut to the 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 displace-⁵³ ment 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

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

⁶⁷ 3.1.2. Fabric compressive unnotched strength

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

76 3.1.3. Fabric off-axis compression tests

Off-axis specimens provide a simple way of studying the mechanical behaviour of UD composites and laminates under combined stresses, useful to derive experimental yield and failure envelopes. In the present work, 15° and 30° off-axis compression tests were performed. These tests were carried out on

- ⁸¹ laminates UDB240 and UDB160.
- Following Koerber et al. [6], unnotched specimens with a nominal width (W)of 10 mm and a nominal length (L) of 20 mm were tested using the same endloading test rig used in the UD unnotched compression tests (Sect. 3.1.2). To

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

$$\bar{\sigma}_{11} = \bar{\sigma}_x \cos^2 \theta \tag{1}$$

$$\bar{\sigma}_{22} = \bar{\sigma}_x \sin^2 \theta \tag{2}$$

$$\bar{\sigma}_{12} = -\bar{\sigma}_x \sin\theta \cos\theta \tag{3}$$

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

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

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

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

¹⁰⁸ DIC technique (Sect. 4).

109 3.2. Structural tests

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

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

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

¹³⁰ 3.2.1. Laminate tensile and compressive unnotched strengths

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

¹³⁶ 3.2.2. Laminate tensile centre-notched strength

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

¹⁴³ 3.2.3. Laminate compressive centre-notched strength

In the present work, Centre-Notched Compression (CNC) tests were conducted on specimens with a nominal width (W) of 30 mm and a nominal length (L_s) of 305 mm. The centre notch had a nominal length (2a) of 5 mm. The separation of 1 mm between the crack faces was sufficient to avoid contact between the crack faces after compressive failure.

149 3.2.4. Open-Hole Tension (OHT) tests

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

157 3.2.5. Open-Hole Compression (OHC) tests

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

162 3.2.6. Bearing tests

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

174 4. Instrumentation

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

All measurements were performed by means of a single camera, using the ARAMIS DIC-2D v6.0.2 system developed by GOM [16]. The optical system, 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

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

Table 4 shows the measured longitudinal Young's moduli E_{1T} , Poisson's ra-200 tios ν_{12} and mean tensile unnotched strengths X_T of the 240 g/m² and 160 g/m² 201 STFs. Interestingly, the difference in the Young's moduli is negligible. However, 202 the tensile strength of the thinner 160 g/m^2 STF is 7.2% lower than the tensile 203 strength of the 240 g/m^2 STF, which is not in line with the results reported in 204 the literature for multidirectional¹ tape laminates [13, 17–19]. Apparently, due 205 to the woven reinforcement architecture, the susceptibility of the 240 g/m^2 STF 206 for earlier development of fibre-matrix splitting leads to some relaxation of the 207 highly stressed longitudinal yarns, which delays the laminate final fracture, an 208 effect not observed in unnotched multidirectional tape laminates. 209

210 5.1.2. Fabric compressive unnotched strength test results

In the unnotched compression tests, before ultimate failure, modest load drops were observed in both STFs, with a negligible effect on the stiffness of 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.

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

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

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

235 5.1.3. Off-axis compression test results

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

In the 15° off-axis compression tests, a small nonlinearity before ultimate failure was observed. A single kink band penetrating completely through the thickness of the specimen, approximately perpendicular to the off-axis direction, or a series of kink bands had formed along the length of the 15° off-axis specimens (Fig. 5). Surface crushing was observed on the failed specimens at the loaded ends. Small delaminations from the end surfaces were often observed. Some 15° off-axis specimens also exhibited a "brush"-like layer splitting failure mode, with no clear longitudinal compressive failure mode. Nevertheless, the different failure modes had no effect on the ultimate failure stress of the 15° off-axis compression tests.

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

Table 5 shows the mean axial compressive strengths, $\bar{\sigma}_x$, of the 240 g/m² and 266 160 g/m^2 STFs for the 15° and 30° off-axis tests, and the respective coefficients 267 of variation. Interestingly, the axial compressive strength of the 15° off-axis 268 specimens of both laminates is virtually the same; it differs by just 1.3%. In 269 fact, no difference was observed between the mechanical response and failure 270 modes of the 15° off-axis specimens of the 240 g/m² and 160 g/m² STFs. On the 271 other hand, the thinner 160 g/m^2 STF exhibits a 30° off-axis axial compressive 272 strength 16.9% higher than the 240 g/m² STF (a difference in the range of that 273 observed for the unnotched compressive strengths in Sect. 5.1.2). 274

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 $\sigma_{11}-\sigma_{12}$ (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 $\sigma_{11}-\sigma_{12}$ stress diagram of Fig. 7.

As observed by Koerber et al. [6] for a 5-harness-satin textile carbon-epoxy 288 composite, an approximately constant value of the in-plane shear stress at fail-289 ure was obtained regardless of the applied multiaxial stress state. A maximum 290 stress failure criterion seems therefore suitable to approximate the failure en-291 velopes of the STFs studied in the present work (Fig. 7). Hence, the obtained 292 off-axis data can be used to estimate the in-plane shear strengths (S_L) of the 293 STFs investigated in the present study (see \times data points in Fig. 7). The result-294 ing in-plane shear strengths are respectively $S_L = 71$ MPa and $S_L = 75$ MPa 295 for the 240 g/m² and 160 g/m² STFs, a difference of 5.6%. The meso-structure 296 of the textile composites, which resembles a cross-ply laminate, apparently pro-297 motes a thickness effect on the in-plane shear strength. In fact, Fig. 7 shows 298 that the thinner 160 g/m^2 STF not only exhibits a markedly superior behaviour 299 in compression, attributed to the uniformity of the thinner reinforcement archi-300 tecture of the 160 g/m^2 STFs (Sect. 5.1.2), but also a slightly higher in-plane 301 shear strength, which can be attributed to the ability of the thinner spread-tow 302 yarns to suppress microcracking caused by shear loading (in situ effect [20]). 303 On the other hand, from the 30° off-axis specimens, for example, it is possible 304 to estimate the shear modulus, G_{12} , of the plain weaves from the measured off-305

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.

310 5.2. Structural test results

311 5.2.1. Laminate tensile unnotched strength test results

Laminate DTO160 was characterised by an approximately linear remote 312 stress-strain relation up to ultimate failure (Fig. 8). Laminate DTO240, on 313 the other hand, exhibited a minor nonlinear behaviour close to the ultimate 314 load (Fig. 8), resulting in a slightly higher failure strain $\bar{\epsilon}_x$ (Table 6). However, 315 laminate DTO160 exhibits a tensile unnotched strength, X_T^L , 13.9% higher than 316 laminate DTO240. This improved laminate unnotched response is attributed to 317 the damage suppression capability of laminates made of thinner reinforcements 318 [13, 17, 19]. On the other hand, the nonlinear response of laminate DTO240319 can be attributed to the development of subcritical damage, including matrix 320 cracking of the transverse spread-tow yarns and longitudinal splitting along the 321 0° spread-tow yarns (Fig. 9), and to the nonlinear behaviour of the off-axis 322 STFs. 323

At failure, both laminates exhibited a catastrophic fibre-dominated failure 324 mode (Fig. 10). However, laminate DTO240 (Fig. 10a) was characterised by ex-325 tensive pull-out, with transverse and longitudinal split cracking along the trans-326 verse and longitudinal spread-tow yarns, respectively. A diffuse failure region 327 was observed, without a clear fracture plane. Laminate DTO160 (Fig. 10b), 328 as expected, exhibited a more brittle net-section failure mode, with a fracture 329 plane perpendicular to the loading direction. Matrix damage and fibre-matrix 330 splitting was effectively precluded when reducing the yarns grade from 240 g/m^2 331 to 160 g/m^2 , resulting in an improved unnotched response (see Table 6). Gauge 332 section delamination was not observed in the tested multidirectional fabric lam-333 inates. 334

335

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

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

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

347 5.2.2. Laminate compressive unnotched strength test results

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

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

Table 6 shows the mean laminate compressive unnotched strengths, X_C^L , of laminates DTO240 and DTO160. Laminate DTO160 exhibits a compressive unnotched strength 17.7% higher than laminate DTO240, which can be attributed to the uniformity of the thinner reinforcement architecture of the ³⁶⁶ 160 g/m² STFs of laminate *DTO160*. In fact, the thinner 160 g/m² STF ex-³⁶⁷ hibits higher compressive strength than the 240 g/m² STF (Sect. 5.1.2), as ³⁶⁸ the better uniformity of the spread-tow yarns, lower fibre waviness and smaller ³⁶⁹ crimp angles of the former can delay micro-instabilities in the fibre direction, ³⁷⁰ 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 approx-378 imately linear response, with small load drops observed close to the peak load, 379 with no effect on the stiffness of the specimens. These small load drops can 380 be attributed to internal damage growth from the notch tips, which blunted 381 the strain concentration and modified the surface strain fields (Fig. 12). In 382 laminate DTO240 (Fig. 12a) transverse split cracks formed in the 90° spread-383 tow yarns, while longitudinal splitting at the vicinity of the notch tips blunted 384 the strain concentration, preventing further intralaminar damage growth until 385 catastrophic failure of the 0° spread-tow yarns. On the other hand, in laminate 386 DTO160 (Fig. 12b), intralaminar damage growth from the notch tips started 387 close to the peak remote stress and propagated quickly across the width, along 388 the off-axis directions. Longitudinal split cracking tangent to the notch tips 389 was also observed, however without preventing the occurrence of intralaminar 390 damage growth from the notch tips. 301

³⁹² Both laminates exhibited a fibre-dominated pull-out failure mode. However, ³⁹³ laminate DTO240 exhibited a more diffuse failure zone; some specimens did ³⁹⁴ not exhibit a clear fracture plane, whereas others exhibited diffuse fracture ³⁹⁵ predominantly along the -45° direction, including pull-out and delamination of large fibre bundles. Laminate DTO160 exhibited fracture predominantly along the -45° direction, with fibre bundle pull-out and delaminations with a triangular shape due to intralaminar fracture along the 45° direction of some offaxis STF layers. Longitudinal splitting of the 0° spread-tow yarns was observed in the specimens of both laminates.

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

⁴¹¹ 5.2.4. Laminate compressive centre-notched strength test results

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

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

425

Unstable propagation across the ligament width occurred just upon ultimate

failure. Both laminates exhibited a catastrophic failure mode, characterised by 426 a steep load drop. All specimens exhibited a net-section failure mode (Fig. 13). 427 However, failure of laminate DTO240 was characterised by a complex combina-428 tion of damage mechanisms, including fibre kinking, wedge transverse fracture 429 and surface fibre/matrix splitting caused by buckling of the outer STF layers 430 (Fig. 13a). On the other hand, failure of laminate DTO160 was characterised 431 predominantly by fibre kinking, which propagated across the ligament section 432 ahead of the notch tips (Fig. 13b). Clear kink bands formed through the thick-433 ness of the laminate, along a plane inclined with respect to the loading direction. 434 Small longitudinal split cracks at the lateral free edges were also observed is some 435 specimens, due to buckling of the thin outer layers. 436

Table 7 shows the mean values of the ultimate remote stress of the CNC tests 437 and corresponding coefficients of variation (C.V.). Following the trends observed 438 for the compressive unnotched strength (Sect. 5.2.2), laminate DTO160 is char-439 acterised by an improved compressive notched response, with a compressive 440 centre-notched strength 10.3% higher than laminate DTO240. The more brit-441 tle failure mode of laminate DTO160, attributed to a better uniformity of the 442 thin 160 g/m² spread-tow yarns that delays the onset of the micro-instabilities 443 that lead to compressive failure, results in an improved compressive response 444 either or not in the presence of stress concentrations, which can be relevant for 445 a number of industrial applications, including in aerospace. 446

447 5.2.5. OHT test results

All OHT specimens exhibited an approximately linear response until ulti-448 mate failure. Small load drops were observed close to the peak load (clearer in 449 the large OHT specimens, with a hole diameter of 5 mm), caused by damage 450 growth at the vicinity of the open hole just before unstable catastrophic failure. 451 The small OHT specimens of both laminates exhibited longitudinal split 452 cracking tangent to the hole boundary, resulting in an important blunting effect 453 that precluded stable intralaminar cracking across the ligament section before 454 catastrophic failure of the longitudinal spread-tow yarns (Fig. 14). In the large 455

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, indepen-462 dently of the coupon geometry. Laminate DTO240 exhibited a diffuse fracture 463 plane either perpendicular or at 45° with the loading direction, dominated by 464 fibre bundle pull-out and split cracking of the longitudinal and off-axis spread-465 tow yarns. Transverse split cracking and delamination of the outer STF layers 466 were also observed. Laminate DTO160 exhibited a more brittle failure mode, 467 with the fracture plane predominantly at 45° with the loading direction. Fibre 468 bundle pull-out and split cracking of the longitudinal and off-axis spread-tow 469 yarns were also observed, but in lesser extent than in laminate DTO240. Lam-470 inate DTO160 also exhibited delaminations with triangular shape across the 471 ligament section. The damage morphology of each laminate was similar in both 472 coupon geometries, even though the extent of diffuse damage increased with 473 specimen size in both cases. 474

Table 7 shows the average results for the ultimate remote stress of the OHT 475 tests, and corresponding coefficients of variation. Interestingly, for the spec-476 imens with a hole diameter of 2 mm, laminate DTO160 exhibits an ultimate 477 remote stress 4.9% higher than laminate DTO240. Because the ligament section 478 is sufficiently small, the extent of diffuse damage observed in both laminates is 479 enough to effectively blunt the notch (Fig. 14), while the stronger unnotched 480 ligaments of laminate DTO160 contribute for a slightly higher tensile notched 481 strength. On the other hand, the ultimate remote stress of the specimens with 482 a hole diameter of 5 mm is virtually the same, as it differs by just 1.4%. In this 483 case, notch blunting in laminate DTO160 is not so effective (Fig. 15b), leading 484 to a notched strength reduction (in the range of 7.3%) with increasing hole di-485 ameter. In laminate DTO240, though, due to its higher susceptibility to develop 486

subcritical damage mechanisms with a significant blunting effect (Fig. 15a), the 487 notched strength remains virtually unchanged with increasing hole diameter 488 (for the hole diameter range studied in the present work); hence, it can be ex-489 pected that, as the specimen size increases, the tensile notched strength of lam-490 inate DTO240 will become higher than the tensile notched strength of laminate 491 DTO160. Nevertheless, the difference is not remarkable, suggesting that thin 492 STFs can be effectively used in notched structures subjected to tensile loads (see 493 also Sect. 5.2.3), in particular if other criteria such as high unnotched strengths 494 and/or improved compressive behaviour are also to be taken into account. 495

496 5.2.6. OHC test results

A linear response was obtained in all OHC specimens of both laminates, 497 which exhibited a catastrophic failure mode, characterised by a steep load drop. 498 Intralaminar compressive damage growth from the vicinity of the hole boundary 490 started early in both laminates. Before ultimate failure, intralaminar compres-500 sive damage propagated stably but quickly across the ligament section in lami-501 nate DTO240, whereas in laminate DTO160 it propagated unstably upon ulti-502 mate failure. The ability of laminate DTO160 to delay through-the-width prop-503 agation of intralaminar damage resulted in an improved compressive notched 504 response (Table 7). 505

After testing, all specimens exhibited a net-section failure mode (Fig. 16). 506 However, failure of laminate DTO240 was characterised by a complex combina-507 tion of damage mechanisms, including fibre kinking, wedge transverse fracture 508 and surface fibre/matrix splitting caused by buckling of the outer STF layers 509 (Fig 16a). Failure of laminate DTO160 was dominated by fibre kinking, which 510 propagated across the ligament section ahead of the hole boundary (Fig. 16b). 511 Clear kink bands formed through the thickness of the laminate, along a plane 512 inclined with respect to the loading direction. Surface splitting due to intralam-513 inar compressive fracture of the outer STF layers along the fracture plane was 514 also observed. 515

516

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

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

527 5.2.7. Bearing test results

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

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

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

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

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

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

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

It is interesting to note that, whereas previous studies [13, 19] have shown 578 that the structural performance of mechanically fastened joints of thin-ply lami-579 nates can be considerably better than laminates with thicker UD plies, the same 580 thickness effect was not observed in the present study, in spite of the improved 581 compressive response of the thinner 160 g/m^2 STF. This is perhaps due to the 582 less significant difference between the thickness of the yarns when compared 583 with previous studies [13, 19], and also due to the fact that the yarns of both 584 STFs were obtained by tow spreading, ensuring a good homogeneity of the mi-585 crostructure in spite of the different tow thicknesses. Nevertheless, it can be 586 expected that, for a wider range of tow thicknesses, or for a comparison with 587 conventional textile composites with less uniform meso-structures, the damage 588 suppression capability of the thin yarns will play a positive role in improving 580 the bearing response of advanced textile composites. 590

⁵⁹¹ 6. Conclusions

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

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

tests also showed that, when subjected to combined compression/in-plane shear 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 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 in shear [20].

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

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

635 Acknowledgements

This work was funded by AIRBUS under project 2genComp — second generation Composites. The authors gratefully acknowledge the support provided by AIRBUS.

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

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

The last author gratefully acknowledges the funding of Project NORTE-010145-FEDER-000022 - SciTech - Science and Technology for Competitive and
Sustainable Industries, co-financed by Programa Operacional Regional do Norte
(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) UDA240 and (ii) UDA160 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.



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



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



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.





(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.





(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.



(b) First load drop.

Figure 17: Micrographs of the bearing plane of representative bolt-bearing specimens of laminate DTO240 after interrupted testing. Magnification factor of 5×.



(b) First load drop.

Figure 18: Micrographs of the bearing plane of representative bolt-bearing specimens of laminate DTO160 after interrupted testing. Magnification factor of 5×.

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Laminate ID	STF grade	STF stacking sequence	Nominal laminate thickness (mm)
Textile characte	erisation		
UDA240	240 g/m^2	[0]8	1.92
UDB240	240 g/m^2	$[0]_{18}$	4.32
UDA160	$160 { m g/m^2}$	$[0]_{12}$	1.92
UDB160	160 g/m^2	$[0]_{26}$	4.16
Structural char	acterisation		
DTO240	240 g/m^2	$[0/45_2/0/45_2/0]$	1.68
DTO160	$160 { m g/m^2}$	$[0/45/0/45_2/0/45_2/0/45/0]$	1.76

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

Table 2: OHT test matrix.

Geometry	$L_{\rm s}~({\rm mm})$	L (mm)	W (mm)	$d \pmod{d}$
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: $1624 \times 1236 \text{ pixels}^2$		
	Sensor format: $1/1.8$ "		
Lens	Nikon AF Micro-Nikkor 200 mm $f/4D$ IF-ED		
DIC measuring parameters			
Subset size	$15 \times 15 \text{ pixels}^2$		
Subset step	$13 \times 13 \text{ pixels}^2$		
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.

Resul	ts	$240 \text{ g/m}^2 \text{ STF}$	$160 \text{ g/m}^2 \text{ STF}$
Tensie	on		
E_{1T}	(MPa)	66909	66229
ν_{12}	(-)	0.097	0.061
X_T	(MPa)	$1408 \ (4.4\%)^{\dagger}$	$1307~(2.8\%)^{\dagger}$
Comp	ression		
E_{1C}	(MPa)	65089	63210
X_C	(MPa)	$456 \ (7.5\%)^{\dagger}$	$530 \ (3.1\%)^{\dagger}$
1 Coo	figiants of up	riction (C V)	

[†] Coefficients of variation (C.V.).

Table 5: Off-axis compression test results.

$240 \text{ g/m}^2 \text{ STF}$	$160 \text{ g/m}^2 \text{ STF}$
$278~(5.3\%)^{\dagger}$	$274~(6.4\%)^{\dagger}$
8725	8317
$151~(1.7\%)^{\dagger}$	$176~(2.0\%)^{\dagger}$
	240 g/m ² STF 278 (5.3%) [†] 8725 151 (1.7%) [†]

[†] Coefficients of variation (C.V.).

Table 6: Laminate tensile and compressive unnotched test results.

Resu	lts	DTO240	<i>DTO160</i>
Tensi	on		
E_x	(MPa)	40732	49317
$\overline{\epsilon}_x$	(%)	1.94	1.84
X_T^L	(MPa)	$753 \ (1.3\%)^{\dagger}$	$857~(2.9\%)^{\dagger}$
Com	pression		
X_C^L	(MPa)	$381 \ (12.1\%)^{\dagger}$	$448~(5.4\%)^{\dagger}$
† Coe	efficients of var	iation (C.V.).	

Table 7: Laminate tensile and compressive notched test results.

	Centr	e notch	Open hole			
Results	2a =	5 mm	d = 2 mm		d = 5 mm	
	DTO240	DTO160	DTO240	<i>DTO160</i>	DTO240	DTO160
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	L					
$\bar{\sigma}^{\infty}$ (MPa)	256	283	-	-	239	257
(C.V.)	(9.9%)	(2.1%)	-	-	(0.9%)	(0.2%)

Table 8: Bearing test results.

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