STRUCTURAL RESPONSE OF AEROSPACE-GRADE THIN-PLY WOVEN AND NON-CRIMP 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 more interest in recent years due to the introduction in the market of spread-tow, ultra-thin carbon-fibre reinforcements. In the present work, an experimental test campaign was carried out to study the structural response of aerospace-grade plain weave STFs of different areal weights, and NCFs with different levels of 0° ply blocking. The results show that multidirectional thin-STF laminates exhibit an improved tensile unnotched strength over the thick-STF laminate, and similar tensile notched strengths. In compression, the thin-STF laminate performed substantially better in both unnotched and notched configurations, but exhibited a similar bearing response. In the case of the thin-ply NCFs, the results show that, by grouping together the 0° plies in thicker blocks, an improved structural response was obtained on scaled coupons, as well as on mechanically fastened joints, without compromising the superior unnotched tensile and compressive strengths intrinsic to thin-ply laminates.

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. Therefore, a clear understanding of the effect of ply thickness on the onset of intralaminar and interlaminar damage mechanisms and how it affects the structural response of laminated composite structures is still a subject of great interest for the composites research and industrial communities.

The spread-tow thin-ply technology allows, for example, the production of STFs 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.

Thin-ply laminates are known for their enhanced mechanical performance, attributed to the ability to delay the onset of damage mechanisms typically observed in conventional composite materials.
This damage suppression capability results in an enhanced unnotched strength [5-8], improved compressive response [6, 7] and higher fatigue resistance [3, 5, 6, 8].

It is recognised, though, that the delay of damage onset typical of thin-ply configurations may have a negative impact in notched structures loaded in tension [8], since it inhibits local stress redistribution at the vicinity of the notch. Nonetheless, studies focused on minimising, or even eliminating this disadvantage without compromising the enhanced mechanical performance of thin plies, are, unfortunately, scarce.

One strategy to suppress this disadvantage of thin-ply laminates is based on a selective combination of thin transverse and off-axis plies with thicker 0° plies [9]. By means of selective ply-level hybridisation, it is possible to obtain a globally enhanced notched behaviour without compromising the unnotched and fatigue responses [9]. The thick 0° plies promote longitudinal split cracking in the regions of high stress concentration at the vicinity of the notch, resulting in a stress redistribution along the loading direction that delays unstable fracture of the notched laminates, increasing their notched strength when compared with laminates with thin 0° plies.

In the present work, an experimental test campaign was carried out to study the structural response of aerospace-grade plain weave STFs of different areal weights. This test campaign included characterisation tests of the STFs, performed on UD STF laminates, and the detailed assessment of the structural response of multidirectional STF laminates defined according to a baseline of the aeronautical industry.

Following this study, focus was then placed on the understanding of how 0° ply blocking can be efficiently used to improve the structural integrity of thin-ply laminates without compromising their intrinsically high unnotched strengths. A detailed experimental programme was, therefore, carried out on two stacking sequences, with dispersed and blocked 0° plies. The unnotched response of both laminates was evaluated in tension and in compression, and structural tests, typical of laminate scrutiny in the aeronautical industry, were carried out to understand the effects of laminate design on the complex behaviour of structural details.

2 STRUCTURAL RESPONSE OF SPREAD-TOW FABRICS

2.1 Material selection and manufacturing

T700SC TeXtreme® STFs from Oxeon AB were pre-impregnated with HexPly® M21 toughened epoxy resin from Hexcel 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.

Characterisation tests were performed on UD textile laminates of both 160 g/m² and 240 g/m² STFs with a plain weave (cross-ply) configuration. Tests on structural details were performed using a multidirectional textile laminate of each STF grade, designed based on a damage tolerance optimised baseline laminate for aeronautical applications: [0/45/0/45/0] 240 g/m² (DTO240) and [0/45/0/45/0/45/0/45/0/45/0] 160 g/m² (DTO160), 1.68 mm and 1.76 mm thick, respectively.

2.2 Characterisation tests

To assess the effect of tow thickness on the structural response of STFs, firstly basic characterisation tests were performed, including:

- Unnotched tension tests [10];
- Unnotched compression tests [11];

Figure 1 shows the unnotched test results. Interestingly, the tensile strength of the thinner 160 g/m² STF is 7.2% lower than the tensile strength of the 240 g/m² STF. This was apparently due to the gradual failure process of the 240 g/m² STF, which exhibited extensive internal damage in the form of split cracking of the spread-tow yarns prior to ultimate failure (see Figure 2), delaying longitudinal fracture.
In compression, however, the thinner 160 g/m² STF exhibits a compressive unnotched strength 16.2% higher than the 240 g/m² STF (Figure 1). This superior compressive unnotched response can be attributed not only to an improved uniformity of the microstructure, but also to a better uniformity of the reinforcement architecture, including lower fibre waviness and smaller crimp angles, which delay micro- and meso-instabilities in the fibre direction and, consequently, improve the longitudinal compressive strength.

The off-axis compression test results are depicted in Figure 3. Interestingly, the axial compressive strength of the 15° off-axis specimens is virtually the same (it differs by just 1.3%). On the other hand, the thinner 160 g/m² STF exhibits a 30° off-axis axial compressive strength 16.9% higher than the 240 g/m² STF, a difference in the range of that observed for the unnotched compressive strength (see Figure 1).

Figure 4 shows the data points of the longitudinal and off-axis compression tests plotted in the $\sigma_{11}-\sigma_{12}$ stress diagram. As can be observed, an approximately constant value of the in-plane shear stress at failure was obtained regardless of the applied multiaxial stress state (horizontal lines). Therefore, a maximum stress failure criterion seems suitable to represent the failure envelopes of the STFs studied in the present work. Similar conclusions were drawn on other textile configurations, such as 5-harness-satin carbon reinforcements [11].
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Figure 3: Off-axis compressive strengths of 240 g/m² and 160 g/m² STFs.

Figure 4: Failure envelopes for the combined compression/in-plane shear stress space.

Assuming that a maximum stress failure criterion adequately approximates the failure envelopes in the $\sigma_{11}$-$\sigma_{12}$ stress space, the obtained off-axis data can be used to estimate the in-plane shear strengths – Figure 5. As can be observed, the estimated in-plane shear strengths (crosses along the $\sigma_{12}$ axis in Figure 4) differ by just 5.6%.

Figure 5: Estimated in-plane shear strengths of 240 g/m² and 160 g/m² STFs.

2.3 Structural tests

To study the effect of tow thickness on multidirectional spread-tow textile laminates, tests on structural details were also performed:

- Laminate unnotched tension tests [10];
- Laminate unnotched compression tests [12];
- Laminate centre-notched tension tests [7];
- Laminate centre-notched compression tests [7,12];
- Open-Hole Tension (OHT) tests [13];
- Open-Hole Compression (OHC) tests [12];
- Bearing tests [14].

Figure 6 summarises the laminate unnotched and centre-notched test results. As expected, contrary to the results for the UD fabric unnotched coupons, the thin-ply 160 g/m² laminate has a tensile unnotched strength 13.9% higher than the 240 g/m² laminate. This improved unnotched response (already observed in previous works [5-8]) is attributed to the damage suppression capability of laminates made of thinner reinforcements.
In compression, the 160 g/m² laminate exhibits an unnotched strength 17.7% higher than the 240 g/m² laminate, which can be attributed to the uniformity of the thinner reinforcement architecture of the 160 g/m² STFs. In fact, as discussed for the UD fabric (Figure 1), the thinner 160 g/m² STF exhibits higher compressive strength than the 240 g/m² STF, promoted by a better uniformity of the spread-tow yarns, lower fibre waviness and smaller crimp angles, which delay micro-instabilities in the fibre direction, allowing the longitudinal yarns to carry higher loads.

Observing the results for the centre-notched tension tests, it is interesting to note that the notched strengths differ by just 0.9%. The similarity of the experimental results can be attributed to the development of internal longitudinal splitting tangent to the notch tips before ultimate failure, as suggested by the straight bands parallel to the loading direction depicted in the strain fields shown in Figure 7.

Following the trends observed for the compressive unnotched strength, the thin-ply 160 g/m² laminate exhibits an improved compressive notched response compared with the 240 g/m² laminate, with a compressive centre-notched strength 10.3% higher (see Figure 6). The brittler failure mode exhibited by the 160 g/m² laminate, where diffuse damage mechanisms such as transverse and split cracking and interlaminar damage are absent, seems to favour an improved compressive response, either or not in the presence of stress concentrations.

In the case of OHT (Figure 8), as expected, as the hole size increases (with constant width-to-hole diameter ratio), the tensile strength of the open-hole specimens decreases. Comparing the two laminates, it is interesting to note that the open-hole tensile strengths do not differ substantially. However, the strength reduction from a hole diameter of 2 mm to a hole diameter of 5 mm is steeper in the thin-ply 160 g/m² laminate.
Figure 8: OHT test results.

For the smaller specimens, with a hole diameter of 2 mm, the extent of diffuse damage is higher – see Figure 9. Both laminates exhibit longitudinal splitting tangent to the hole boundary, and intralaminar fracture perpendicular or at an angle with the loading direction is absent before ultimate failure. In the larger specimens, with a hole diameter of 5 mm, intralaminar cracking perpendicular to the loading direction is observed in both laminates. In the 240 g/m² laminate, a diffuse damage process zone in the vicinity of the open hole has propagated into transverse intralaminar cracking ahead of the open hole boundary and into longitudinal splitting tangent to the hole free edge. In the 160 g/m² laminate clear intralaminar fracture ahead of the hole boundary can be observed, originating other damage mechanisms ahead of the crack tips, namely longitudinal splitting.

Figure 9: Longitudinal strain fields, $\varepsilon_y$, of representative OHT test specimens obtained with digital image correlation before ultimate failure. The vertical $y$-axis is aligned with the loading direction.

For OHC (Figure 10), following the trends observed for the compressive unnotched and centre-notched strengths, the thin-ply 160 g/m² laminate exhibits an open-hole compressive strength 7.4% higher than the 240 g/m² laminate. As observed before, the brittle failure mode exhibited by the 160 g/m² laminate, where diffuse damage mechanisms, such as transverse and split cracking, are absent, potentiates an improved compressive response, either or not in the presence of stress concentrations.

Figure 10: OHC test results.
Regarding the bolt-bearing tests, both laminates exhibited a similar bearing response (see Figure 11). Interestingly, through-the-thickness shear cracking in the 240 g/m² laminate occurred gradually due to the propagation of fibre kinking and matrix cracking through the thickness of the laminate. On the other hand, the suppression of matrix cracking in the 160 g/m² laminate delays the occurrence of fibre compressive failure, which then propagates suddenly in the form of brittle kink bands or shear-driven oblique fracture, inducing quick through-the-thickness shear cracking. Despite the different interactions, the formation of through-the-thickness shear cracking occurs at similar applied loads in both laminates, leading to approximately the same bearing response.

Figure 11: Bolt-bearing test results.

3 STRUCTURAL RESPONSE OF THIN-PLY NON-CRIMP FABRICS

The use of thin plies is recognised for delaying, or even suppressing damage occurrence in the transverse and off-axis plies and on their interfaces, improving the laminate strength [5-8]. In fact, thick transverse and off-axis plies promote transverse cracking, conducting to premature laminate failure due to stress concentrations on the load carrying plies. In addition, laminates with thick plies develop higher interlaminar stresses, promoting delamination onset and growth, which usually conducts to the loss of structural integrity of the laminates, particularly when loaded in compression. Although local growth of these damage mechanisms can blunt the stress concentrations near geometrical discontinuities and contribute for the superior notched strength of the laminates, they are also responsible for lower laminate strengths due to premature damage growth.

Alternatively, longitudinal split cracking can also act as an important notch blunting mechanism, without affecting the laminate strength [9], and the thickness of the 0° plies is known to drive, in a great extent, the growth of longitudinal split cracks [15]. Because notch blunting is important for the notched strength of laminates, a detailed study on the effect of 0° ply blocking on the structural behaviour of an aerospace-grade laminate was carried out, with emphasis on the blunting mechanisms – split cracking and local delamination – and notched response.

3.1 Material selection and manufacturing

T700GC/M21 C-Ply™ bi-angle NCFs from Chomarat, with an areal weight of 75 g/m² per layer, were used in the present experimental campaign. Each layer is made of 12k tow-spread T700GC carbon fibres, pre-plied and mechanically sewn with fine stitching yarns, forming bi-axial NCFs. Two configurations were used in the present work: (0/45) and (0/-45) bi-angle fabrics. Both configurations were pre-impregnated with HexPly® M21 toughened epoxy resin from Hexcel.

A symmetric, balanced stacking sequence of bi-angle NCFs was defined based on a damage tolerance optimised baseline laminate for aeronautical applications, with dispersed 0° plies: [(90/-45)/(0/45)/(0/45)/(90/-45)/(0/45)/(0/-45)]₁₅. An alternative stacking sequence was also defined,
but with blocked 0° plies: \[ \{(90/-45)/(45/0)/(0/-45)/(90/-45)/(45/0)/(0/-45)\}_n \]. Here \( n \) is the number of repetitions, and the 0° fibre orientation is coincident with the loading direction.

### 3.2 Structural tests

To study the effect of 0° ply blocking on the structural response of thin-ply NCF laminates, the following tests on structural details were performed:

- Laminate unnotched tension tests [10];
- Laminate unnotched compression tests [12];
- Centre-notched tension tests and large damage capability [15, 16];
- Tests on mechanically fastened joints [14].

Figure 12 shows the results of the unnotched tests. For the tensile unnotched strengths, a negligible difference of just 2.3% has been observed between the two laminates. The longitudinal strain field of the outer 90° plies (Figure 13) show that transverse matrix cracking is absent, confirming the potential of thin transverse plies to suppress subcritical failure mechanisms. It is interesting to note that, as reported in Reference [9], restricting ply blocking to the 0° plies does not affect the final tensile unnotched strength of the laminates.

![Figure 12: Unnotched strengths of dispersed and blocked thin-ply NCF laminates.](image)

In compression, a negligible difference (0.5%) is also observed. However, it is interesting to note (Figure 14) that the post-failure behaviour of the dispersed and blocked laminates is remarkably different. The dispersed laminate shows a progressive failure mode, characterised by a series of load drops, deeper as the specimen approaches final failure. The blocked laminate is characterised by a sudden failure mode soon after the first load drops.

The dispersed laminate exhibited a more brittle failure mode, with more limited fibre kinking, and a high degree of abrasion of the inclined crack surfaces, typical of shear-driven brittle compressive failure. The blocked laminate exhibited more irregular failure surfaces, dominated by fibre kinking, suggesting that blocking the 0° plies results in a higher susceptibility to grow kink bands before compressive failure, which propagate unstably, resulting in a catastrophic ultimate failure.

To study the effect of the thickness of the 0° ply on the notched response of the thin-ply NCF laminates, centre-notched tension tests were performed, ranging from small coupons, with 6 mm-long notches, to large damage capability panels, with 30 mm-long notches (Figure 15). As expected, as the size of the specimens increases, the mean ultimate remote stress decreases.

In the small specimens, small split cracks in the off-axis plies can be identified by X-ray and digital image correlation before ultimate failure. These split cracks propagate from the notch tips where the fibre direction is tangent to the semi-circular boundary of the notch tips. Figure 15 also shows that the extent of damage in the blocked laminate before ultimate failure is slightly higher.

As the size of the specimens increases, off-axis split cracking and delamination ahead of the notch tips can be observed. In the largest specimens, severe split cracking propagating from the notch tips parallel to the loading direction towards the ends of the specimen were observed before catastrophic intralaminar failure.

These results show that, by grouping together the 0° plies in thicker blocks, it is possible to promote fibre-matrix splitting, which acts as an important notch blunting mechanism. Following this strategy, an improved structural response was obtained.
Figure 13: Coloured distributions of grey levels (0–255), longitudinal strain fields, $\varepsilon_x$, and local longitudinal strain measured along the edges of the outer 90° ply of representative unnotched tension test specimens of the dispersed (i) and blocked (ii) laminates obtained with the digital image correlation technique at the stage prior to ultimate failure. The reference coordinate system is depicted in the figures, where the horizontal x-axis is aligned with the loading direction.

Figure 14: Unnotched compression response of dispersed and blocked thin-ply NCF laminates.

Bolt-bearing tests were also performed (Figure 16), showing that blocking the 0° plies while having thin off-axis and transverse plies has the potential to improve the bearing response over thin plies alone. Comparing the damage morphology of the two laminates, a brittler through-the-thickness shear cracking failure mode can be observed in the dispersed laminate, characterised by thin shear bands and shear-driven fibre compressive failure. Damage propagation is also more abrupt. In the blocked laminate, wider shear bands in the off-axis plies and wider kink bands in the longitudinal plies can be observed, apparently promoting an improved bearing response.

To assess the effect of the lateral support on the bearing response, pin-bearing tests were also performed (Figure 16). Unlike the results for bolted joints, there is virtually no difference between the results of the dispersed and blocked laminates when subjected to pin-bearing loads. The lateral support provided by the bolt/washer assembly in the bolted joints can apparently add stability to the thicker 0° plies in the region confined by the bolt/washer assembly, delaying the onset and propagation of fibre kinking, increasing locally the laminate compressive strength.
Finally, net-tension tests were performed to study the effect of 0° ply blocking on the different failure modes occurring on composite mechanically fastened joints (Figure 16). The ultimate bearing stresses of the 9 mm-wide dispersed and blocked laminates are virtually the same. Due to the small ligament width of the 9 mm-wide specimens, propagation of damage mechanisms such as matrix cracking in the off-axis plies and delamination along the short ligament section occurs rapidly in both laminates, making any differences in the blunting effects unnoticeable. On the other hand, the ultimate bearing stress of the larger 12 mm-wide blocked specimens was 4.3% higher than the ultimate bearing
stress of the dispersed laminate. In this case, the larger ligament width results in a superior blunting effect in the blocked laminate due to the clustered 0° plies, which delays unstable net-tension failure.

4 CONCLUSIONS

The results of the present work show that multidirectional thin-STF laminates exhibit 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, despite a slightly higher resistance of the thin-STF laminate to the propagation of subcritical damage mechanisms.

On the other hand, by grouping together the 0° plies in thicker blocks, it is possible to promote fibre-matrix splitting, which acts as an important notch blunting mechanism, while the dispersed transverse and off-axis thin plies ensure that matrix cracking and delamination can be effectively delayed or even suppressed. Following this approach, an improved structural response was obtained on scaled coupons of a structural laminate, as well as on mechanically fastened joints. More importantly, this improved structural response was obtained without compromising the superior unnotched tensile and compressive strengths intrinsic to thin-ply laminates.

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