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C. Furtado, A. Arteiro, G. Catalanotti, J. Xavier, P.P. Camanho

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Selective ply-level hybridisation for improved notched response of composite laminates

C. Furtado\textsuperscript{a}, A. Arteiro\textsuperscript{a}, G. Catalanotti\textsuperscript{a,b}, J. Xavier\textsuperscript{b,c}, P.P. Camanho\textsuperscript{a,b,*}

\textsuperscript{a}DEMec, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal
\textsuperscript{b}INEGI, Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial, Rua Dr. Roberto Frias, 400, 4200-465 Porto, Portugal
\textsuperscript{c}CITAB, Universidade de Trás-os-Montes e Alto Douro, Engenharias I, Apartado 1013, 5001-801 Vila Real, Portugal

Abstract

This work presents an experimental study on the effect of ply-level hybridisation on the tensile unnotched and notched response of composite laminates. In a first assessment, notched tests were performed on laminates with nominal ply thicknesses between 0.03 mm and 0.30 mm. From the understanding of the effect of ply thickness on the damage mechanisms that govern the notched response of laminates, the concept of ply-level hybridisation is introduced, which consists in combining plies of different grades. A uniform combination of thin and conventional plies resulted in a hybrid laminate with intermediate notched response. Selective hybridisation, where thin off-axis plies are combined with thicker 0\textdegree plies, resulted in a globally enhanced notched behaviour without compromising the unnotched and fatigue responses. This work clearly shows how ply-level hybridisation, when designed to trigger specific damage mechanisms, can be used to improve the notched response of composite laminates.

Keywords: thin-ply laminates, hybrid, mechanical properties, notched response

\*Corresponding author. Tel.: +351 225081753; fax: +351 225081445.
Email address: pcamanho@fe.up.pt (P.P. Camanho)
1. Introduction

Laminates with sufficiently thin plies are known to fail by fibre fracture, showing extensive pull-out in the smaller specimens or a brittle fracture in the larger ones. In addition, for laminates with plies of moderate thickness the strength decreases with increasing hole size, giving rise to the conventional hole size effect [1, 2]. On the other hand, laminates with sufficiently thick plies fail by delamination, and the strength increases with increasing hole diameter [1, 2]. Laminates with intermediate ply thickness show an intermediate response, where specimens with small holes fail by delamination, and specimens with large holes fail by fibre fracture; in some cases, a constant strength over a range of hole sizes may be achieved [1, 2].

The different trends observed for the hole size effect are explained by the role of subcritical damage in the laminates’ failure mode [1, 2], in particular delamination [2]. In other words, even though conventional laminates show similar subcritical damage modes, their extent will determine the ultimate failure stress and failure mechanism.

Previous studies addressing the effect of ply thickness on the hole size effect were limited to a minimum ply thickness of 0.125 mm [1, 2]. In this work, an assessment of the hole size effect on laminated composites incorporating spread-tow thin plies [3] is presented.

The enhanced mechanical performance of thin-ply laminates is mainly due to the ability to delay the onset of damage typically observed in composite materials. In general, thin-ply composites exhibit enhanced unnotched strengths [4–7], potential for improved compressive notched strengths [5, 6] and higher fatigue resistance [4, 5, 7, 8]. However, the delay of damage onset has a negative impact in notched structures loaded in tension [7], since it inhibits local stress redistribution at the vicinity of the notch leading to premature brittle failure of the composite. This disadvantage has been pointed out as one of the main obstacles to the introduction of thin plies in a large scale. Therefore, the objective of this paper is to develop innovative laminates that include both thin...
plies and plies of intermediate thickness, aiming at improved notched strengths.

An experimental study is carried out to address the hole size effect on quasi-isotropic carbon fibre-reinforced polymer laminates with different reinforcement configurations and different ply thicknesses. In a first assessment, open-hole tension tests are performed on laminates produced from unidirectional (UD) prepregs with ply thicknesses between 0.03 mm and 0.30 mm. From the understanding of the effect of ply thickness on the damage mechanisms that govern the notched response of laminates, the concept of ply-level hybridisation is introduced. This concept consists in combining in the same laminate plies of the same material system but of different grades to trigger specific damage mechanisms in an attempt to improve the notched response of laminates made of thin plies. The effect of ply-level hybridisation on the mechanical response of quasi-isotropic laminates loaded in tension is then analysed by comparing the experimental results obtained for the hybrid lay-ups with those obtained for lay-ups with equivalent in-plane properties but incorporating a single grade.

2. Experimental test programme

2.1. Material selection and manufacturing

Initially, a complementary work to the comprehensive experimental study reported in Ref. [7] is presented. Three UD prepreg tapes with 30 g/m², 100 g/m² and 300 g/m² were used to study the hole size effect in laminates of different ply thicknesses. The UD prepreg tapes were produced from M40JB carbon fibres and ThinPreg™ 80EP/CF epoxy resin.

Quasi-isotropic laminates, [45/90/−45/0]_nS, with the same nominal thickness, t = 2.4 mm, were manufactured, and cured in an autoclave following the recommended curing cycle (80°C for 8 hours, and a 5 atm peak pressure): a [45/90/−45/0]_{10S} laminate (n = 10) with 30 g/m² plies, hereafter referred to as THIN; a [45/90/−45/0]_{3S} laminate (n = 3) with 100 g/m² plies, hereafter referred to as INT; and a [45/90/−45/0]_S laminate (n = 1) with 300 g/m² plies, hereafter referred to as THICK. A fourth laminate, [45_{10}/90_{10}/−45_{10}/0_{10}]_S,
hereafter referred to as THICK - PLY LEVEL, equivalent to the THICK laminate (same nominal ply thickness) but obtained blocking together plies with 30 g/m² with the same fibre orientation, was also tested to assess the effect of blocking together plies with the same fibre orientation instead of using plies with higher areal weight on the notched response of thick-ply laminates [7].

To emphasise the potential and flexibility of ply-level hybridisation also in terms of design, different reinforcement configurations were used. Uniform ply-level hybridisation, which consists in combining plies of different grades along all fibre orientations, is studied using laminates consisting of spread tow fabrics (STFs) of different grades. In the present study, two plain weave T700SC TeXtreme® STF configurations with 160 g/m² and 240 g/m² per fabric layer, pre-impregnated with HexPly® M21 toughened epoxy resin, were selected. The thickness of each tow was reduced using a pneumatic tow spreading system [3], resulting in especially wide tows. It is noted that, according to the manufacturer, the thinner the tows, the smaller the maximal local waviness. Moreover, due to the uniformity of the STFs and due to their low crimp angles, low tow waviness and reduced interlacing regions with small resin rich areas [8–11], no particular nesting rule was employed when stacking the STF layers during production of the laminates. In fact, the mechanical response of STFs approaches more closely the performance of UD tapes than conventional textile composites [8–11].

Alternatively, T700GC/M21 C-Ply™ bi-angle non-crimp fabrics (NCFs), with an areal weight of 150 g/m² per bi-angle layer, were used to study selective ply-level hybridisation. The 0/45 and 0/-45 bi-angle NCF configurations were used in the present work.

Symmetric quasi-isotropic laminates were manufactured from TeXtreme® and C-Ply™ material systems, including a thin-ply, an intermediate-ply and a hybrid laminate, all cured in an autoclave (gauge pressure of 4 bar, heat-up rate of 2°C/minute, holding at 180°C for 120 minutes, and cool-down rate of 2°C/minute). The thin-ply STF configuration, hereafter referred to as STF-THIN, consisted of 160 g/m² fabric layers only, whereas the intermediate-ply
STF configuration, hereafter referred to as STF-INT, consisted only of 240 g/m² fabric layers. For the hybrid STF laminate, hereafter referred to as STF-HYBRID, a combination of both grades was used.

With the NCF reinforcements, the thin-ply laminate, hereafter referred to as NCF-THIN, is obtained adopting a dispersed stacking sequence, with single plies of each orientation dispersed through the laminate thickness. Consequently, all plies have the same thickness (except at the symmetry plane). On the other hand, since only one grade is available, the intermediate-ply laminate, hereafter referred to as NCF-INT, is obtained blocking the plies with the same orientation when possible. Selective ply-level hybridisation is obtained dispersing the off-axis plies and grouping, as possible, the 0° plies. The corresponding hybrid laminate will be referred to as NCF-HYBRID.

Table 1 shows the final laminates selected for the ply-level hybridisation study, where the 0° fibre orientation is coincident with the loading direction. The laminates’ nominal thickness is 1.80 mm for the NCF laminates and ranges between 1.92 mm for the STF-THIN and STF-INT laminates and 2.24 mm for the STF-HYBRID laminate.

| Table 1 about here. |

All specimens were cut to nominal dimensions using a diamond-coated disk. The holes of the specimens were drilled using drill bits with the required diameters. Two sacrificial plates of a similar carbon/epoxy laminate were used between the machined specimens to avoid damaging the outer plies in the machining process.

2.2. Ply thickness effect study

Open-hole tension tests were performed on specimens with a centrally located hole with different in-plane dimensions, scaled by a factor between 2 and 6, to study the hole size effect. All tests were carried out under displacement control, at a controlled speed of 1 mm/min, in an INSTRON 4208 electro-
mechanic universal testing machine equipped with a 100 kN load cell. Wedge grips were used to hold and load the specimens.

Table 2 shows the test matrix of the ply thickness and hole size effects study, where $L$ is the specimens’ length, $W$ is the specimens’ width, and $d$ is the hole diameter. This table includes the results obtained by Amacher et al. [7] in a previous study. The width-to-hole diameter ratio ($W/d$) is kept constant and equal to 6.

After testing, the notched strength $\bar{\sigma}^\infty$ of each specimen is calculated as:

$$\bar{\sigma}^\infty = \frac{P_{\text{max}}}{A}$$

where $P_{\text{max}}$ is the maximum applied load during the test, measured by the load cell, and $A = W \times t$ is the cross-sectional area of the specimen.

2.3. Ply-level hybridisation

2.3.1. Unnotched tension tests

Unnotched tension tests were carried out on all STF and NCF laminates, following the ASTM D3039/D3039M – 14 test standard [12]. The unnotched tension tests were performed under displacement control, at a speed of 1 mm/min, in an MTS 810 servo-hydraulic testing machine equipped with a 250 kN load cell. Coarse-grain sandpaper was used between the specimen and the bolted grips to avoid sliding. The grips were clamped by six M10 bolts fastened with a torque of 45 Nm.

The unnotched specimens have a nominal width of 25 mm and a nominal length of 300 mm. After testing, the unnotched tensile strength $X^L_T$ is calculated as:

$$X^L_T = \frac{P_{\text{max}}}{A}$$
2.3.2. Open-hole tension tests

Open-hole tension tests were performed on scaled specimens with three different sizes but the same width-to-hole diameter ratio \( W/d = 6 \). The dimensions of the specimens are presented in table 3. All tests were carried out under displacement control, at a controlled speed of 1 mm/min. The STF specimens were tested in an INSTRON 4208 electro-mechanic universal testing machine equipped with a 300 kN load cell. Hydraulic grips were used to hold the specimens in the loading frame. The NCF specimens were tested in a servo-hydraulic MTS 810 testing machine equipped with a 250 kN load cell.

[Table 3 about here.]

2.3.3. Open-hole fatigue tests

Given the major effect of ply thickness on the behaviour of notched laminates subjected to cyclic loading, it is deemed important to assess how the fatigue response is affected by ply-level hybridisation. Hence, open-hole fatigue tests were also performed. Fatigue tests were carried out on the 30 mm wide notched configuration, with a hole diameter of 5 mm. Three specimens of each laminate were tested. Following Amacher et al. [7], the specimens were subjected to a sinusoidal loading, under load control, with a frequency of 2 Hz, a peak stress corresponding to 70% of the quasi-static notched strength, and a load ratio \( R = 0.1 \). All specimens were subjected to a maximum of 50000 loading cycles, followed by visual inspection for external damage assessment. An estimate of the stiffness reduction of each specimen was obtained by monitoring the relative applied displacement between the maximum and minimum load (sinusoid’s peak and valley, respectively), \( \Delta u = \Delta u|_{P_{max}}^{P_{min}} \), measured by the LVDT of the testing machine:

\[
1 - \frac{E_d}{E_i} = 1 - \frac{\Delta u_i}{\Delta u_d}
\]  

(3)
where index i refers to the undamaged specimen and index d refers to the damaged specimen. All fatigue tests were performed in a servo-hydraulic MTS 810 loading frame equipped with a 250 kN load cell.

2.4. Digital image correlation

The digital image correlation (DIC) technique was used in the quasi-static tests to evaluate the displacement and strain fields of the outer plies, and assess damage formation at the straight free edges and notch boundaries. The ARAMIS DIC-2D v6.0.2 developed by GOM [13] was used. The adopted configuration and the measuring parameters, which lead to an expected spatial resolution in the order of $2 \times 10^{-2}$ pixels and a strain resolution in the range 0.01-0.04% [14], are summarised in tables 4 and 5.

[Table 4 about here.]

[Table 5 about here.]

Before testing, the observation surface of each specimen analysed with the DIC system was polished by hand using sandpaper and cleaned with acetone. This prevents the specimen’s surface texture from influencing the quality of the applied speckle patterns [15]. The smoothed surfaces were then painted using white matte ink, and a pattern of black spots was applied using an airbrush (Iwata Custom 181 Micron CM-B model) with a fluid nozzle of 0.18 mm in diameter, or using aerosol spray, depending on the specimen’s size.

Two white light sources were used to ensure an even illumination of the specimen’s surface and to avoid over-exposition (i.e., the saturation of pixels over the field of view) [16, 17]. The shutter time was set in the range of 5.0–18.0 ms, maximising the grey level distribution over the 8-bit dynamic range of the camera while avoiding saturation of the image [15]. The working distance, defined between the specimen’s surface and the support of the camera, was set in the range of 375–900 mm, depending on the size of the region of interest (table 5). The acquisition frequency was set to 1 Hz in all specimens.
3. Experimental results and discussion

3.1. Effect of ply thickness

Amacher et al. [7] conducted unnotched tension tests on the same laminates manufactured from M40JB/ThinPreg™ 80EP/CF carbon/epoxy. The ultimate strength of the unnotched specimens increased 39% and 42% when decreasing the grade of the UD plies from 300 g/m² to 100 g/m² and 30 g/m², respectively. These results were attributed to an increased stability of intralaminar cracking in the transverse and angle plies close to the free edges and to the suppression of damage propagation until fibre fracture in the 0° plies.

Amacher et al. [7] also identified the stress at the onset of damage (first-ply-failure) by acoustic emission monitoring. A large increase (of about 230%) was reported for the stress at the onset of damage when decreasing the grade of the UD plies from 300 g/m² to 30 g/m². In order to clarify the nature of this size effect, Amacher et al. [7] tested thick-ply laminates produced from blocks of 30 g/m² ultra-thin plies and from 300 g/m² plies. No substantial difference was found between these two laminates, demonstrating that the observed size effect is not related to changes in intrinsic ply properties, but to a deterministic in situ effect [18]. For intermediate ply thicknesses, a linear trend was reported [7]. Additionally, it was observed that, for the laminates with the thinnest plies, the onset of damage occurred at a stress just 3% lower than the ultimate stress, and nearly no damage could be identified before final failure.

The role of ply thickness on damage growth in notched coupons is similar to that observed in the unnotched specimens, but with a more profound effect on the structural response due to the presence of the stress concentration. This is clearly observed in figures 1 and 2, which show, respectively, for each laminate, representative specimens of the different geometries after testing and the surface strain fields for specimens with the 2 mm diameter hole at the last stage before failure. Specimens of different ply thickness show different failure modes. In addition, different failure modes may also occur as the geometry changes.
Generally, the THIN laminate (figure 1a) exhibits a brittle type of net-section failure mode, where subcritical damage such as transverse cracking or delamination is absent. Observing figure 2a, it can be seen that, before final fracture, damage is restricted to the hole free edge. Furthermore, in spite of having a 45° surface ply, intralaminar damage propagates in a plane perpendicular to the loading direction, and not parallel to the fibres. This is a clear evidence of the damage suppression capability of thinner plies, which can be particularly advantageous in the case of cyclic loading or in cases of load reversal.

The INT specimens (figure 1b) have a fibre-dominated pull-out failure mode, where delaminations with a triangular shape across the width and matrix and splitting cracks in the 45° outer layers were present. Observing figure 2b, matrix cracks in the 45° surface ply, propagating along the fibre direction, can be identified before final fracture, starting where the fibre direction is tangent to the hole free edge (compare with figure 2a). Therefore, by increasing the ply thickness from the ultra-thin 0.03 mm (THIN laminate) to the low grade 0.10 mm (INT laminate), a modification of the failure mode has occurred, in particular for the wider specimens, which changed from brittle to pull-out failure, including subcritical damage.

For the THICK and THICK - PLY LEVEL laminates (figures 1c and 1d), a totally different, matrix-dominated failure mode, common to all specimen geometries, is observed, characterised by progressive, multi-mode damage [7]. Before fibre fracture of the 0° plies, extensive delamination has occurred, extending across the entire gauge section and terminating at the end tabs. The ±45° and 90° plies failed due to transverse cracking. Observing figures 2c and 2d, it can be seen that matrix cracks in the 45° outer ply, starting where the fibre direction is tangent to the hole free edge and propagating along the fibre direction, extend across the specimens’ width, terminating at the straight free edges. It means that the outer 45° ply, as well as the inner 90° and −45° plies, have failed before the specimen final fracture, separating from the 0° plies. Be-
fore failure of the 0° ligaments, the specimens had lost their structural integrity. It is assumed that the laminate has failed at this point.

The mean values of the notched strengths obtained in the experimental tests for each laminate and geometry, and corresponding coefficients of variation (C.V.), are given in table 2. These results are also plotted in figure 3 as a function of the hole diameter. As can be observed, the notched strengths of the THIN and INT laminates increase as the hole diameter decreases. However, the INT laminate has higher notched strengths than the THIN laminate, independently of the specimens’ geometry. These results can be explained by the differences in the failure modes. In the THIN laminate, early subcritical damage is suppressed and the onset of damage delayed until the ultimate stress is reached [7], preventing local stress redistribution at the hole boundaries. As the hole diameter increases, the relative size of the damage process zone compared with the dimensions of the open hole becomes smaller, decreasing the blunting effect and, consequently, resulting in the brittle type of net-section failure mode shown in figure 1a. On the other hand, the development of subcritical damage mechanisms in the INT laminate before fibre-dominated pull-out failure leads to a blunting effect in the regions of higher stress concentration, delaying unstable net-section intralaminar fracture.

It is interesting to note that, as the hole diameter becomes smaller, the notched strengths of the THIN and INT laminates tend to the same value; moreover, the failure modes of both laminates and the extent of subcritical damage become similar (see figures 1a and 1b). For this geometry, the ligament width is so small that delaminations quickly propagate across the width of the specimens in both laminates, and the effect of ply thinness becomes less important. A small difference between the strengths of the THIN and INT laminates was also observed on the unnotched coupons [7], with the THIN laminate performing slightly better in this case.

Regarding the laminates with thick plies, both THICK and THICK - PLY
LEVEL laminates exhibit an inverse size effect, which was originally reported in Refs. [1, 2]. As the hole diameter increases, the ligament width increases too, and delamination propagation across the specimens’ width is more difficult. The stress field at the hole edge is severely modified due to the development of extensive subcritical damage across the gauge section. Consequently, the notched strengths increase, becoming higher than the notched strengths of the laminates with thinner plies (table 2), tending to the strengths of a notch-insensitive material. Nevertheless, the development of large-scale subcritical damage, in particular delamination, which may propagate extensively in finite, abrupt steps, is typically highly undesirable due to the early loss of structural integrity and due to the severe reduction of the laminates’ residual strength.

Amacher et al. [7] also studied the effect of ply thickness on the response to open-hole tensile fatigue. Very significant improvements for the onset of damage and, in some cases, ultimate strength were obtained when decreasing the ply thickness. This was related to a major change in the damage progression and failure modes of the laminates, caused by a systematic delay or even suppression of transverse cracking and delamination growth in thin-ply laminates, resulting in no stiffness degradation nor damage occurrence. Thick-ply laminates, on the other hand, exhibited a progressive damage accumulation by delamination and transverse/shear cracking of the 90° and ±45° plies, resulting in a clear fatigue life reduction trend. It is therefore clear that using thin plies delays the onset of damage, resulting in a substantial increase of the fatigue lifetime [7].

3.2. Discussion

Previous studies about the effect of ply thickness on the tensile unnotched and notched response of advanced composite laminates [1, 2, 6, 19-21] have clearly identified a trend regarding the relation between ply thickness and the damage mechanisms and failure modes observed in a multidirectional laminate, and how they affect its unnotched and notched response. Such studies have been complemented by the work presented in section 3.1 with laminates made from UD tapes of different grades that vary in a tenfold range. The main findings
are:

- Laminates with thick plies, or thick ply blocks, exhibit a severe unnotched strength reduction when compared to laminates with tow-spread or conventional low grade plies dispersed in sublaminate repetitions [7, 19]. In notched coupons, delamination, which is the predominant failure mechanism, easily propagates across the specimen’s width [1, 2], blunting the stress concentration at the notch edge and conducting to higher notched strengths. However, laminates generally fail due to complete gauge section delamination of the interface between the $0^\circ$ and its adjacent plies [1, 20], resulting in premature delamination failure, early loss of structural integrity, and a drastic reduction of the fatigue life [7].

- Laminates with conventional low grade plies, stacked in sublaminate repetitions, exhibit higher unnotched strength when compared with laminates with thick plies, with no load drops or visual indications of damage prior to ultimate failure [19]. In notched coupons, the failure stress is also reached before extensive delamination growth [1, 2]. The development of subcritical damage mechanisms before fibre-dominated pull-out failure leads to a blunting effect in the regions of higher stress concentration, delaying unstable net-section intralaminar fracture.

- Laminates with tow-spread thin plies exhibit slightly higher unnotched strengths compared to laminates with conventional low grade plies [7]. First-ply-failure is delayed until the ultimate stress, and nearly no damage can be identified before final failure. In notched coupons, this strong damage suppression capability prevents local stress redistribution at the hole boundary, conducting to a brittle type of net-section failure mode and to lower strengths when compared with conventional low grade plies.

From the previous observations, it becomes clear that controlling the damage mechanisms and failure modes in multidirectional laminates by means of ply thickness scaling across the laminate can be used as a solution to achieve
a better compromise between the unnotched and notched responses. For instance, incorporating plies of different thicknesses in the same laminate has the potential to improve its notched response through localised growth of subcritical damage, without deteriorating excessively its unnotched strength, structural integrity and fatigue resistance. In addition, there are also advantages in design, such as faster lay-up and lower material cost due to the introduction of high grade materials. This is the principle behind the concept of ply-level hybridisation. Plies of the same material system but of different grades can be combined to trigger specific damage mechanisms. Laminates with intermediate unnotched and notched responses can be easily designed to target a given application. It is important to stress that, based on the previous observations, to avoid complete gauge section delamination, and therefore preclude early loss of structural integrity and low fatigue resistance, very thick plies should not be considered in the hybrid laminate design process.

Ply-level hybridisation can be more effectively done by including thin plies in the hybrid laminate design process, as their addition allows higher flexibility in terms of laminate thickness design (thin plies can be incorporated in the outer layers of a laminate to more finely achieve the desired laminate thickness), and because the laminate regions with thin plies will be less susceptible to subcritical damage [22], ensuring that pre-failure damage will only grow at the desired locations across the laminate thickness. Moreover, Arteiro et al. [6] demonstrated that by proper laminate design with thin plies it is possible to decrease the notch sensitivity while reducing the development of subcritical damage, such as delamination and matrix cracking, to a minimum.

To explore this hypothesis two concepts are introduced: uniform ply-level hybridisation and selective ply-level hybridisation.

3.3. Uniform ply-level hybridisation

A hybrid quasi-isotropic laminate combining T700SC/M21 STFs with areal weights of 160 g/m² and 240 g/m² is compared with equivalent thin-ply and intermediate-ply configurations including only 160 g/m² or 240 g/m² STFs (ta-
ble 1). Here, the concept of uniform ply-level hybridisation is explored, where plies of different grades are combined along all fibre orientations. In order to maximise the structural integrity of the hybrid laminate while ensuring an adequate blunting effect caused by subcritical damage growth, the intermediate-ply sublaminate region is placed in the core of the laminate and the thin-ply sublaminates in the outer layers. This avoids early outer ply failure [18] and ensures that subcritical damage growth, which is expected to occur mainly across the intermediate-ply sublaminate region, is always confined.

3.3.1. Experimental results

After testing, the STF-THIN unnotched specimens exhibit a brittle type of net-section failure mode, with a failure section perpendicular to the loading direction (figure 4a). The STF-INT and STF-HYBRID specimens (figures 4b and 4c respectively), show a fibre-dominated pull-out failure mode, with split cracking along the $0^\circ$ spread tow yarns and delamination between the STF layers. Monitoring the surface longitudinal strain field of representative specimens, measured with the DIC technique, small transverse cracks can be identified at the free edges of the 240 g/m$^2$ outer $90^\circ$ spread tow yarns of the STF-INT laminate before ultimate failure (figure 5a). Transverse cracking along the outer plies of the STF-THIN and STF-HYBRID laminates, which have 160 g/m$^2$ outer STFs, was totally precluded (figure 5b).

[Figure 4 about here.]

[Figure 5 about here.]

The notched specimens all show a fibre-dominated pull-out failure mode after testing, with a failure section perpendicular to the loading direction (figure 6). However, the STF-INT and STF-HYBRID laminates (figures 6b and 6c respectively) exhibit a more diffuse fracture surface, with matrix splitting and local delaminations across the ligament width in a greater extent when compared with the open-hole specimens of the STF-THIN laminate (figure 6a). It is interesting to note that, as expected, extensive gauge section delamination was
not observed in the unnotched and notched coupons of the STF laminates, and the structural integrity of the laminates was not affected until the ultimate failure stress was reached.

[Figure 6 about here.]

The mean values of the tensile unnotched and notched strengths of the STF laminates, and respective coefficients of variation, are presented in table 6. Despite the different failure modes, the tensile unnotched behaviour of these laminates is virtually the same; the STF-THIN specimens have a tensile unnotched strength only 1.57% higher than the STF-INT specimens, whereas the unnotched strength of the STF-HYBRID laminate is 1.70% and 0.14% lower than the STF-THIN and STF-INT laminates, respectively.

[Table 6 about here.]

As expected, the notched strengths of the STF laminates increase as the hole diameter decreases (figure 7). However, the STF grade has clearly an effect on the notched response of the tested laminates. The intermediate-ply STF-INT laminate exhibits higher notched strengths than the thin-ply STF-THIN laminate (9.3%, 14.0% and 7.6% higher for specimens with $d = 2 \text{ mm}$, $d = 5 \text{ mm}$ and $d = 8 \text{ mm}$, respectively). Combination of the two grades in the hybrid STF-HYBRID laminate resulted in an intermediate response, with higher notched strengths than the thin-ply laminate (2.9%, 5.4% and 6.2% higher for $d = 2 \text{ mm}$, $d = 5 \text{ mm}$ and $d = 8 \text{ mm}$, respectively), but lower notched strengths than the intermediate-ply laminate (5.8%, 7.6% and 1.3% lower for $d = 2 \text{ mm}$, $d = 5 \text{ mm}$ and $d = 8 \text{ mm}$, respectively).

[Figure 7 about here.]

The intermediate behaviour of the STF-HYBRID laminate shows that the intermediate-ply sublamine block combined with thin-ply sublaminates successfully redistributed the stresses at the vicinity of the notch by means of local
subcritical damage growth, blunting the notch and reducing the stress concentration more effectively than the thin-ply STF-THIN laminate. This can be observed in figure 8, which shows the surface longitudinal strain field obtained with the DIC technique from representative open-hole specimens with a 5 mm diameter hole loaded at 90% of the corresponding average notched strengths. Whereas the STF-THIN specimen (figure 8a) shows high strain concentration at the hole boundary, without signs of subcritical damage growth, the STF-INT specimen (figure 8b) shows a diffuse strain concentration, indicating the occurrence of internal subcritical damage near the hole boundary. The STF-HYBRID laminate (figure 8c), in spite of having a thin, 160 g/m² outer STF, shows an intermediate response, with signs of subcritical damage growth from the hole boundary, perpendicularly to the applied load.

[Figure 8 about here.]

It should be noted that, at the vicinity of geometrical discontinuities, high strain concentrations can occur due to the shear stresses generated, for instance inducing plasticity in the matrix, without being necessarily linked to intralaminar cracking, as observed in figure 8a for the thin-ply laminate. Nevertheless, a discontinuity of the strain field as observed respectively in figures 8b and c for the intermediate-ply and hybrid laminates, unambiguously indicate the development of a fracture process zone, which even though can be linked to other inelastic deformation mechanisms such as plasticity, results mainly from intralaminar damage mechanisms such as transverse cracking parallel to the fibres or longitudinal fibre breakage. It should be noted that assessing damage development, for instance from the edges, in woven composites using only surface full-field measurements obtained from DIC are not necessarily representative of the damage state within the material, and that alternative online damage detection techniques such as acoustic emission, as used by Amacher et al. [7], or post-testing analysis using, for example, X-ray tomography, would provide more accurate data. Even though the authors recognise that this surface information needs to be considered carefully, it provides a preliminary assessment that helps
understanding the differences in terms of damage development in the different laminate configurations.

The effect of ply-level hybridisation on the evolution of damage in notched laminates can be further assessed by monitoring their notched response in fatigue. Table 6 shows the mean stiffness reduction after 50000 loading cycles for the STF notched coupons with a 5 mm diameter hole. When compared with quasi-static loading, an inversion of the mechanical performance is observed, with the thin-ply STF-THIN laminate exhibiting a considerably lower stiffness reduction, indicating that limited damage growth has occurred during the cyclic loading. As before, the STF-HYBRID laminate exhibited an intermediate response. Whereas no visible damage could be observed in the STF-THIN specimens after 50000 loading cycles, the STF-INT and STF-HYBRID laminates show some split cracking near the hole (figure 9). It is interesting to note that the same damage mechanisms that improve the quasi-static notched response of laminates have a detrimental effect on the fatigue response. The use of hybrid laminate configurations, which give intermediate quasi-static and fatigue responses, is an interesting solution to design composite structures for applications where both loading configurations are important design drivers.

Taking into account that the results of uniform ply-level hybridisation were obtained from laminates with a textile reinforcement architecture, they should be regarded cautiously. Nevertheless, due to the special architecture of the STFs, characterised by high uniformity of the individual tows, low crimp angles, low tow waviness and reduced interlacing regions with small resin rich areas between the tows, and whose mechanical response approaches more closely the performance of UD tapes than conventional textile composites [8–11], the present results provide sufficient insight into the effect of uniform ply-level hybridisation, in particular the possibility to tailor the structural response of a laminate by incorporating reinforcements of different grades.
3.4. Selective ply-level hybridisation

Erçin et al. [21] observed that fibre-matrix splitting in the 0° plies acts as an important notch blunting mechanism, improving the notched strength of partially blocked-ply laminates when compared with dispersed-ply laminates of the same material system. In addition, the stress redistribution due to the formation of longitudinal splitting alone was addressed numerically and compared with experiments by Iarve et al. [23], showing its importance for the notched strength of laminates. The detrimental effect of longitudinal splitting on the unnotched strength of laminates is more moderate, with transverse cracking and delamination playing a substantially more important role in this case [7].

Xu et al. [24, 25] have recently shown that thicker 0° plies promote the propagation of longer splits before local fibre breakage, blunting the stress concentration at the crack tips in a greater extent than in single 0° plies. This crack restraining effect in thick 0° plies results in an apparent increase of the fracture toughness, which must be attributed to the development of a large damage process zone containing substantial splitting and local delamination.

To promote longitudinal fibre-matrix splitting while limiting the occurrence of transverse matrix cracking and delamination, ply-level hybridisation is performed by selectively grouping only the 0° plies, namely those in the inner sublamine regions of the hybrid laminate, to avoid early outer ply failure [18] and to ensure that subcritical damage growth is always confined, as discussed in section 3.3. Ultimately, a truly selective hybrid laminate could be obtained combining high or intermediate grade 0° plies with tow-spread off-axis plies.

For comparison, two NCF baseline laminates, where plies of the same orientation are either dispersed across the laminate or blocked together, are also studied. The thin-ply NCF-THIN and blocked-ply NCF-INT quasi-isotropic T700GC/M21 laminate configurations (table 1) have an effective ply thickness of 0.075 mm and 0.150 mm, respectively, while the hybrid NCF-HYBRID quasi-isotropic T700GC/M21 laminate has 0.075 mm thick plies combined with 0.150 mm thick blocks of 0° plies.
3.4.1. Experimental results

After testing (figure 10), the NCF-THIN unnotched specimens exhibit a net-section failure mode, with a failure section perpendicular to the loading direction. Some diffuse damage close to the fracture plane can also be observed, apparently caused by the catastrophic type of failure exhibited by this laminate configuration. The NCF-INT and NCF-HYBRID specimens show a fibre-dominated pull-out failure mode, including some delamination and a diffuse fracture plane.

Monitoring the surface longitudinal strain field of representative specimens, measured with the DIC technique (figure 11), it can be seen that no free-edge transverse cracking in the outer 90° plies has occurred before ultimate failure. It is important to note that all NCF laminates have a thin outer 90° ply with the same thickness (see table 1), and similar results for the occurrence of surface transverse cracking were expected. However, small discontinuities in the NCF-INT laminate (figure 11b) and, less importantly, in the NCF-HYBRID laminate (figure 11c) can be seen at the free edges, indicating that internal transverse damage growth has occurred, starting at and propagating from the free edges. This may justify the diffuse fracture plane observed in these laminates, particularly in the NCF-INT laminate.

All notched specimens show a fibre-dominated pull-out failure mode (figure 12). Only the larger NCF-THIN laminates exhibit a brittle failure section, approximately perpendicular to the loading direction (figure 12a). The remaining specimens show transverse fracture planes along the off-axis plies, specially the NCF-INT specimens (figure 12b), with matrix splitting and local delaminations across the ligament width. The occurrence of internal subcritical damage near the hole boundary can be identified observing the surface longitudinal strain field of representative open-hole specimens. Figure 13 shows the surface longitudinal strain field of representative specimens with a 5 mm diameter hole
loaded at 90% of the corresponding average notched strengths, obtained with the DIC technique. Even though the outer transverse ply of the NCF laminates has the same thickness, the NCF-INT and NCF-HYBRID laminates (figures 13b and 13c) have a more diffuse strain concentration in the vicinity of the hole compared to the NCF-THIN laminate (figure 13a). Taking into account that surface transverse damage cannot be observed in any of the NCF laminate configurations, this diffuse strain concentration is probably caused by internal damage growth in the NCF-INT and NCF-HYBRID laminates.

[Figure 12 about here.]

[Figure 13 about here.]

The clear transverse fracture planes along the off-axis plies exhibited by the NCF-INT laminate across all specimen geometries (figure 12b) results from the fact that this laminate includes thicker off-axis plies (table 1), with lower in situ strengths, promoting early failure along these directions. Interestingly, the NCF-HYBRID laminate (figure 12c) exhibits the most diffuse failure mode. This is possibly caused by internal growth of longitudinal split cracking along the thicker 0° ply blocks while suppressing transverse cracking due to the off-axis plies thinness, blunting the notch and redistributing the stress concentration more effectively along the loading direction. As in the STF laminates, no extensive gauge section delamination is observed in the unnotched and notched coupons (figures 10 and 12 respectively).

The mean values of the tensile unnotched and notched strengths of the NCF laminates, and respective coefficients of variation, are presented in table 7. As reported elsewhere [6, 7], dispersed thin-ply laminates have higher unnotched tensile strength than blocked-ply laminates, a result confirmed by the present study, with the thin-ply NCF-THIN specimens exhibiting a mean unnotched tensile strength 11.1% higher than the NCF-INT specimens. However, selectively blocking the 0° plies in a thin-ply laminate with dispersed off-axis plies results in an unnotched strength that is virtually the same of the fully dispersed
thin-ply laminate (the mean unnotched strength of the tested NCF-HYBRID specimens is only 0.9% lower than the NCF-THIN specimens). This is the expected result as long as the 0° ply block thickness is small enough to avoid gauge section delamination from the longitudinal split cracks. Because all off-axis plies have the same thickness, the in situ effect is the same. In addition, the UD tensile strength of a ply in the direction of the fibres ($X_T$) is not a function of the ply thickness, with no effect on the strength of the laminate.

The notched strengths of the tested NCF laminates increase as the hole diameter decreases (figure 14). As opposed to the unnotched response, the thinly NCF-THIN laminate shows lower notched strength than the blocked-ply NCF-INT laminate (5.9%, 2.2% and 5.9% lower for specimens with $d = 2$ mm, $d = 5$ mm and $d = 8$ mm, respectively). On the other hand, the selected hybrid laminate (NCF-HYBRID) revealed a higher notched strength than both thinly and blocked-ply laminates (10.1%, 9.8% and 11.4% higher than the NCF-THIN laminate and 3.6%, 7.4% and 4.8% higher than the NCF-INT laminate for $d = 2$ mm, $d = 5$ mm and $d = 8$ mm, respectively). It is argued that selective ply-level hybridisation of the 0° plies effectively promoted fibre splitting while suppressing damage in the 45° and 90° plies. The stress redistribution along the loading direction, which limited detrimental damage growth in the vicinity of the notch, successfully enhanced the tensile notched strength of the composite laminate.

The effect of selective ply-level hybridisation on the evolution of damage in notched laminates can be further assessed by monitoring their fatigue response. Table 7 shows the mean stiffness reduction after 50000 loading cycles for the NCF notched coupons with a 5 mm diameter hole. Similarly to what was observed in the STF laminates (section 3.3), the NCF-HYBRID laminate shows an intermediate fatigue response. This intermediate response is the result of
the internal damage growth that occurs in this laminate. Whereas negligible damage is expected to occur in the NCF-THIN specimen, internal longitudinal splitting in the NCF-HYBRID laminate is likely to reduce the overall laminate stiffness as it grows due to the applied cyclic load. Still, the consequences of this stable damage growth is not as severe as in the case of the NCF-INT laminate, which exhibits the lowest fatigue performance (table 7), caused not only by the propagation of split cracks but also by local delamination growth and matrix cracking. This becomes clear observing figure 15, which shows the NCF-INT and NCF-HYBRID laminates after fatigue testing. Small transverse splits can be observed in the outer ply of both laminates, as well as local delamination at the free edge of the open hole of the NCF-INT laminate (figure 15b).

[Figure 15 about here.]

4. Conclusions

Open-hole tension tests were performed on specimens with a centrally located hole with different in-plane dimensions, scaled by a factor between 2 and 6, to study the hole size effect on laminates with different ply thicknesses. In general, the thin-ply laminate exhibited a net-section failure mode, where sub-critical damage such as transverse cracking or delamination was absent. The laminate with plies of intermediate thickness exhibited a fibre-dominated pull-out failure mode, with extensive sub-critical damage. The thick-ply laminates exhibited a matrix-dominated failure mode, characterised by extensive gauge section delamination and matrix cracking in the $\pm 45^\circ$ and $90^\circ$ plies, losing their structural integrity well before failure of the $0^\circ$ ligaments. An inverse size effect was found for the thick-ply laminates, as already described elsewhere [1, 2]. No differences were found in the notched response of thick-ply laminates manufactured with 300 g/m$^2$ plies or by blocking together ten 30 g/m$^2$ plies with the same fibre orientation.

From the understanding of the effect of ply thickness on the structural behaviour of composite laminates, it became clear that controlling the damage
mechanisms and failure modes in multidirectional laminates by means of ply thickness scaling across the laminate can be used as a solution to achieve a better compromise between their unnotched and notched responses, and to understand how thin-ply laminates can be used to their full potential. Combining thin plies and conventional plies of intermediate thickness along all fibre orientations resulted in a hybrid laminate with intermediate unnotched and notched responses, which can be tailored for specific applications. This intermediate behaviour results from subcritical damage suppression in the outer thin-ply sublaminate region, accompanied by stable internal damage growth across the inner intermediate-ply sublaminate region, which is responsible for redistributing the stresses at the vicinity of the notch, reducing the stress concentration. This is valid for both static and fatigue loading conditions.

Selective ply-level hybridisation, where thin off-axis plies are combined with $0^\circ$ plies of intermediate thickness, resulted in an unnotched response equivalent to the thin-ply laminate of the same material system, and enhanced the quasi-static notched response as compared to the blocked-ply laminate. The use of sufficiently thin off-axis plies ensures that transverse cracking and delamination can be delayed or even suppressed before ultimate failure, an effect observed in both notched and smooth coupons. Combined with thicker $0^\circ$ plies, as long as the $0^\circ$ ply block thickness is small enough to avoid gauge section delamination from the longitudinal split cracks, the unnotched tensile strength will be unchanged when compared with a fully dispersed thin-ply laminate. In notched specimens, the thick $0^\circ$ ply block promotes longitudinal split cracking in the regions of high stress concentration at the vicinity of a notch, resulting in a stress redistribution along the loading direction. Because damage in the thin off-axis plies is suppressed, detrimental damage growth in the vicinity of the notch is limited, enhancing the tensile notched strength of the composite laminate when compared with a fully blocked-ply laminate and with a laminate with only thin plies. The internal damage growth promoted by the thick $0^\circ$ ply block results in an intermediate open-hole fatigue response; still, the stiffness reduction was considerably below that observed in the blocked-ply laminate.
This work shows how ply-level hybridisation, when designed to trigger specific damage mechanisms, can result in a globally enhanced laminate response, overcoming some of the disadvantages related with the quasi-static notched behaviour of thin-ply composites, without compromising the unnotched and fatigue responses. The fact that combining thin off-axis plies with thicker $0^\circ$ plies increases the notched strength compared to laminates with ply-blocking and thin plies might be the solution to overcome the reduced tensile strength of thin-ply composites in the presence of stress concentrations.

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tigation of stress redistribution in open hole composite laminates due to 

vestigation into size effects in quasi-isotropic carbon/epoxy laminates with 

response in Over-height Compact Tension tests, Compos Part A-Apppl S 69 
List of Figures

1  Representative unnotched specimens after testing. .......................... 31
2  Surface longitudinal strain field ($\varepsilon_y$) of representative specimens with the 2 mm diameter hole, obtained with the DIC technique at the stage before failure. The reference DIC coordinate system is depicted in the figures, where the y-direction is coincident with the loading direction. ................................................................. 32
3  Notched response of the M40JB/ThinPreg$^\text{TM}$ 80EP/CF laminates. 33
4  Close-up of the fracture plane of representative T700SC/M21 STF unnotched specimens after testing. ................................................................. 34
5  Surface longitudinal strain field ($\varepsilon_x$) and local longitudinal strain measured along the edges of the outer ply of representative unnotched tension test specimens of the T700SC/M21 STF laminates, obtained with the DIC technique before ultimate failure. The reference DIC coordinate system is depicted in the figures, where the x-axis is aligned with the loading direction. ..................................................... 35
6  Representative T700SC/M21 STF notched specimens after testing. 36
7  Notched response of the T700SC/M21 STF laminates. .......................... 37
8  Surface longitudinal strain field ($\varepsilon_x$) and local longitudinal strain tangent to the hole boundary along the loading direction of representative open-hole tension test specimens with a 5 mm diameter hole of the T700SC/M21 STF laminates, obtained with the DIC technique at 90% of the ultimate stress. The reference DIC coordinate system is depicted in the figures, where the x-axis is aligned with the loading direction. ..................................................... 38
9  Representative T700SC/M21 STF open-hole specimens after fatigue testing. ................................................................. 39
10 Close-up of the fracture plane of representative T700GC/M21 NCF unnotched specimens after testing. 40
11 Surface longitudinal strain field ($\varepsilon_x$) and local longitudinal strain measured along the edges of the outer ply of representative unnotched tension test specimens of the T700GC/M21 NCF laminates, obtained with the DIC technique before ultimate failure. The reference DIC coordinate system is depicted in the figures, where the x-axis is aligned with the loading direction. ..................................................... 41
12 Representative T700GC/M21 NCF notched specimens after testing. 42
13 Surface longitudinal strain field ($\varepsilon_x$) and local longitudinal strain tangent to the hole boundary along the loading direction of representative open-hole tension test specimens with a 5 mm diameter hole of the T700GC/M21 NCF laminates, obtained with the DIC technique at 90% of the ultimate stress. The reference DIC coordinate system is depicted in the figures, where the x-axis is aligned with the loading direction. ..................................................... 43
14 Notched response of the T700GC/M21 NCF laminates. .......................... 44
Representative T700GC/M21 NCF open-hole specimens after fatigue testing.
Figure 1: Representative unnotched specimens after testing.
Figure 2: Surface longitudinal strain field ($\varepsilon_y$) of representative specimens with the 2 mm diameter hole, obtained with the DIC technique at the stage before failure. The reference DIC coordinate system is depicted in the figures, where the $y$-direction is coincident with the loading direction.
Figure 3: Notched response of the M40JB/ThinPreg\textsuperscript{TM} 80EP/CF laminates.
Figure 4: Close-up of the fracture plane of representative T700SC/M21 STF unnotched specimens after testing.
Figure 5: Surface longitudinal strain field ($\varepsilon_x$) and local longitudinal strain measured along the edges of the outer ply of representative unnotched tension test specimens of the T700SC/M21 STF laminates, obtained with the DIC technique before ultimate failure. The reference DIC coordinate system is depicted in the figures, where the $x$-axis is aligned with the loading direction.
Figure 6: Representative T700SC/M21 STF notched specimens after testing.
Figure 7: Notched response of the T700SC/M21 STF laminates.
Figure 8: Surface longitudinal strain field ($\varepsilon_x$) and local longitudinal strain tangent to the hole boundary along the loading direction of representative open-hole tension test specimens with a 5 mm diameter hole of the T700SC/M21 STF laminates, obtained with the DIC technique at 90% of the ultimate stress. The reference DIC coordinate system is depicted in the figures, where the $x$-axis is aligned with the loading direction.
Figure 9: Representative T700SC/M21 STF open-hole specimens after fatigue testing.
Figure 10: Close-up of the fracture plane of representative T700GC/M21 NCF unnotched specimens after testing.
Figure 11: Surface longitudinal strain field ($\varepsilon_x$) and local longitudinal strain measured along the edges of the outer ply of representative unnotched tension test specimens of the T700GC/M21 NCF laminates, obtained with the DIC technique before ultimate failure. The reference DIC coordinate system is depicted in the figures, where the x-axis is aligned with the loading direction.
Figure 12: Representative T700GC/M21 NCF notched specimens after testing.
Figure 13: Surface longitudinal strain field ($\varepsilon_x$) and local longitudinal strain tangent to the hole boundary along the loading direction of representative open-hole tension test specimens with a 5 mm diameter hole of the T700GC/M21 NCF laminates, obtained with the DIC technique at 90% of the ultimate stress. The reference DIC coordinate system is depicted in the figures, where the $x$-axis is aligned with the loading direction.
Figure 14: Notched response of the T700GC/M21 NCF laminates.
(a) NCF-INT laminate.

(b) NCF-HYBRID laminate.

Figure 15: Representative T700GC/M21 NCF open-hole specimens after fatigue testing.
List of Tables

1 Laminate stacking sequences used in the ply-level hybridisation study. Bold characters are used to highlight the thick-ply building blocks. ........................................ 47
2 Hole size effect test matrix for the M40JB/ThinPreg™ 80EP/CF laminates and corresponding experimental results. .......... 48
3 Open-hole tension test matrix for the STF and NCF laminates. .... 49
4 Configuration of the digital image correlation system. .......... 50
5 Optical system parameters. ........................................ 51
6 Test results for the T700SC/M21 STF laminates. ............... 52
7 Test results for the T700GC/M21 NCF laminates. ............... 53
Table 1: Laminate stacking sequences used in the ply-level hybridisation study. Bold characters are used to highlight the thick-ply building blocks.

<table>
<thead>
<tr>
<th>Laminate ID</th>
<th>Stacking Sequence</th>
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<tbody>
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<td>STF-THIN</td>
<td>[(0/90)/(45/−45)]_s</td>
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<td>STF-INT</td>
<td>[(0/90)/(45/−45)]_s</td>
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<tr>
<td>STF-HYBRID</td>
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<td>NCF-THIN</td>
<td>[(90/45)/(0/−45)]_s</td>
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<td>NCF-INT</td>
<td>[(90/45)/(45/0)/(0/−45)/(-45/90)/(90/45)/(0/−45)]_s</td>
</tr>
<tr>
<td>NCF-HYBRID</td>
<td>[(90/45)/(0/−45)(90/45)/(90/−45)/(45/0)/(0/−45)]_s</td>
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Table 2: Hole size effect test matrix for the M40JB/ThinPreg™ 80EP/CF laminates and corresponding experimental results.

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<th>Laminate and Geom. ID</th>
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<th>$d$ (mm)</th>
<th>$\sigma^\infty$ (MPa)</th>
<th>C.V. (%)</th>
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* Test results from Amacher et al. [7].
Table 3: Open-hole tension test matrix for the STF and NCF laminates.

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Table 4: Configuration of the digital image correlation system.

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<td>Sensor format of 1/1.8&quot;</td>
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<td>Facet size</td>
<td>15 x 15 pixel$^2$</td>
</tr>
<tr>
<td>Facet step</td>
<td>13 x 13 pixel$^2$</td>
</tr>
<tr>
<td>Strain base length</td>
<td>5 subsets</td>
</tr>
<tr>
<td>Strain validity code</td>
<td>55.0%</td>
</tr>
<tr>
<td>Strain computation method</td>
<td>Total</td>
</tr>
</tbody>
</table>
Table 5: Optical system parameters.

<table>
<thead>
<tr>
<th>Specimen geometry</th>
<th>Captured region (approx.) (mm²)</th>
<th>Conversion factor (typical value) (mm/pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M40JB/ThinPreg™ 80EP/CF laminates</td>
<td>W = 6 mm 6 × 6</td>
<td>0.0056</td>
</tr>
<tr>
<td></td>
<td>W = 12 mm 12 × 10</td>
<td>0.0088</td>
</tr>
<tr>
<td></td>
<td>W = 18 mm 18 × 13</td>
<td>0.0119</td>
</tr>
<tr>
<td></td>
<td>W = 24 mm 24 × 17</td>
<td>0.0157</td>
</tr>
<tr>
<td>T700SC/M21 STF and T700GC/M21 NCF laminates</td>
<td>W = 25 mm 33 × 25</td>
<td>0.0228</td>
</tr>
<tr>
<td></td>
<td>W = 12 mm 16 × 12</td>
<td>0.0115</td>
</tr>
<tr>
<td></td>
<td>W = 30 mm 30 × 30</td>
<td>0.0169</td>
</tr>
<tr>
<td></td>
<td>W = 48 mm 63 × 48</td>
<td>0.0400</td>
</tr>
</tbody>
</table>
Table 6: Test results for the T700SC/M21 STF laminates.

<table>
<thead>
<tr>
<th>Laminate ID</th>
<th>hole diameter (mm)</th>
<th>Mean ultimate stress (MPa)</th>
<th>C.V. (%)</th>
<th>Mean stiffness reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STF-THIN</td>
<td>-</td>
<td>887</td>
<td>1.2</td>
<td>-</td>
</tr>
<tr>
<td>STF-INT</td>
<td>-</td>
<td>874</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>STF-HYBRID</td>
<td>-</td>
<td>872</td>
<td>2.3</td>
<td>-</td>
</tr>
<tr>
<td>STF-THIN 2</td>
<td>2</td>
<td>558</td>
<td>0.8</td>
<td>-</td>
</tr>
<tr>
<td>STF-INT 2</td>
<td>2</td>
<td>610</td>
<td>5.0</td>
<td>-</td>
</tr>
<tr>
<td>STF-HYBRID 2</td>
<td>2</td>
<td>574</td>
<td>3.7</td>
<td>-</td>
</tr>
<tr>
<td>STF-THIN 5</td>
<td>5</td>
<td>498</td>
<td>2.6</td>
<td>1.58</td>
</tr>
<tr>
<td>STF-INT 5</td>
<td>5</td>
<td>568</td>
<td>2.7</td>
<td>6.96</td>
</tr>
<tr>
<td>STF-HYBRID 5</td>
<td>5</td>
<td>524</td>
<td>2.8</td>
<td>2.26</td>
</tr>
<tr>
<td>STF-THIN 8</td>
<td>8</td>
<td>463</td>
<td>1.6</td>
<td>-</td>
</tr>
<tr>
<td>STF-INT 8</td>
<td>8</td>
<td>498</td>
<td>4.3</td>
<td>-</td>
</tr>
<tr>
<td>STF-HYBRID 8</td>
<td>8</td>
<td>491</td>
<td>2.7</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 7: Test results for the T700GC/M21 NCF laminates.

<table>
<thead>
<tr>
<th>Laminate ID</th>
<th>hole diameter (mm)</th>
<th>Mean ultimate stress (MPa)</th>
<th>C.V. (%)</th>
<th>Mean stiffness reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCF-THIN</td>
<td>-</td>
<td>799</td>
<td>6.7</td>
<td>-</td>
</tr>
<tr>
<td>NCF-INT</td>
<td>-</td>
<td>719</td>
<td>4.1</td>
<td>-</td>
</tr>
<tr>
<td>NCF-HYBRID</td>
<td>-</td>
<td>791</td>
<td>2.6</td>
<td>-</td>
</tr>
<tr>
<td>NCF-THIN 2</td>
<td>2</td>
<td>531</td>
<td>4.5</td>
<td>-</td>
</tr>
<tr>
<td>NCF-INT 2</td>
<td>2</td>
<td>564</td>
<td>4.3</td>
<td>-</td>
</tr>
<tr>
<td>NCF-HYBRID 2</td>
<td>2</td>
<td>584</td>
<td>9.6</td>
<td>-</td>
</tr>
<tr>
<td>NCF-THIN 5</td>
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<td>1.9</td>
<td>3.96</td>
</tr>
<tr>
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<td>5</td>
<td>491</td>
<td>0.7</td>
<td>6.23</td>
</tr>
<tr>
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<td>5</td>
<td>527</td>
<td>5.3</td>
<td>4.21</td>
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<tr>
<td>NCF-THIN 8</td>
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<td>445</td>
<td>2.8</td>
<td>-</td>
</tr>
<tr>
<td>NCF-INT 8</td>
<td>8</td>
<td>473</td>
<td>2.7</td>
<td>-</td>
</tr>
<tr>
<td>NCF-HYBRID 8</td>
<td>8</td>
<td>495</td>
<td>6.0</td>
<td>-</td>
</tr>
</tbody>
</table>