SELECTIVE PLY-LEVEL HYBRIDISATION FOR IMPROVED NOTCHED RESPONSE

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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° 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.

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].

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 [3–6], great potential for improved compressive notched strengths [4, 5] and higher fatigue resistance [3, 4, 6, 7]. However, the delay of damage onset has a negative impact in notched structures loaded in tension [6], 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 work is to develop innovative laminates that include both thin plies and plies of intermediate thickness, aiming at improved notched strengths.

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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

Quasi-isotropic laminates, $[45_m/90_m/-45_m/0_m]_{nS}$, with the same nominal thickness (2.4 mm), produced from M40JB carbon fibres and ThinPreg™ 80EP/CF epoxy resin, were manufactured and cured in an autoclave following the recommended curing cycle [6], and used to study the hole size effect in laminates with different ply thickness. The tested laminates are hereafter referred to as *THIN* (30 g/m^2 plies, m = 1, n = 10), *INT* (100 g/m^2 plies, m = 1, n = 3), *THICK* (300 g/m^2 plies, m = 1, n = 1) and *THICK - PLY LEVEL* (30 g/m^2 plies, m = 10, n = 1). 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. All specimens had a constant width-to-hole diameter ratio W/d = 6.

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, was studied using laminates consisting of T700SC/M21 TeXtreme® plain weave spread tow fabrics (STFs) of different grades (160 g/m^2 and 240 g/m^2 per fabric layer). Alternatively, T700GC/M21 C-Ply™ bi-angle non-crimp fabrics (NCFs), with an areal weight of 150 g/m^2 per bi-angle layer, were used to study selective ply-level hybridisation. Symmetric quasi-isotropic laminates were manufactured, including a thin-ply, an intermediate-ply and a hybrid laminate of each reinforcement configuration, all cured in an autoclave: a thin-ply (160 g/m^2) STF laminate, referred to as *STF-THIN*; an intermediate-ply (240 g/m^2) STF laminate, referred to as *STF-INT*; an STF laminate with uniform ply-level hybridisation, combining both STF grades, referred to as *STF-HYBRID*; an NCF thin-ply laminate, obtained dispersing the plies along all fibre orientations, referred to as *NCF-THIN*; an intermediate-ply laminate, obtained grouping, as possible, consecutive plies with the same orientation, referred to as *NCF-INT*; and an NCF laminate with selective ply-level hybridisation, obtained dispersing the off-axis and transverse plies and grouping, as possible, the 0° plies, referred to as *NCF-HYBRID*.

Unnotched tension tests were carried out to determine the unnotched strength of all STF and NCF laminates, following the ASTM D3039/D3039M – 14 test standard [8]. Open-hole tension tests were performed on scaled specimens with hole diameters of 2 mm, 5 mm and 8 mm and constant width-to-hole diameter ratio W/d = 6. Additionally, open-hole fatigue tests were also performed on 30 mm wide notched specimens with a hole diameter of 5 mm, 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 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.

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3. Experimental results and discussion

3.1. Effect of ply thickness

Amacher et al. [6] conducted unnotched tension tests on the same M40JB/ThinPreg™ 80EP/CF carbon/epoxy laminates. The ultimate strength of the unnotched specimens increased 39% and 42% when decreasing the grade of the UD plies from 300 g/m^2 to 100 g/m^2 and to 30 g/m^2, respectively. The stress at the onset of damage (first-ply-failure) was also identified, by means 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/m^2 to 30 g/m^2. In order to clarify the nature of this size effect, Amacher et al. [6] tested thick-ply laminates produced from blocks of 30 g/m^2 ultra-thin plies and from 300 g/m^2 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 [9].

The role of ply thickness on damage growth in notched coupons was 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. Generally, the THIN laminate exhibited a brittle type of net-section failure mode, where subcritical damage such as transverse cracking or delamination was absent. The INT specimens had 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. 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 fibre-dominated failure mode has occurred, which changed from brittle to pull-out failure, including subcritical damage.

For the THICK and THICK - PLY LEVEL laminates, a totally different, matrix-dominated failure mode was observed, characterised by progressive, multi-mode damage [6]. Before fibre fracture of the 0° plies, extensive delamination had occurred, extending across the entire gauge section and terminating at the end tabs. The ±45° and 90° plies failed due to transverse cracking. It was observed that, before failure of the 0° ligaments, the specimens had lost their structural integrity.

The mean values of the notched strengths obtained in the experimental tests for each laminate and geometry are plotted in Fig. 1 as a function of the hole diameter. As can be observed, the notched strengths of the THIN and INT laminates increased as the hole diameter decreased. However, the INT laminate had higher notched strengths than the THIN laminate, independently of the specimens' geometry. Regarding the laminates with thick plies, both THICK and THICK - PLY LEVEL laminates exhibited an inverse size effect, which was originally reported in Refs. [1, 2].

Amacher et al. [6] 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.

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. In addition,

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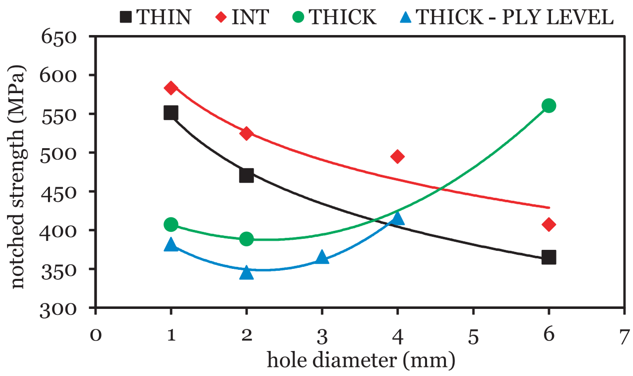

Figure 1. Notched response of the M40JB/ThinPreg^{TM} 80EP/CF laminates.

there are also advantages in design, such as faster lay-up and lower material cost due to the introduction of high grade materials. To explore this hypothesis two concepts are introduced: uniform ply-level hybridisation and selective ply-level hybridisation.

3.2. Uniform ply-level hybridisation

The STF-THIN unnotched specimens exhibited a brittle type of net-section failure mode, with a failure section perpendicular to the loading direction. The STF-INT and STF-HYBRID specimens showed a fibre-dominated pull-out failure mode, with split cracking along the 0° spread tow yarns and delamination between the STF layers. The mean values of the tensile unnotched strengths of the STF laminates, and respective coefficients of variation (C.V.), are presented in Table 1. Despite the different failure modes, the tensile unnotched strengths of these laminates are virtually the same.

Table 1. Unnotched and open-hole fatigue test results.

Laminate ID	Unnotched tension		Open-hole fatigue	
	Unnotched strength (MPa)	C.V. (%)	hole diameter (mm)	Mean stiffness reduction (%)
STF-THIN	887	1.2	5	1.58
STF-INT	874	1.0	5	6.96
STF-HYBRID	872	2.3	5	2.26
NCF-THIN	799	6.7	5	3.96
NCF-INT	719	4.1	5	6.23
NCF-HYBRID	791	2.6	5	4.21

The notched specimens all showed a fibre-dominated pull-out failure mode after testing, with a failure section perpendicular to the loading direction. However, the STF-INT and STF-HYBRID laminates exhibited 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. 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.

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The notched strengths of the STF laminates increased as the hole diameter decreased (Fig. 2). However, the STF grade had clearly an effect on the notched response of the tested laminates. The intermediate-ply STF-INT laminate exhibited higher notched strengths than the thin-ply STF-THIN laminate. 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, but lower notched strengths than the intermediate-ply laminate.

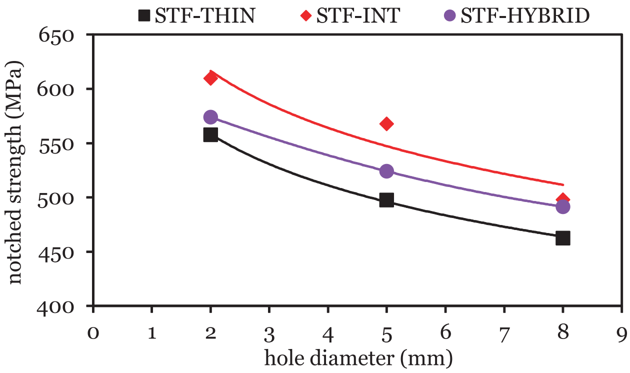

Figure 2. Notched response of the T700SC/M21 STF laminates.

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 1 shows the mean stiffness reduction after 50,000 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 had occurred during the cyclic loading. As before, the STF-HYBRID laminate exhibited an intermediate response.

3.3. Selective ply-level hybridisation

To promote longitudinal fibre-matrix splitting while limiting the occurrence of transverse matrix cracking and delamination, ply-level hybridisation was performed by selectively grouping only the 0° plies, namely those in the inner sublaminate regions of the hybrid laminate. This choice avoids early outer ply failure [9] and ensures that subcritical damage growth is always confined.

After testing, the NCF-THIN unnotched specimens exhibited a net-section failure mode, with a failure section perpendicular to the loading direction. Some diffuse damage close to the fracture plane was also observed. The NCF-INT and NCF-HYBRID specimens showed a fibre-dominated pull-out failure mode, including some delamination and a diffuse fracture plane.

The mean values of the tensile unnotched strengths of the NCF laminates, and respective C.V., are presented in Table 1. As reported elsewhere [5, 6], dispersed thin-ply laminates have higher unnotched tensile strength than blocked-ply laminates, a result confirmed by the present study. 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.

All notched specimens showed a fibre-dominated pull-out failure mode. Only the larger NCF-THIN laminate exhibited a brittle failure section, approximately perpendicular to the loading direction. The remaining specimens showed transverse fracture planes along the off-axis plies, specially the NCF-INT

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specimens, with matrix splitting and local delaminations across the ligament width.

The notched strengths of the tested NCF laminates increased as the hole diameter decreased (Fig. 3). As opposed to the unnotched response, the thin-ply NCF-THIN laminate showed lower notched strength than the blocked-ply NCF-INT laminate. On the other hand, the hybrid laminate NCF-HYBRID revealed a higher notched strength than both thin-ply and blocked-ply laminates. 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.

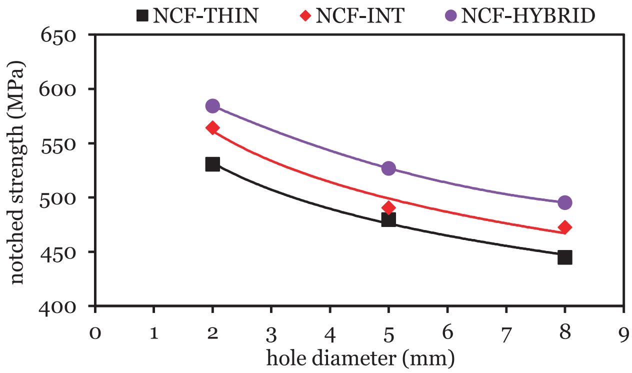

Figure 3. Notched response of the T700GC/M21 NCF laminates.

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 1 shows the mean stiffness reduction after 50,000 loading cycles for the NCF notched coupons with a 5 mm diameter hole. 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.

4. Conclusions

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 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.

Selective ply-level hybridisation, where thin off-axis plies are combined with 0° 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. The thick 0° 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

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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.

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° 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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