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Notched response of non-crimp fabric thin-ply laminates: analysis methods

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Abstract

Analysis methods to predict the open-hole tensile and compressive response of thin-ply non-crimp fabric laminates are investigated in this paper. The point- and average-stress models and the Finite Fracture Mechanics model are used. It is shown that all models predict with reasonable accuracy the observed size effects in both tension and compression. The Finite Fracture Mechanics model, which requires two material properties (the unnotched strength and the fracture toughness) and does not need calibration from a baseline specimen, is used to predict the notched response of thin-ply non-crimp fabric laminates and of typical aerospace grade laminates based on unidirectional pre-impregnated plies. No substantial differences in notch sensitivity and inherent material/geometry brittleness is predicted.

Keywords:

A. Laminate, B. Fracture, C. Stress concentrations.

1. Introduction

Tow-spread thin-ply laminates are a new class of composite materials with particular interest for the aircraft industry. These laminates are based on flat and straight plies with dry ply thicknesses as low as 0.02 mm, obtained by continuously and stably opening fiber tows in a pneumatic device.

Thin-ply laminates have several advantages with respect to traditional laminates. In a previous work [1], an extensive experimental test program was conducted to investigate the mechanical response of thin-ply laminates, including notched strength, size effects, brittleness, and bearing strength. It was concluded that the spread tow thin-ply technology is able to produce laminates

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9 whose application in primary structures may result in some structural integrity improvements, with-
10 out degradation of the notched response of the composite structures, including (i) delay of subcritical
11 damage such as delamination and transverse cracking, which is particularly important in applica-
12 tions subjected to mechanical fatigue and load reversals, and (ii) optimized behavior in mechanically
13 fastened joints, due to the superior performance of these laminates when subjected to bearing loads.
14 However, in order to accurately predict the notched response of these laminates, a study on the
15 applicability of existing analysis methods should be performed.

16 The first objective of this paper is to assess the validity of current analytical tools in predicting
17 the notched response of thin-ply laminates. The results obtained in the experimental test program
18 discussed in a previous paper [1] are compared with the predictions of the traditional point-stress
19 (PS) and average-stress (AS) models [2], and of the newly developed Finite Fracture Mechanics
20 (FFMs) model [3]. The second objective is to complement the previous experimental work [1], using
21 the FFMs model to evaluate size effects, notch sensitivity and brittleness of carbon fiber reinforced
22 polymer (CFRP) composites. Adequate trends, predicted for the same conditions and geometries,
23 are used to compare the notched response of non-crimp fabric (NCF) thin-ply laminates and typical
24 aerospace grade CFRP laminates, for which experimental data is only available for a limited range
25 of geometries.

26 **2. Strength prediction model**

27 The model recently proposed by Camanho et al. [3], which is based on the concept of Finite
28 Fracture Mechanics (FFMs) originally developed by Leguillon [4] and Cornetti et al. [5], results in
29 improvements over the traditional strength prediction methods (see refs. [3, 6, 7] for comparisons).
30 The FFMs model assumes that crack propagation occurs when a stress-based criterion, similar to
31 Whitney and Nuismer's AS model [2], and an energy-based criterion are simultaneously satisfied, and
32 considers that failure occurs by the propagation of kinematically admissible cracks with finite sizes.
33 The strength predictions using the FFMs model can be obtained in a few seconds, without the need
34 to use finite element analysis (FEA) or complex computational methods, using only independently
35 measured material properties: the laminate unnotched strength (X^L) and fracture toughness ($\mathcal{K}_{Ic}$)
36 [3].

37 Since there are no standard test methods to measure the laminate fracture toughness, Camanho

et al. [3] propose the use of the FFMs analysis of the specimens with a central crack, as shown in figure 1. These specimens are particularly suitable due to the simplicity of the geometry and data reduction method. Following this approach, the tensile and compressive remote stresses at failure, obtained in center-notched tension and compression tests, respectively, and the tensile and compressive unnotched strengths measured in the experimental program [1] are used for the calculation of the tensile and compressive fracture toughness of the laminates. However, unlike Camanho et al. [3], who used the stress distribution and the stress intensity factor solution for an infinite plate, finite-width corrected solutions are used here. In addition, since cracks in laminated plates are similar to elliptical openings with high aspect ratios, which more closely resemble the elliptical notch than the theoretical crack (which has zero notch tip radius that cannot be obtained experimentally) [8], the stress distribution for a central elliptical notch is used to solve the FFMs stress-based criterion. Also, by using the stress distribution for a central elliptical notch, the stress singularity at the crack tip is avoided and a finite stress concentration is considered, which more closely approximates the real problem.

[Figure 1 about here.]

According to the FFMs model [3], failure in a specimen with a central crack (figure 1) occurs when the following system of equations is satisfied:

$$\begin{cases} \frac{1}{l} \int_a^{a+l} \sigma_{yy}(x, 0) dx = X^L \\ \frac{1}{l} \int_a^{a+l} \mathcal{K}_I^2(a) da = \mathcal{K}_{Ic}^2 \end{cases} \quad (1)$$

where $\sigma_{yy}(x, 0)$ is the stress distribution along the x -axis, $\mathcal{K}_I(a)$ is the stress intensity factor (SIF), and l is the crack extension at failure.

Assuming that the normal stress profile for a finite plate is identical to that for an infinite plate except for a finite-width correction (FWC) factor, the stress distribution along the x -axis, $\sigma_{yy}(x, 0)$, is given as [8]:

$$\sigma_{yy}(x, 0) = \frac{K_T}{K_T^\infty} \sigma_{yy}^\infty(x, 0) \quad (2)$$

where K_T^∞ and K_T are, respectively, the stress concentration factors at the edge on the axis normal to the applied load of the central notch of an infinite orthotropic plate and a finite orthotropic plate,

62 and $\sigma_{yy}^\infty(x, 0)$ is the stress distribution along the x -axis of an infinite orthotropic plate containing a
 63 central notch. Approximating the central notch by an elliptical opening of major semi-axis a and
 64 minor semi-axis b , K_T^∞ , K_T and $\sigma_{yy}^\infty(x, 0)$ read [8]:

$$K_T^\infty = 1 + \frac{1}{\lambda} \sqrt{2 \left(\sqrt{\frac{E_y}{E_x}} - \nu_{yx} \right) + \frac{E_y}{G_{xy}}} \quad (3)$$

$$\begin{aligned} \frac{K_T^\infty}{K_T} = & \frac{\lambda^2}{(1-\lambda)^2} + \frac{1-2\lambda}{(1-\lambda)^2} \sqrt{1 + (\lambda^2 - 1) (2a/W)^2} - \\ & - \frac{\lambda^2}{(1-\lambda)^2} \frac{(2a/W)^2}{\sqrt{1 + (\lambda^2 - 1) (2a/W)^2}} + \\ & + \frac{\lambda^7}{2} \left(\frac{2a}{W} \right)^6 \left(K_T^\infty - 1 - \frac{2}{\lambda} \right) \left\{ \left[1 + (\lambda^2 - 1) \left(\frac{2a}{W} \right)^2 \right]^{-\frac{5}{2}} - \right. \\ & \left. - \left(\frac{2a}{W} \right)^2 \left[1 + (\lambda^2 - 1) \left(\frac{2a}{W} \right)^2 \right]^{-\frac{7}{2}} \right\} \end{aligned} \quad (4)$$

$$\begin{aligned} \frac{\sigma_{yy}^\infty(x, 0)}{\sigma^\infty} = & \frac{\lambda^2}{(1-\lambda)^2} + \frac{(1-2\lambda)\gamma}{(1-\lambda)^2 \sqrt{\gamma^2 - 1 + \lambda^2}} + \frac{\lambda^2 \gamma}{(1-\lambda) (\gamma^2 - 1 + \lambda^2)^{\frac{3}{2}}} - \\ & - \frac{\lambda^7}{2} \left(K_T^\infty - 1 - \frac{2}{\lambda} \right) \left[\frac{5\gamma}{(\gamma^2 - 1 + \lambda^2)^{\frac{7}{2}}} - \frac{7\lambda^2 \gamma}{(\gamma^2 - 1 + \lambda^2)^{\frac{9}{2}}} \right] \end{aligned} \quad (5)$$

65 where σ^∞ is the remote applied stress, and the parameters λ and γ are defined as:

$$\lambda = \frac{b}{a} \quad (6)$$

$$\gamma = \frac{x}{a} \quad (7)$$

66 For quasi-isotropic laminates, $K_T^\infty = 1+2/\lambda$, and equations (4) and (5) get considerably simplified.
 67 The stress profile around a central notch is the same for tension and compression, and the same
 68 solution will be used in the calculation of fracture toughnesses in both types of loading.

69 When approximating a central notch, such as the one shown in the specimen of figure 1, by an
 70 elliptical opening, different approaches may be chosen to define the ellipse's minor semi-axis b . For
 71 example, Tan [8] simulated central cracks of length $2a$ by an elliptical opening of major axis $2a$ and

constant aspect ratio $\lambda = 50$. Alternatively, the central notch of length $2a$ can be simulated by an elliptical opening of major axis $2a$, with a minor axis $2b$ equal to the notch height h (or two times the radius of the milling cutter used to obtain the notch); another possibility is to define the ellipse's minor axis $2b$ such that the ellipse's curvature in the major axis, $\rho|_{\theta=0}$, is equal to the notch tip radius (or radius of the milling cutter).

Figure 2 shows a comparison of the stress distribution in the vicinity of the notch tip considering the different approaches to simulate the central notch by an elliptical opening. In addition, figure 2 also shows the stress distribution of a plate with a U-shaped central notch obtained from a finite element model developed using the commercial finite element package Abaqus 6.11-2; 0.05 mm long 4-node bilinear plane stress quadrilateral finite elements, with reduced integration and hourglass control (CPS4R), were used in the vicinity of the notch tip. By defining the ellipse's minor axis $2b$ such that the ellipse's curvature in the major axis is equal to the notch tip radius gives the best approximation for the stress distribution along the x -axis in U-shaped notched plates, since the corresponding analytical stress distribution for the elliptical opening fits perfectly the FEA of the U-shaped notch, as can be observed. Consequently, this is the approach followed in the present work.

[Figure 2 about here.]

The SIF solution $\mathcal{K}_I(a)$ needed to solve the energy-based criterion corresponds to a central notch that is extended by two cracks of finite dimension, which can be reasonably approximated by a plate with a central crack. For an isotropic plate, $\mathcal{K}_I(a)$ is given as:

$$\mathcal{K}_I(a) = Y\sigma^\infty\sqrt{\pi a} \quad (8)$$

where Y is the FWC factor. Several FWC factors exist in the literature. In this work, the simple FWC factor proposed by Chen et al. [9] is used. This FWC factor was derived from a force balance between the remotely applied stress and the internal stress in the elastic material in front of the crack tip, and it is given as:

$$Y = \frac{1}{\sqrt{1 - \left(\frac{2a}{W}\right)^2}} \quad (9)$$

Note that, by including finite-width corrected solutions for the stress distribution and for the SIF and by approximating the central notch by an elliptical opening instead of a crack, the overall accuracy of the FFMs predictions increase 1–3%, without noticeable increase in computational effort (these are all closed-form solutions); although it may seem to be a very small improvement, notice that the relative errors of the FFMs predictions are typically below 10% (see, for example, [3, 6]), which means that this is, in fact, a good improvement. Also, the introduction of these modifications in the FFMs model formulation initially proposed in [3] relaxes some of the restrictions regarding the in-plane dimensions and the aspect ratio of the central notch of the specimens used to quantify the fracture toughness. Therefore, the differences in the FFMs predictions obtained with the solution proposed in the present paper to calculate the fracture toughness or with the solution shown in [3] could be noticeably higher if using center-notched specimens with lower width to notch length ratios ($W/(2a)$) and/or notches obtained with larger milling cutters (and therefore lower aspect ratios).

3. Notched strength predictions

The material investigated by Arteiro et al. [1], and whose notched response is further analysed in this work, is Chomar’s carbon thin-ply NCF C-PLYTM T700 combined with the AR-2527 epoxy system from Aldila. Two balanced thin-ply laminates, having a nominal ply thickness of 0.08 mm, are investigated: *lay-up 1*, a $[(0/-45)/(90/45)]_{6T}$ asymmetric laminate, and *lay-up 2*, a $[(0/-45)/(45/0)/(90/45)/(-45/90)]_S$ laminate, both manufactured at VX Aerospace using vacuum bagging.

The test results obtained in [1] for the open-hole tension specimens with a 6 mm diameter hole and for the open-hole compression specimens with a 5 mm diameter hole were used to calibrate the PS and AS models and calculate the corresponding characteristic distances (r_{ot}). The tensile and compressive fracture toughness required in the FFMs model were calculated using the FFMs analysis, as described in section 2. Table 1 shows the characteristic distances for the PS and AS models (respectively r_{ot}^{PS} and r_{ot}^{AS}), and the laminate fracture toughness ($\mathcal{K}_{Ic}$) calculated using the FFMs analysis for both thin-ply laminates in tension and compression.

[Table 1 about here.]

Figure 3 and table 2 show the comparisons between the predictions of the PS, AS and FFMs models and the open-hole tests results obtained using the NCF thin-ply laminates. Table 2 also

shows the relative errors (ϵ_r) of the predictions for each tested geometry. It can be observed that all models reasonably predict the notched strength of the NCF thin-ply laminates loaded in both tension and compression.

[Figure 3 about here.]

[Table 2 about here.]

Nevertheless, according to the predictions presented in this work and to discussions presented elsewhere [3, 6, 7], it can be concluded that the FFMs model shows higher versatility and generality than the alternative PS and AS models, making it better suited to evaluate macroscopic size effects on CFRPs. Because it combines a stress-based criterion with an energy-based criterion, without requiring an inverse calibration from baseline specimens, the FFMs model enables the direct comparison between the notched response of different CFRP laminates. Only the elastic properties, unnotched strengths and fracture toughness of the CFRP laminates under analysis are required to perform such comparisons.

4. Finite Fracture Mechanics analysis

4.1. Notched response and size effect

Figure 4 shows the notched responses in tension and compression of the thin-ply laminates studied in this work, obtained using FFMs analysis, in terms of the normalized notched strength, defined as $\bar{\sigma}_N = \bar{\sigma}^\infty / X^L$. In addition, figure 4 shows the FFMs analysis for the alternative [90/45/0/−45]_{3S} (laminate 1) and [90₂/0₂/45₂/−45₂/90/0/45/−45]_S (laminate 2) T800/M21 CFRP laminates, which have a nominal ply thickness of 0.133 mm; these laminates were previously tested by Erçin et al. [6]. Note that laminate 1, as the thin-ply NCF lay-up 1, has dispersed plies with minimal relative ply orientations between adjacent plies (hereafter referred to as “*non-blocked laminates*”), whereas laminate 2, as the thin-ply NCF lay-up 2, maximizes the fiber orientation angle between some adjacent plies and it has some plies with the same fiber orientation “blocked” together (hereafter referred to as “*blocked laminates*”). The FFMs analyses were computed for a width to hole diameter ratio $W/d = 4$. The tensile and compressive unnotched strengths (respectively X_T^L and X_C^L), obtained experimentally by Erçin et al. [6], and the tensile and compressive fracture toughnesses ($\mathcal{K}_{Ic}^T$ and

151 $\mathcal{K}_{Ic}^C$) for both T800/M21 CFRP laminates, calculated as described in section 2 using the remote
 152 stresses at failure (respectively $\bar{\sigma}_T^\infty$ and $\bar{\sigma}_C^\infty$) measured in center-notched tests [6], are shown in table
 153 3.

154 [Table 3 about here.]

155 [Figure 4 about here.]

156 The FFMs analysis presented in figure 4(a) for the notched response in tension indicates that the
 157 hole size effect is more pronounced in the T800/M21 laminates, when compared with the equivalent
 158 NCF thin-ply laminates; as expected, blocked laminates show a superior performance as a result of
 159 their higher susceptibility to develop sub-critical damage that blunt the notch, ultimately conducting
 160 to laminates that are less sensitive to macroscopic size effects. On the other hand, figure 4(b)
 161 shows that, unlike what is observed for the tensile case, the hole size effect in compression is less
 162 pronounced for the T800/M21 laminates. When comparing the FFMs analyses shown in figure 4
 163 with the experimental results presented in [1], it can be concluded that the FFMs model is able to
 164 establish adequate trends that can be very useful in preliminary studies of size effects in composite
 165 materials, without the need to conduct extensive experimental programs or complex FEA.

166 4.2. Design charts

167 The FFMs model can be effectively used to generate design charts for notched laminates. In such
 168 design charts, the predicted normalized notched strength is represented as a function of the $2R/W$
 169 ratio for different hole sizes. These design charts must also include the predictions obtained for a
 170 notch-sensitive material, whose normalized strength is a function of the stress concentration factor
 171 K_T ($\bar{\sigma}_N = 1/K_T$), and the predictions for a notch-insensitive material, whose normalized strength is
 172 a function of the geometry ($\bar{\sigma}_N = 1 - 2R/W$) — see refs. [1, 3].

173 Figures 5 and 6 show, respectively, the design charts of the notched response in tension and
 174 compression for the thin-ply laminates studied in this work, and for the $[90/45/0/-45]_{3S}$ (laminate 1)
 175 and $[90_2/0_2/45_2/-45_2/90/0/45/-45]_S$ (laminate 2) T800/M21 CFRP laminates [6]. For a constant
 176 $2R/W$ ratio, the predicted normalized strengths for the different hole sizes that are closer to the
 177 notch-insensitive boundary correspond to the less notch sensitive laminate.

178 [Figure 5 about here.]

[Figure 6 about here.]

It should be stressed that the design charts presented in figures 5 and 6 can be obtained in a fraction of a minute, without the need of extensive experimental programs to determine calibration factors (or “*characteristic distances*”) for each geometry, making it very useful for preliminary sizing and optimization of composite structures with notches. Note also that calculating these design charts using any of the alternative closed-form models would not be effective, since, to do so, a set of open-hole tests would be necessary for inverse identification of the characteristic distances, at least for different $2R/W$ ratios.

4.3. Notch sensitivity factor

The FFMs model can be used to assess the inherent brittleness of different combinations of materials and geometries by means of a dimensionless parameter, designated *notch sensitivity factor* [3]. This dimensionless parameter is defined as:

$$\eta_N = \frac{2R}{l} \quad (10)$$

where l is the crack extension at failure and R is the hole radius [3].

Figure 7 shows the relations between the notch sensitivity factor (η_N), calculated using the FFMs model, and the hole size ($2R$) for the NCF thin-ply laminates studied in this work, and for the $[90/45/0/-45]_{3S}$ (laminate 1) and $[90_2/0_2/45_2/-45_2/90/0/45/-45]_S$ (laminate 2) T800/M21 CFRP laminates [6]. For the notched response in tension (figure 7(a)), the thin-ply NCF lay-up 2 is clearly less notch sensitive than the remaining laminates, since its notch sensitivity factor is the lowest. This effect is emphasized for large hole diameters. These results also indicate that, for the notched response in tension, use of thin-ply laminates do not necessarily result in a more brittle (or notch sensitive) material, despite their brittle type of failure mode observed in [1]. For the notched response in compression, figure 7(b) shows that the T800/M21 laminate 2 has a notch sensitivity substantially lower than the other laminates. Therefore, and unlike what was observed for the notched response in tension, these results indicate that using NCF thin-ply laminates may result in a reduced notched response in compression.

[Figure 7 about here.]

205 4.4. Discussion

206 The FFMs analysis of the notched response, size effect and notch sensitivity presented before
207 clearly shows that thin-ply laminates have great potential, discarding any evidence of inherent brit-
208 tleness, despite the brittle type of net-section failure mode exhibited in the experimental program
209 presented in [1]. This is particularly true when subjected to tensile loading; although manufactured
210 by vacuum-bagging (resulting in a nominal fiber volume fraction of approximately 50%), the notched
211 response of the NCF thin-ply laminates is slightly superior to that exhibited by alternative aerospace
212 grade T800/M21 laminates, which were manufactured using the autoclave and hot-press techniques
213 (nominal fiber volume fraction of 57%). In addition, the FFMs analysis showed that changing the
214 stacking sequence, i.e. maximizing the relative ply orientations between adjacent plies and “blocking”
215 plies with the same fiber orientation, results in a decrease of the notch sensitivity of both thin-ply
216 and standard laminates; however, with thin-ply laminates, this is achieved reducing the development
217 of subcritical damage, such as delamination and transverse cracking, to a minimum, and keeping a
218 similar, or even superior, notched response.

219 When subjected to compressive loading, a different picture applies. In this case, the NCF thin-ply
220 laminates exhibit higher notch sensitivity than the corresponding T800/M21 laminates. As in the
221 tensile case, changing the stacking sequence, i.e. maximizing the relative ply orientations between
222 adjacent plies and “blocking” plies with the same fiber orientation, the notch sensitivity decreases
223 in both thin-ply and T800/M21 laminates; however the latter show the best performance. On the
224 other hand, looking to the unnotched compressive strengths of the NCF thin-ply laminates [1] and
225 comparing with those of the corresponding T800/M21 laminates [6], it is observed that, contrary to
226 the tensile case, they do not differ substantially, despite the lower fiber volume fraction of the NCF
227 thin-ply laminates. Therefore, it seems that the use of thin plies, which results in a brittle failure
228 mode dominated by fiber fracture [1], may have a large positive effect in the unnotched compressive
229 behavior (indicating that the *in situ* effect plays a role not only in tension, but also in compression, as
230 proposed in [10]), although it may also conduct to higher notch sensitivity. Still, an inherently brittle
231 type of compressive behavior is not expected, since the difference between the notched compressive
232 strengths obtained for the NCF thin-ply laminates [1] and for the corresponding T800/M21 laminates
233 [6] is typically below 10%.

234 Finally, it is important to note that the previous discussion did not take into account the laminate

thickness effect. According to a previous work on scaling of notched composites [11], independently of the laminate stacking sequence, an increase in the laminate thickness with constant hole diameter leads to a decrease in failure stress. So, lowering the thickness of the thin-ply laminates may result in an improvement of its notched response.

5. Conclusions

The closed-form models developed for the strength prediction of notched laminates were able to reasonably predict both tensile and compressive notched responses of thin-ply laminates. The FFMs model is considered to be the most appropriate model to evaluate the macroscopic size effects and notch sensitivity of CFRP laminates, by means of reliable notched strength predictions, versatile design charts, and by the identification of the *notch sensitivity factor*.

The FFMs analysis of the notched response, size effect and notch sensitivity presented before clearly shows that thin-ply laminates have great potential, discarding any evidence of inherent brittleness in both tension and compression. It also showed that changing the stacking sequence, i.e. maximizing the relative ply orientations between adjacent plies and “blocking” plies with the same fiber orientation, the notch sensitivity of the thin-ply and standard laminates decreases in both tension and compression. However, with thin-ply laminates, this is achieved reducing the development of subcritical damage, such as delamination and transverse cracking in tension, and fiber kinking in compression, to a minimum.

Although these results give an insight on the notched response of the NCF thin-ply laminates, it should be kept in mind that further investigations should be conducted. In particular, future works should address the development of new experimental programs focused on the notched response (including large through-penetration damage), size effects, and bearing strength of tow-spread thin-ply and thick-ply laminates with the same laminate thickness and made of the same material system.

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Figure 1: Composite laminate with a central notch loaded in tension.

Figure 2: Normalized stress distributions along the x -axis in the vicinity of the notch tip. The elliptical openings resemble a 4 mm long notch, with a notch tip radius of 0.5 mm and a width to notch length ratio ($W/(2a)$) equal to 7.5. Finite-width corrected solutions are considered.

(a) Open-hole lay-up 1 specimens.

(b) Open-hole lay-up 2 specimens.

Figure 3: Predictions and experimental results.

(a) Tension.

(b) Compression.

Figure 4: Finite Fracture Mechanics analysis and notched response of the NCF thin-ply laminates, and comparison with alternative T800/M21 CFRP laminates.

(a) Thin-ply NCF (lay-up 1).

(b) Thin-ply NCF (lay-up 2).

(c) T800/M21 (laminate 1).

(d) T800/M21 (laminate 2).

Figure 5: Design charts for the notched response in tension of different CFRP laminates.

(a) Thin-ply NCF (lay-up 1).

(b) Thin-ply NCF (lay-up 2).

(c) T800/M21 (laminate 1).

(d) T800/M21 (laminate 2).

Figure 6: Design charts for the notched response in compression of different CFRP laminates.

(a) Notched response in tension.

(b) Notched response in compression.

Figure 7: Notch sensitivity factor as a function of the hole size for the NCF thin-ply laminates, and for the alternative $[90/45/0/-45]_{3S}$ (laminate 1) and $[90_2/0_2/45_2/-45_2/90/0/45/-45]_S$ (laminate 2) T800/M21 CFRP laminates.

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Table 1: Characteristic distances and laminate fracture toughnesses required to predict the notched response of the NCF thin-ply laminates.

Laminate	Load type	r_{ot}^{PS} (mm)	r_{ot}^{AS} (mm)	$\mathcal{K}_{Ic}$ (MPa $\sqrt{\text{m}}$)
Lay-up 1	Tension	0.75	1.84	49.1
	Compression	0.69	1.71	27.0
Lay-up 2	Tension	1.11	2.97	53.1
	Compression	1.15	3.30	32.2

Table 2: Predictions and relative errors.

$2R$ (mm)	PS model		AS model		FFMs model	
	$\bar{\sigma}_T^\infty$ (MPa)	ϵ_r (%)	$\bar{\sigma}_T^\infty$ (MPa)	ϵ_r (%)	$\bar{\sigma}_T^\infty$ (MPa)	ϵ_r (%)
Open-hole lay-up 1 specimens loaded in tension						
3	490	13.6	466	7.9	465	7.8
6	385	n/a	385	n/a	392	1.9
10	333	-9.2	339	-7.6	345	-5.8
Open-hole lay-up 2 specimens loaded in tension						
3	497	10.8	468	4.4	447	-0.3
6	390	n/a	390	n/a	385	-1.2
10	329	-13.6	339	-10.9	338	-11.1
Open-hole lay-up 1 specimens loaded in compression						
5	268	n/a	268	n/a	250	-6.7
7	241	-2.4	245	-0.8	230	-6.8
Open-hole lay-up 2 specimens loaded in compression						
5	276	n/a	276	n/a	254	-8.1
7	245	3.0	252	5.9	233	-1.9

Table 3: Tensile and compressive unnotched strengths and predicted tensile and compressive fracture toughnesses for the $[90/45/0/-45]_{3S}$ (laminate 1) and $[90_2/0_2/45_2/-45_2/90/0/45/-45]_S$ (laminate 2) T800/M21 CFRP laminates.

Laminate	X_T^L (MPa)	X_C^L (MPa)	$\mathcal{K}_{Ic}^T$ (MPa $\sqrt{m}$)	$\mathcal{K}_{Ic}^C$ (MPa $\sqrt{m}$)
Laminate 1	1053	539	57.6	35.2
Laminate 2	973	503	64.2	43.8