



# Effect of the level of anisotropy on the macroscopic failure of notched thin-ply laminates

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## ABSTRACT

This work presents a detailed experimental study conducted for a range of different lay-ups using thin-ply carbon fiber reinforced polymer (CFRP) laminates. The selection of the laminates was performed relying on their level of anisotropy. The laminates vary from a quasi-isotropic (QI) laminate, which is weakly anisotropic, to a cross-ply (CP) laminate, which is strongly anisotropic. The laminates were tested in on-axis and off-axis open hole tension (OHT). The main objective was to observe the effect of the level of anisotropy of the laminate on the macroscopic failure and observed failure patterns. It is shown that, contrary to most existing observations so far, depending on the lay-up and consequently its level of anisotropy, open-hole, quasi-homogeneous thin-ply laminates do not necessarily exhibit a fiber dominated failure mode, but could develop sub-critical damage mechanisms in a large extent prior to ultimate failure, reminiscent of what is observed for standard-ply CFRP laminates.

## 1. Introduction

While carbon fiber reinforced polymer (CFRP) composite materials have long captured the interest of the aerospace field, the definition of proper design metrics remains a pertinent challenge for the community. Specific attention is often devoted to notched strength since it is not uncommon for aerostructures to contain holes, e.g., due to rivets, or other geometric cutouts. Accurate predictions of the notched strength, especially for CFRPs, is still a topic of great scientific interest given the vast versatility of this material type, in terms of reinforcement geometry and areal weight [1].

Failure in CFRPs typically consists of multiple, complex interacting mechanisms that are observed across various length scales. For standard-ply composites, meaning laminates made of plies with thicknesses equal or above 0.125 mm, it is common to observe a combination of delaminations, transverse cracking and splitting (often referred to as sub-critical damage), and then final failure dominated by fiber breakage events [1–8]. However, thin-ply laminates, consisting of plies of thicknesses under 0.1 mm, have shown to present a distinct macroscopic behavior. Final failure results from the growth of a macroscopic, fiber-

dominated through-thickness (translaminar) crack, while all other (sub-critical) mechanisms are suppressed, potentially due to a more prominent *in-situ* effect [9–18]. Because of this, recent works pertaining to strength of such composites and modeling them have in fact relied on equivalent single layer (ESL) representations and the assumption of a quasi-brittle type of failure [19–22].

Despite the growing literature addressing failure of thin-ply laminates, most studies refer to laminates that have predominantly been quasi-isotropic (QI) laminates, with just a few exceptions [3,12,15,17,23]. Moreover, these refer to cases of on-axis loading (meaning that the load is applied along one of the principal axes of orthotropy of the laminate) [9,10,12,15]. Thus, it becomes evident that a significant portion of possible load case scenarios and lay-up configurations is missing from the previous investigations.

An interesting case corresponds to off-axis loading, i.e., loading that does not lie along a principal axis of orthotropy of the laminate. Only a few studies regarding off-axis loading, and the effect it has on strength and failure patterns in composites, have been conducted. This slightly neglected case is not irrelevant for composite laminates where such off-axis loading affects the local stress and strain fields which can eventually

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play a significant role in the final response of the laminate at the macro-scale. In this regard, Oz et al. [24] performed tests on off-axis QI standard-ply composite laminates to evaluate the effect the lay-up rotation essentially has on the failure patterns revealing that the same lay-up could show a different sequence of failure when loaded along a different direction. Similarly, Chuaqui et al. [3] tested an array of lay-ups containing typical and unconventional angles on-axis and off-axis OHT with the main purpose of studying the effect angle ply blocking has on the strength, and how this affects the failure patterns observed, concluding that blocking and angle could have a significant effect on the evolution or not of sub-critical damage. Not much else exists other than the work of Kawai and Arai [25] that showed off-axis open hole tension (OHT) testing of Glare with the goal of developing a robust empirical criterion for strength predictions. Furtado et al. [17] are among the few, if not the only ones, to have tested notched thin-ply laminates in off-axis OHT as a subcase of a broader testing campaign that aimed at evaluating the effect lay-up architecture had on the notched response of CFRPs once again reporting the effect the load angle and lay-up had on the strength.

The goal of the present study is, thus, to expand the available experimental database and enhance the understanding of the failure of CFRP laminates, particularly of notched thin-ply laminates. This study, presents the results of an extensive testing campaign with notched thin-ply laminates of varying levels of anisotropy to study their failure behavior, ultimately guiding the development and the validation of more general analysis tools for this class of CFRP materials. The theories of the laminate selection and the lay-ups selected are presented in Section 2 followed by the test results alongside a discussion on the observations in Section 3. The conclusions of this study are presented in Section 4.

## 2. Laminate selection and manufacturing

### 2.1. Definition of the level of anisotropy

The metric used to define the lay-ups of the laminates that are to be tested is, as mentioned, their level of anisotropy. This term has been used in works pertaining to the fracture of generally anisotropic materials where the effect of the distribution of the fracture toughness (i.e., fracture toughness driving cracks at different angles with respect to the material principal axes) on the obtained failure pattern is evaluated [26,27]. Such a study is that of Takei et al. [27] that conducted trouser tests and observed zig-zag failure patterns. As explained in their work, these patterns seem to occur due to the presence of concave regions in the plot of the inverse fracture toughness. These concavities produced restricted fracture paths and led to the zig-zig crack rather than a straight line crack. Per their definition, in such a case the material is considered to hold a level of anisotropy that is strong (i.e., is strongly anisotropic). If there were no regions of concavity (i.e., it was fully convex) then the material would be weakly anisotropic.

It should be noted that defining the level of anisotropy for a composite laminate, however, by means of a distribution of fracture toughness is not necessarily direct and intuitive. Fracture toughness for a net-section through thickness type crack, especially in terms of energy release rate is not easily measurable. In fact, it is common to have standardized tests for fracture toughness for interlaminar failure forms [28–30], but not particularly for translaminar/intralaminar failure forms [31–33]. If one considers that this measure would be needed for angles at which the material would cease to be orthotropic (and potentially neither balanced or symmetric), this feat would understandably become extremely complicated.

So, an analogous terminology that relies on the elasticity of the laminate alone is sought to facilitate the application of such a metric the selection of laminates in this work. It is noted that multidirectional (MD) thin-ply laminates, under the assumption of macro-mechanical homogenization [34], can be modeled based on their extensional stiffness matrix, assumed as an equivalent stiffness [35], considering an ESL

homogenized plate representation, so theoretical aspects of mechanics of anisotropic materials can be considered. There are a few geometrical constructions that can express the directional variance of the material properties of interest, as explained by Lekhnitskii [36]. One of them was first introduced by Saint-Venant and refers to a direction surface and the direction curves later determined by Rabinovich [36]. Direction curves, as mentioned in [36], can be used to express and visualize the variance of elastic moduli in various directions of a medium. The direction surface as per Saint-Venant is a 3D surface where the radial distance from the arbitrary origin represents a scaled modulus. The direction curves then occur as the intersections of planes that pass by the origin and the direction surface. An example of this curve can be seen in Fig. 1. These geometrical constructions have only been used in a few analytical works in the literature that worked on defining interactions of moduli [37–39] and the definition of stationary points of these curves [40]. Considering that the strain stress relationship is given as:

$$\varepsilon_{ij} = S_{ijkl}\sigma_{kl} \quad (1)$$

where  $\varepsilon_{ij}$  is the strain tensor,  $S_{ijkl}$  the compliance tensor of the material, and  $\sigma_{ij}$  the stress tensor. Considering extension along a specific direction,  $n$ , the Young's modulus can be given as [40]:

$$1/E(n) = S_{ijkl}n_i n_j n_k n_l \quad (2)$$

and if this is to be applied for an orthotropic material viewed on the principal axes of orthotropy (here noted with 1 and 2 corresponding to the x and y axis respectively) and for the 1 direction<sup>1</sup> (interaction between the x-y plane and the surface) one gets for the direction curve the equation [36]:

$$\lambda x^4 + 2Bx^2y^2 + y^4 = \lambda \quad (3)$$

where:

$$\lambda = \frac{E_2}{E_1}, \quad B = \frac{E_2}{2G_{12}} - \nu_{12}$$

where  $E_1$  and  $E_2$  are the tensile moduli,  $G_{12}$  is the shear modulus for 1-2 plane and  $\nu_{12}$  is the respective Poisson's ratio.  $\lambda$  and  $B$  are parameters that can be seen as measures of how far the material lies from a purely isotropic state. The combination of  $\lambda = B = 1$  refers to an isotropic material state and would lead to a circle for the direction curve (or to a sphere for the direction surface), and when one or both veer far from 1 the material exhibits a stronger level of anisotropic behavior. In this study, the shape of these direction curves or surfaces are used to characterize the level of anisotropy of the laminates, based on convexity and concavity, analogously to the definition in [27]. So, if the direction curve is convex in its totality, then the laminate will be considered weakly anisotropic; otherwise, if it also presents concave regions, it will be considered strongly anisotropic.

### 2.2. Lay-up and material selection

With the above in mind, the lay-ups shown in Table 1 were selected in order to have varying levels of anisotropy, from the strongest, i.e., cross-ply (CP), to the weakest, i.e., the quasi-isotropic (QI). All other laminates, starting from the SOFT laminate, have a varying level of anisotropy that lies somewhere between the two listed in Table 1 in order of increasing level of anisotropy. The material system selected was the T800/736LT from North Thin Ply Technology (NTPT) with a nominal ply thickness of 0.05 mm, which was characterized in-house and whose properties are presented in Appendix A. All the laminates were designed considering the same number of total plies, 32, to achieve the

<sup>1</sup> For more detailed mathematics on this, please refer to the works of Ting [37,38,40].

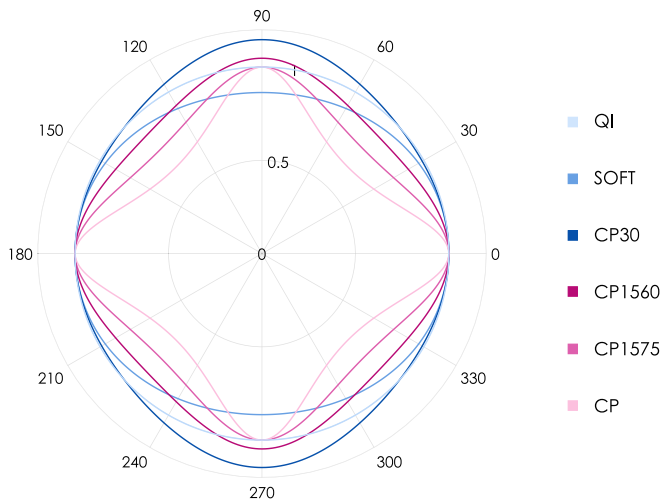


Fig. 1. (a) Direction curves and (b) inverse ERR plots for all selected laminates.

Table 1

Laminate lay-ups and respective  $\lambda$ , B values for the direction curves.

|        | Lay-up                                 | $\lambda$ | B      |
|--------|----------------------------------------|-----------|--------|
| QI     | $[90, -45, 0, 45]_{4s}$                | 1.0000    | 1.0000 |
| SOFT   | $[90, \pm 45, 90, \pm 45, 90, 0]_{2s}$ | 0.5557    | 0.6839 |
| CP30   | $[90, 0, \pm 30, 0, 90, \pm 30]_{2s}$  | 1.7296    | 2.0333 |
| CP1560 | $[90, \pm 60, 0, \pm 15, 90, 0]_{2s}$  | 1.2025    | 2.8291 |
| CP1575 | $[90, \pm 75, 0, \pm 15, 0, 90]_{2s}$  | 1.0000    | 4.4246 |
| CP     | $[90, 0]_{8s}$                         | 1.0000    | 9.9951 |

same nominal thickness of 1.6 mm. As for definition of the ply angles, they were selected to achieve a smooth transition between direction curves (Eq. 3), which are shown in Fig. 1. Additionally, the lay-ups after definition of the ply angles were set-up so as to achieve minimal blocking in the final total lay-up.

Observing Fig. 1, the clearly convex curves are the ones of the QI, SOFT and CP30 laminates whereas the ones of the CP1575 and CP present evident concavities.<sup>2</sup> The direction curve for CP1560 is *border-line* convex and will be for the sake of this discussion grouped with the non-convex curves as minimal changes in the values of the elastic moduli would render it not fully convex. Thus, the former three, QI, SOFT and CP30 will be considered as the weakly anisotropic laminates in this study and the CP1560, CP1575, and CP as the strongly anisotropic ones in the discussions that follow. In Appendix B, Energy Release rate (ERR) plots are also presented for each laminate alongside a discussion on their classification to provide a form of a comparison based on the definition for the level of anisotropy using fracture toughness.

### 3. Experiments

#### 3.1. Specimens and testing method

The characterization of the notched response of the previously detailed thin-ply MD laminates with different levels of anisotropy (Table 1) was carried out via open hole tension (OHT) tests following the ASTM D5766 standard as a reference but employing nonstandard geometry. The specimens were all 20 mm in width, 170 mm in length and had a 5 mm diameter hole in the center (nominal dimensions). In

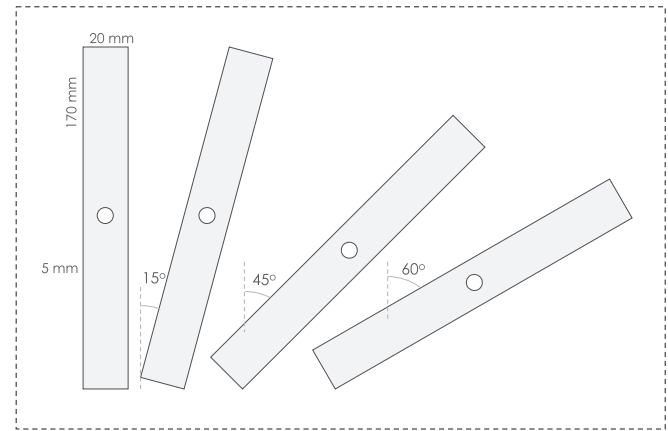


Fig. 2. Schematic of cutting angles and specimen dimensions.

addition to on-axis OHT tests, off-axis tests were performed by cutting specimens at an angle on the main manufactured plate. Fig. 2 provides the schematic representation of the specimen as well as the cutting layout. The selected angles for cutting and consequent off-axis load were selected to be 0° (on-axis), 15°, 45° and 60°. For each laminate type and loading angle, 3 to 5 specimens were manufactured. X-ray inspection was performed on a few specimens, and none showed delaminations, so the quality of the manufactured holes was deemed good to proceed with testing. All specimens but some of the CP laminate were tested on an Instron 5900R 4208H 0138–3 electro-mechanical universal testing machine equipped with hydraulic grips and a 200 kN load cell. Certain CP laminate specimens were tested on a Universal Testing Machine MTS 370.10 with 100 kN capacity. The gauge length was approximately 120 mm for all specimens.

#### 3.2. Test results

Fig. 3 provides the force–displacement data for all the lay-ups and off-axis loading angles. As can be seen, satisfactory consistency was achieved between the response of the tested specimens of each set for which the average values of notched strength are reported in Table 2. The notched strength is defined as the maximum remote stress, and it is equal to the force at failure divided by the unnotched cross-sectional area. As expected, the strength values for the QI laminate are uniform while all other laminates show variance in strength for different loading angles with the most significant differences obtained for the CP laminate. This is attributed to changes in the damage patterns obtained. Comparing the force–displacement evolutions, all specimens denote a brittle type of failure for the on-axis loading case, demonstrated by the presence of an abrupt drop in the load. Analyzing the curves for the rest of the angles, however, it can be seen that, for the CP1560 and CP1575 laminates, earlier load drops occur before failure, predominantly for loading at 45° and 60°. The CP, as will be also shown later, exhibited high nonlinearities in addition to load drops before failure. In all three latter laminates, these small drops indicate that premature failure events commence in a subcritical manner.

To better monitor the evolution of failure events during testing, digital image correlation (DIC) was employed, and the fracture surfaces were visually investigated afterwards. The 2D DIC set-up consists of a Canon EOS 80D camera fitted with a Canon EF-S 18–135 mm f/3.5–5.6 IS STM lens that was used to record video at 60 fps with a 1080p full HD resolution. The video was used as an input to do the DIC analysis using the GOM Correlate software and by using a subset size of 12 pixels and a subset length of 10 pixels and for strain calculations using a strain neighborhood of 4 that resulted in an average reference length of around

<sup>2</sup> Apart from visual evaluation of the polar plot to check for concavities one could mathematically evaluate it by keeping in mind that for the *inverse* of a function  $f = f(\theta)$  the polar plot of  $1/f(\theta)$  will be concave where  $f''(\theta) + f(\theta) \leq 0$  for any  $\theta \in [0, 2\pi]$  [27].

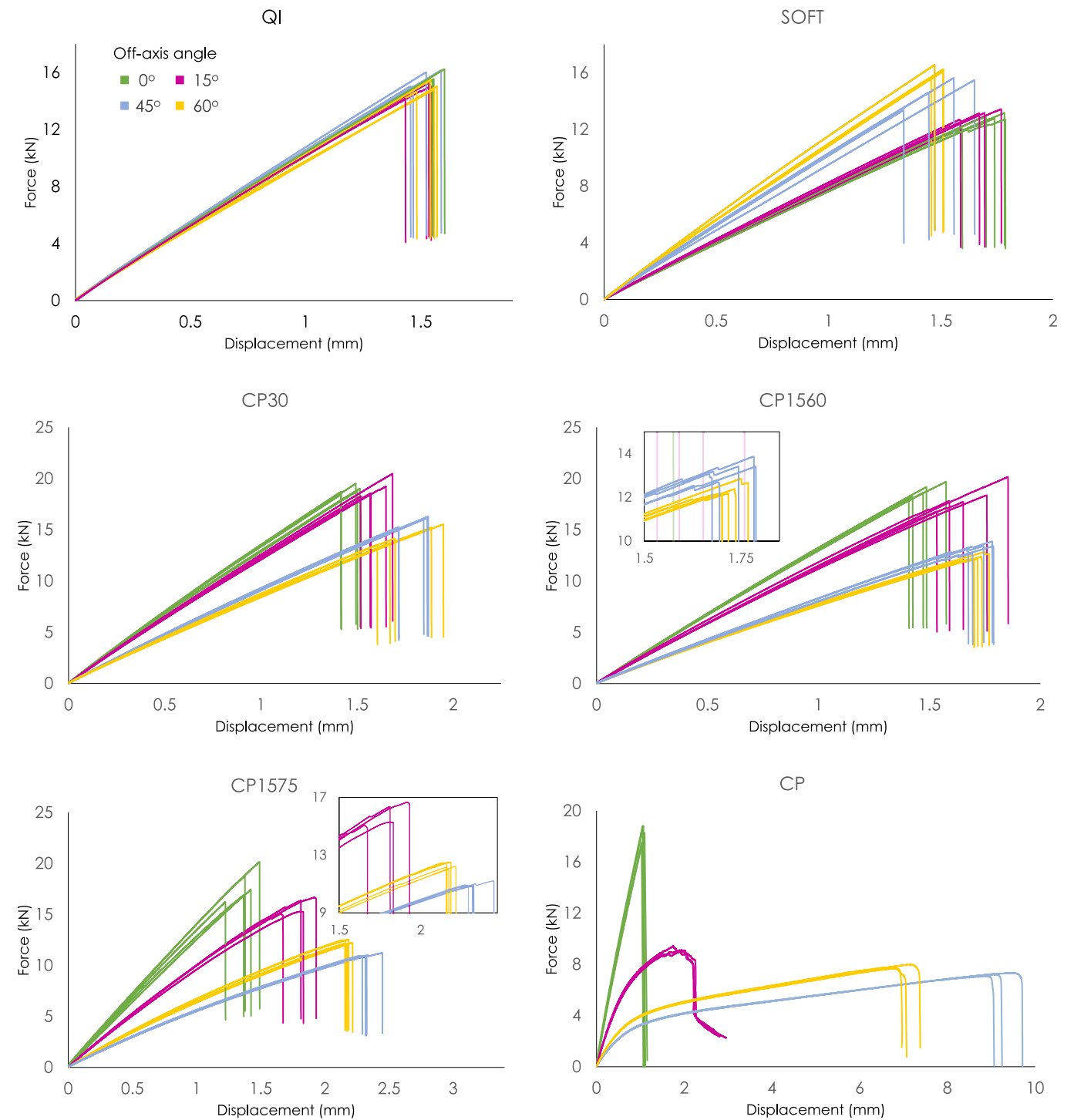


Fig. 3. Force-displacement curves for all tested laminates.

**Table 2**  
Notched strength values for all the laminates (in MPa) alongside the coefficient of variance for each set in parenthesis expressed in percentage (%).

| Angle | QI        | SOFT      | CP30      | CP1560    | CP1575    | CP        |
|-------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0°    | 492 (2.8) | 397 (3.3) | 590 (2.2) | 586 (3.7) | 559 (8.8) | 568 (3.6) |
| 15°   | 468 (3.7) | 410 (2.3) | 594 (4.7) | 568 (6.9) | 495 (4.9) | 287 (2.3) |
| 45°   | 486 (2.5) | 462 (3.2) | 492 (6.2) | 387 (3.3) | 343 (1.8) | 225 (2.0) |
| 60°   | 472 (3.9) | 498 (7.1) | 451 (3.7) | 416 (2.2) | 383 (1.3) | 244 (1.8) |



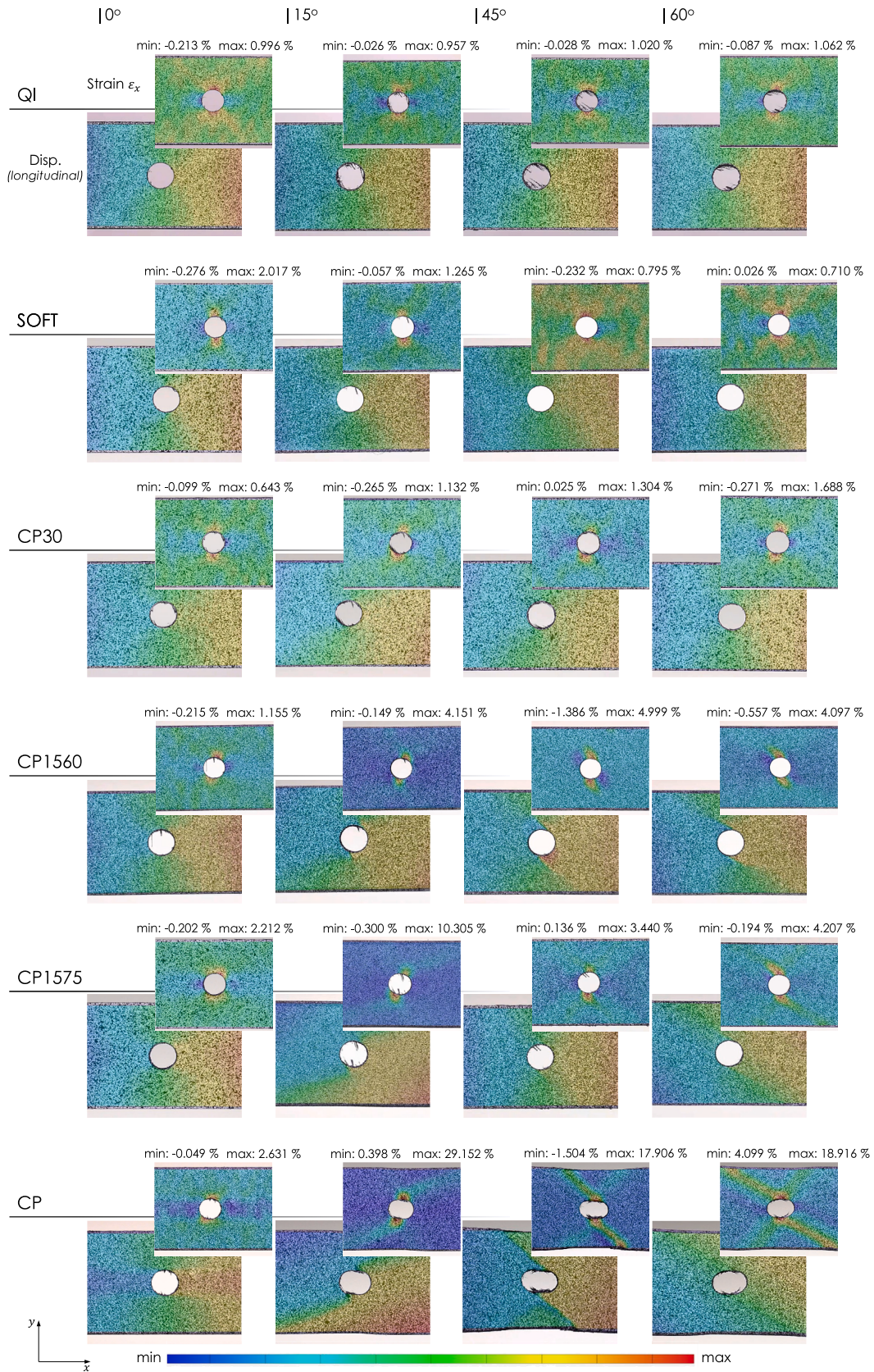
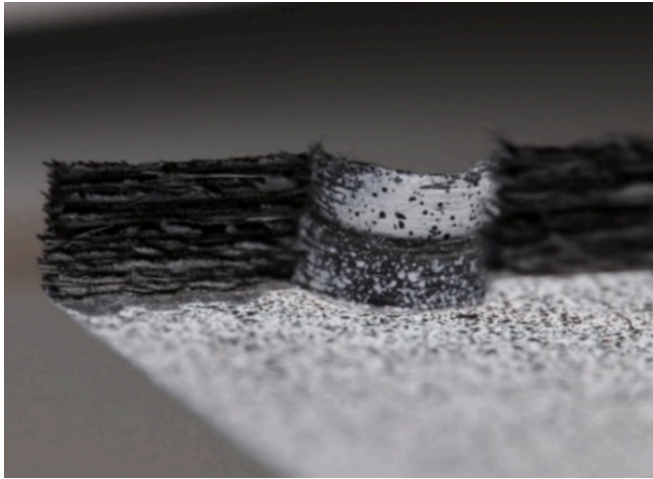


Fig. 4. DIC displacement and longitudinal strain fields for all tested laminates and loading angles at 95% of the remote failure strain. The loading direction and length of the specimen lie in the horizontal axis of the page.



**Fig. 5.** Representative net-section type through thickness failure form typical of the weakly anisotropic laminates (QI, SOFT and CP30) for on-axis and off-axis loading, and observed on all remaining laminates for on-axis loading. The specific specimen is from the CP30 laminate loaded on-axis.

2.5 mm.<sup>3</sup> Fig. 4 shows a comparison of the longitudinal displacement and strain fields for all angles and all layups at a remote strain of 95% of the mean remote failure strain observed. The remote failure strain is calculated using a virtual extensometer connecting two points along the length of the specimen lying on opposing points of the hole at a sufficient distance to not be affected by local phenomena. The observations on the failure of the specimens can be complemented by the post-mortem failure surfaces presented in Figs. 5–7.

As can be seen in Fig. 4, all specimens loaded on-axis present a rather smooth and uniform displacement field. For the QI, SOFT and CP30 laminates this extends to all other load angles as well. The same is observed for the longitudinal strain field shown as well. These specimens all failed demonstrating a type of net-section failure with a through-thickness crack driven by fiber failure, as shown in the example of Fig. 5. This “crack” for the off-axis angles also develops deflected at an angle with respect to the global specimen frame (and principal material axes of orthotropy), and not necessarily following a certain ply angle as shown in Fig. 6(a). Indeed, this was more prevalent for the QI and CP30 laminates whereas the SOFT laminate tended to start showing signs of a more complex post-mortem failure surface for the 60° off-axis loading case only (Fig. 6(b–c)). This, however, is not indicative of the existence of these mechanisms in a subcritical form before final failure as can be understood from the force displacement curve presented in Fig. 3 as no early load drops were identified and post-mortem investigation reveals a translaminar type “crack” in most cases as is seen for the specimen in Fig. 6(c) left side. The splitting on the outer surface is attributed to

<sup>3</sup> The DIC strains measurement is locally contingent to the value of the reference length. Thus, the maximum and minimum values refer to the regions near the hole where local events have occurred considering this reference length as the accuracy over which strains are calculated. It is obvious that if this value would be different so would the extrema of the strains reported. However, for the sake of this study this was not considered limiting to the analysis and discussion as these are based on relative differences between the specimens. It is noted that the minimum reference length the DIC analysis could achieve without compromising pattern quality was 0.8mm. For remote strains, i.e., far from the hole, the values are the same no matter what the reference length chosen, as long as it is in bounds of the DIC pattern limitations. The accuracy of the DIC measurement was evaluated by the indications during processing of GOM Correlate, and finite elements analysis was not considered necessary to evaluate the accuracy of the measurements based on previous experience of the authors with the acquisition setup and correlation software.

stochastic events and breaking that happens due to the abrupt failure and energetic release, not subcritical premature damage.

For the CP1560, CP1575 and CP laminates, the off-axis angles show displacement discontinuities before failure, which is also evident when looking at the longitudinal strain field. This is primarily indicative of a split crack developing in the outer ply and possible delaminations occurring in the underlying plies. Indeed, as can be seen in the post-mortem images in Fig. 7, it is evident that the CP1560 (Fig. 7(a–b)) and CP1575 (Fig. 7(c)) laminates suffered a combination of delaminations, pull-outs and split cracking sub-critically until these mechanisms alongside fiber failure eventually led to final failure. The CP (Fig. 7(d–e)) laminate demonstrated high versatility in damage patterns with loading at 45° and 60° leading to damage driven solely by delaminations Fig. 7(d) and very interestingly 15° off-axis loading leading to failure by development of a band of rotated fibers as shown in Fig. 7(e). It is noted that the delaminations seen here are not considered a result of free-edge effects by considering the DIC field images seen in Fig. 4 showing no significant strain concentrations at the specimen edges. While free-edge delaminations would be something expected of standard grade composites [1,8,24] given the background on studies on the topic that have reported thin-ply to being able to suppress delaminations and consequently free-edge delaminations even in angle-ply lay-ups [14–16] the observations reported here are considered consistent and expected in that regard.

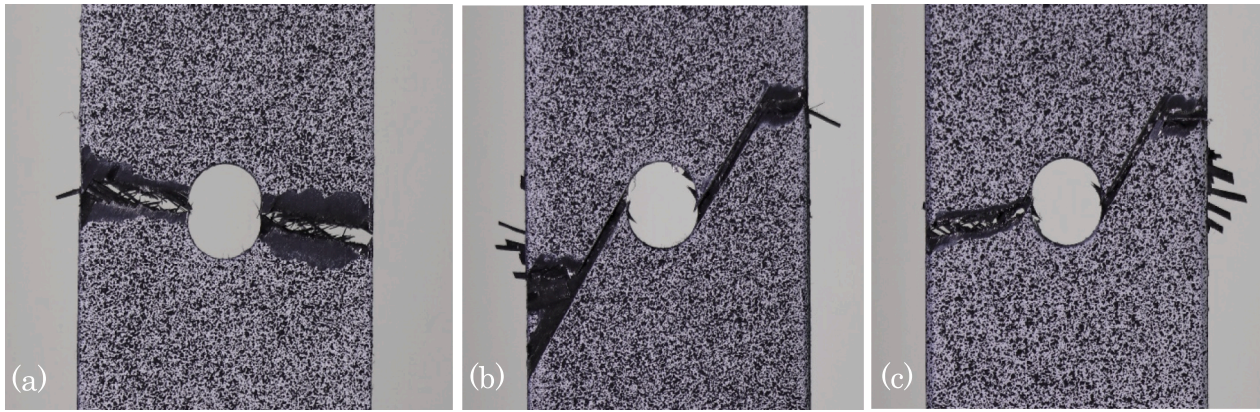
### 3.3. Discussion

The literature on failure of thin-ply CFRP laminates has mostly reported net section, crack-like, failure patterns, as mentioned in the introduction. This type of failure observed till date for thin-ply laminates has differentiated thin-ply significantly from standard-ply composites. In fact, this was observed for all laminates tested in this work for an on-axis loading state, but not necessarily for off-axis loading. Indeed, the net section type failure pattern for both on-axis and off-axis loading in this study is associated with the laminates categorized as weakly anisotropic (QI, CP30, SOFT). The strongly anisotropic CP1560, CP1575, and CP laminates, however, as mentioned, were the ones that, contrary to what would be expected, developed premature damage in the form of matrix failure (delaminations, split cracking etc.) under off-axis loading. Such a failure pattern is indicative of the failure of standard-ply CFRPs regardless of the level of anisotropy, as delaminations tied with splitting and extensive premature damage would be the expectation for a QI and a CP of a standard-ply CFRP laminate subjected to OHT [2–5,8].

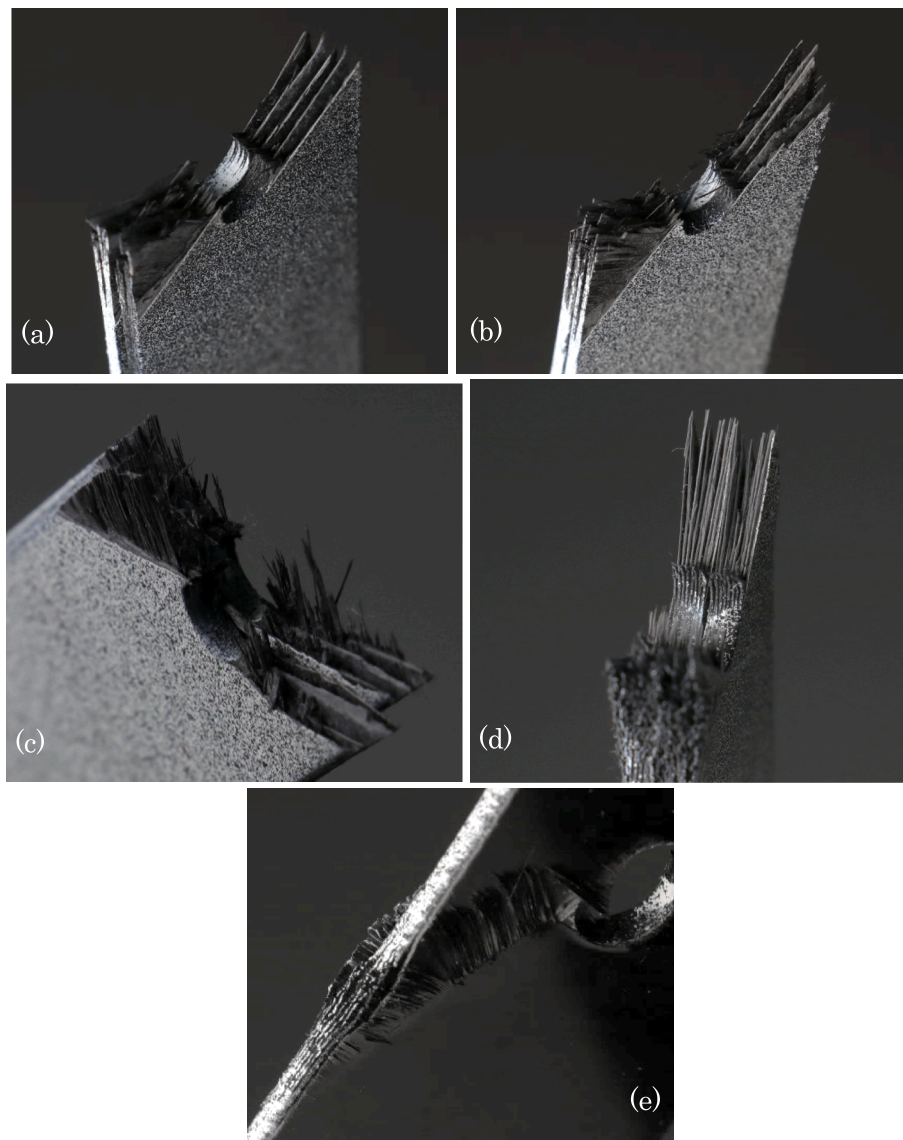
The observations of the present experiments seem to, for the unique case of thin-ply laminates, give a correlation of the macroscopic damage form, including matrix cracking, to the level of anisotropy the laminate has. Intuitively, this suggests that the severity of the differences in the elastic properties, as the material vs load angle changes, could directly affect the response of a MD thin-ply laminate. Additionally, the effect of the level of anisotropy, seen by the severity of the difference of the observed failure patterns between the net-section type failure of the on-axis loading case and each subsequent angle, based on these results, becomes more prominent as the laminates tend to the CP laminate.

What has been seen to drive the difference in the failure pattern for thin-ply laminates overall is a stronger *in-situ* effect. Thus, when the mismatch angle between two plies is high enough, the inner ply is constrained to a higher level and matrix damage (matrix cracking) is markedly suppressed. Interestingly, Korbelen et al. [23] reported a larger extent of matrix cracking before final failure in OHT testing of Bouligand thin-ply laminates. This Bouligand structure had a pitch angle of 2.5° (ply mismatch angle) and thus the *in-situ* effect in that case would not be as strong. This could serve to explain some of the observations in this work, since, for instance, the CP1575 laminate presents a mismatch angle of 15° for most interfaces, and the CP30 laminate 30°. The reduced suppressive effect to matrix damage phenomena in these laminates





**Fig. 6.** Failure form typical of the laminates with weaker anisotropy for off-axis loading (a) crack like macroscopic failure as seen from the front of the CP30 15° off-axis specimen, and (b) & (c) two failed SOFT laminate specimens for 60° off-axis loading.



**Fig. 7.** Failure forms observed in the laminates with stronger anisotropy that alongside fiber failure also presented more complex failure events: (a) CP1560 45° off-axis loading featuring delaminations and fiber pull-outs, (b) CP1560 60° off-axis loading featuring mainly delaminations, (c) CP1575 60° off-axis loading featuring extensive fiber pull out and some delaminations, (d) CP 45° off-axis loading featuring pure delamination in all plies, and (e) CP 15° off-axis loading featuring a band of rotated fibers as the localized damage event.



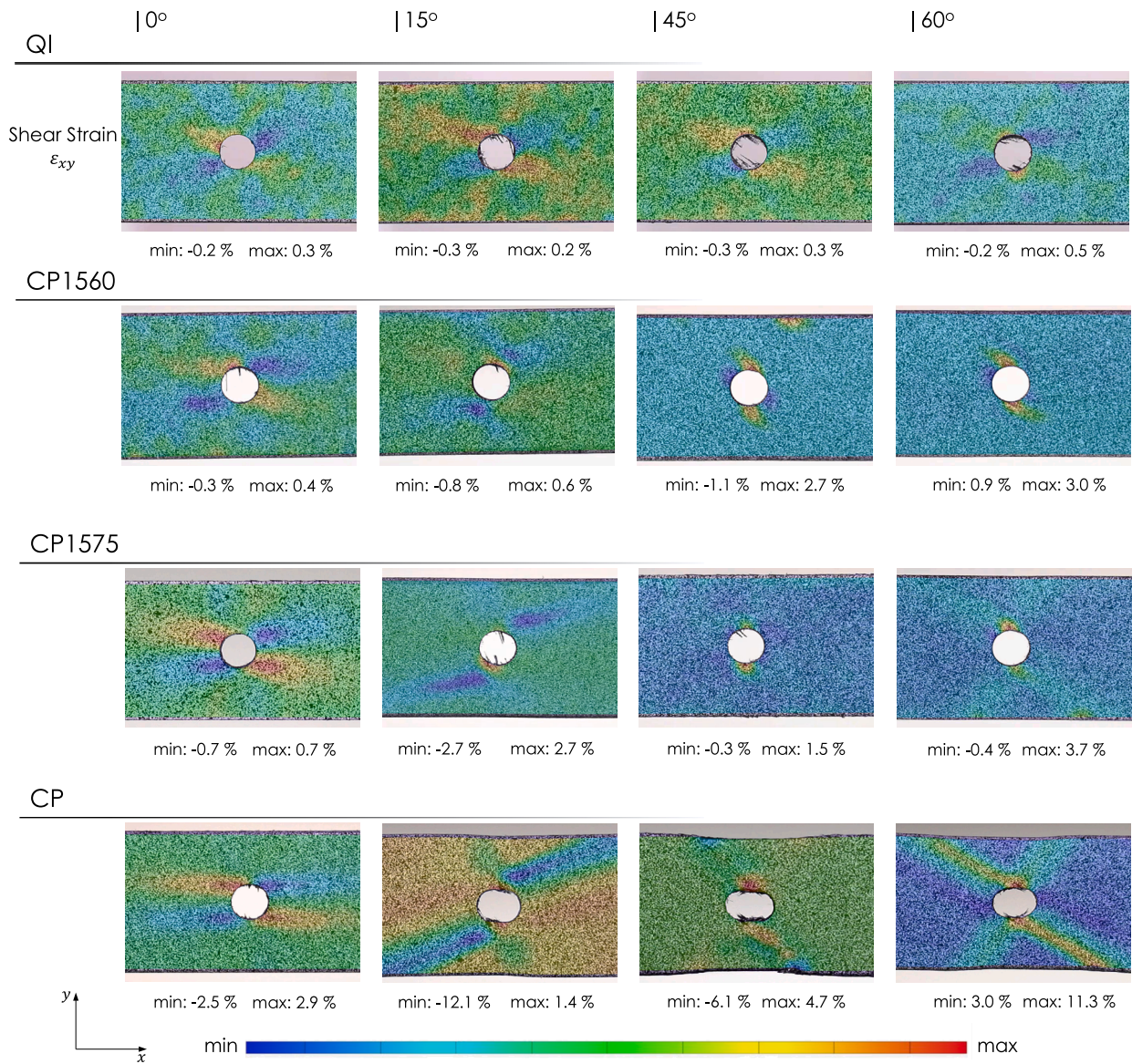


Fig. 8. Comparison of the shear strain fields for the QI, CP1560, CP1575 and CP laminate at 95% of the remote failure strain.

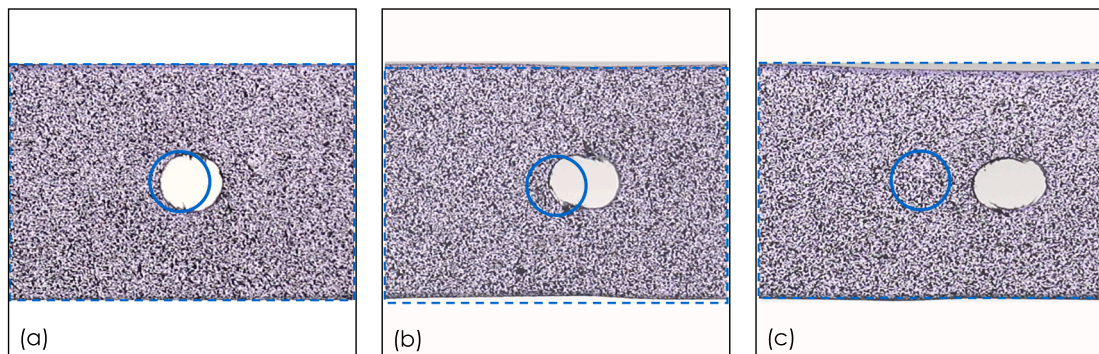


Fig. 9. Images of the deformed and undeformed (blue wireframe) CP specimens for (a)  $0^\circ$ , (b)  $15^\circ$  and (c)  $60^\circ$  off-axis loading demonstrating the difference in overall deformation observed for different load angles.

could explain the observed patterns. In the case of CP laminates under off-axis loading, matrix damage can be mostly attributed to the fact that deformation becomes mostly matrix-dominated, considering the

mismatch between loading direction and orientation of the fibers, leading to high nonlinear deformations.

As seen in Fig. 4 and in Fig. 8, which compares the shear strain,  $\epsilon_{xy}$ ,

field for the QI, CP1560, CP1575 and CP laminate at 95% of the remote failure strain, the strain components for each respective laminate at different angles have a rather different trend. The longitudinal strains in the QI laminate for all angles are at a minimum around  $-0.2\%$  and a maximum of about  $1.0\%$  and the shear component ranges from  $-0.3\%$  and  $0.5\%$  for all angles. These maximum and minimum values refer to the overall field but as evident from the DIC plots they occur at the area near the notch. For the CP1560 laminate, the longitudinal strains, for all off-axis angles, lie around  $4\%$ , which is rather uniform. But as seen in Fig. 8, the shear strains show broader differences ranging from  $0.4\%$  maximum for loading on-axis and  $3.0\%$  for  $60^\circ$  off-axis loading. Similar trends are observed for the CP1575 as well, with slightly more prominent differences in the longitudinal strain maximum values, i.e.,  $10.305\%$  at  $15^\circ$  and  $3.44\%$  at  $45^\circ$ , and shear strains ranging from  $0.7\%$  to  $3.7\%$  maximum observed for  $60^\circ$  off-axis loading. For the laminate with the highest level of anisotropy, the CP laminate, the on-axis loading resulted in a minimum of longitudinal strain of  $-0.049\%$  and a maximum  $2.6\%$  and for the shear component  $-2.5\%$  to  $2.9\%$ . But when loaded at the rest of the angles, the absolute shear strains increase significantly, especially for  $15^\circ$  and  $60^\circ$  off-axis angles, where the effects of shear extension coupling can also be clearly observed in the deformed shape of the specimens (Fig. 9). Deformation is significantly different and larger in off-axis load angles something not observed for the weakly anisotropic plates. This vast difference in longitudinal strain values and the occurrence of a prominent local shear strain component on the outer ply as the loading angle is altered, visible through the DIC measurements, altered could explain why indeed for the laminates with a stronger level of anisotropy premature failure in the form of matrix dominated events was unexpectedly observed, while also explaining the significant difference in observed failure patterns for different loading angles of the tested laminates.

Based on these observations, it seems that such ESL modeling approaches, relying on the assumption of a net-section quasi-brittle type failure, are definitely suitable to model the behavior of MD thin-ply laminates, but with caution of them lying in a range of a weakly anisotropic behavior. For laminates lying well within the strongly anisotropic range, where there is a prominent difference in the failure patterns observed at each loading angle, ply level effects lead to diffuse damage that cannot be properly represented by use of an ESL approach identified using on-axis properties. In effect, the direction curves can provide a simple way, relying on easily attainable elastic properties of the composite's lamina, to evaluate the level of anisotropy of a MD thin-ply laminate and estimate how failure will appear for the laminate in terms of pattern (i.e., containing or not diffuse damage) and uniformity (i.e., remaining the same for all loading angles). With many new emerging design ideas for laminates, and as practices might navigate towards the use of unconventional lay-ups, e.g., the double-double lay-up concept [16,23,34,41] or Bouligand (anisotropic) structures [23,41], the suitability of efficient modeling should be properly considered, based on not only on-axis loading scenarios but also more complex cases.

#### 4. Conclusions

Stemming from the earlier work of the authors on applying an ESL

modeling approach to simulate failure of MD thin-ply laminates, this work represents an effort to extend the experimental database and observations regarding the notched response of thin-ply laminates. The study involved testing in OHT of a range of laminate lay-ups in on-axis and off-axis loading. The selection of the lay-ups was performed based on their level of anisotropy defined using direction curves that only require the homogenized elastic properties of the laminate to be determined.

The on-axis response for all laminates followed a net-section type failure with a crack like macroscopic appearance. The same trend was observed for the weaker anisotropic plates for all other tested angles. However, it was shown that for the laminates of a stronger anisotropic nature, failure could occur due to a combination of other failure mechanisms such as split cracking and delaminations, which are typically observed in the OHT tests of standard-ply CFRPs. This shows that the level of anisotropy could significantly change the failure pattern and the notched strength of thin-ply, quasi-homogeneous laminates.

#### CRedit authorship contribution statement

**Anatoli Mitrou:** Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Albertino Arteiro:** Writing – review & editing, Supervision. **José Reinoso:** Writing – review & editing, Supervision. **Pedro P. Camanho:** Writing – review & editing, Supervision, Conceptualization.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

Data will be made available on request.

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#### Appendix A. Material characterization for the T800/736LT system

To provide the direction curves and choose the laminates for the experiments, a prior characterization of the material system at hand had to be performed. The elastic ply properties of the CFRP T800/736LT thin-ply prepreg from NPTT were obtained following the ASTM standards D3039 and D3518. The results of the tests resulted in the properties stated in Table A.1 below. The subscript 1 denotes the longitudinal, along the fibers, direction and 2 the transverse direction.

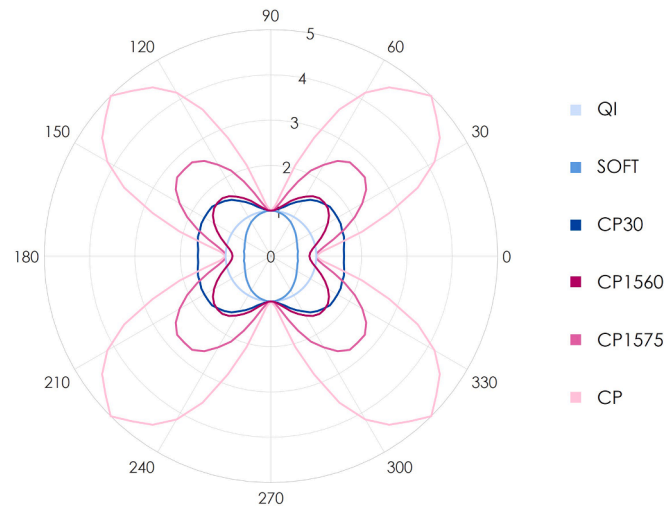


**Table A1**  
-Ply elastic properties of the T800/736LT material system.

| $E_1$ (GPa) | $E_2$ (GPa) | $G_{12}$ (GPa) | $\nu_{12}$ |
|-------------|-------------|----------------|------------|
| 143.83      | 7.85        | 3.80           | 0.38       |

## Appendix B. Inverse ERR plots for the tested laminates

In Section 2, it was explained that the level of anisotropy has been defined in the literature using the fracture toughness of a material expressed in terms of energy release rate. However, as mentioned, this is not easy to do for composite laminates. It is noted that this refers to the fracture toughness for a through-thickness crack in a composite laminate at the homogenized plate level. In an effort to provide some form of a relevant representation at least in a qualitative manner of the shape of the inverse polar curve of the fracture toughness distribution the following assumption is made; the fracture toughness distribution of the composite laminate will be analogous to the distribution of the ERR at a certain opening displacement of an initial crack present in that material. Following that assumption, the ERR is numerically calculated using the VCCT as in [19]. These curves are presented in Figure B.1.



**Fig. B1.** Inverse plots of the scaled ERR for all tested laminates

The ERR values taken per angle of the crack were normalized so that the ERR for a crack at 90° with respect to the principal material axes and on-axis loading is equal to 1. As seen in Figure B.1, when looking directly at the ERR, the QI and SOFT laminates are convex whereas all the other laminates present concave regions. Following the assumption mentioned previously, this would indicate that the QI and SOFT are the weakly anisotropic laminates and the rest strongly anisotropic. It is interesting that, excluding the CP30 and CP1560 laminates, all other laminates presenting concave parts in the inverse ERR plots also present concave parts in their direction curves seen in Fig. 1 and vice versa. Indeed, if the fracture toughness would have a form following a scaled ERR distribution and after evaluating the experimental results it seems that these laminates can be expected to lie directly in between the states of weak and strong anisotropy, in a sort of transitional region. The failure form type of CP30, which did not show any premature damage events and load drops or evident delaminations from the post-mortem image of the surface, is close to the QI and SOFT, while the CP1560 laminate failed similarly to the CP1575 and CP. The ERR plot shows that, for the CP30, the ERR is still quite uniform in its value for different angles, not exhibiting very large differences in the values at the concave parts with the convex parts, and thus the laminate lies closer to a purely convex shape. Contrarily, the ERR distribution form for the CP1560 laminate is evidently non-convex in its totality with vast differences. This does emphasize that the ERR would still be a better metric than pure elasticity to define and categorize the laminates in terms of level of fracture anisotropy.

## References

- [1] Hallett SR, Green BG, Jiang W-G, Cheung KH, Wisnom MR. The open hole tensile test: a challenge for virtual testing of composites. *Int J Fract* 2009;158:169–81. <https://doi.org/10.1007/s10704-009-9333-8>.
- [2] Green BG, Wisnom MR, Hallett SR. An experimental investigation into the tensile strength scaling of notched composites. *Compos Part A Appl Sci Manuf* 2007;38: 867–78. <https://doi.org/10.1016/J.COMPOSITESA.2006.07.008>.
- [3] Chuaqui TRC, Nielsen MWD, Colton J, Butler R, Rhead AT. Effects of ply angle and blocking on open-hole tensile strength of composite laminates: A design and certification perspective. *Compos B Eng* 2021;207:108582. <https://doi.org/10.1016/J.COMPOSITESB.2020.108582>.
- [4] O'Higgins RM, McCarthy MA, McCarthy CT. Comparison of open hole tension characteristics of high strength glass and carbon fibre-reinforced composite materials. *Compos Sci Technol* 2008;68:2770–8. <https://doi.org/10.1016/J.COMPOSITECH.2008.06.003>.
- [5] Erçin GH, Camanho PP, Xavier J, Catalanotti G, Mahdi S, Linde P. Size effects on the tensile and compressive failure of notched composite laminates. *Compos Struct* 2013;96:736–44. <https://doi.org/10.1016/J.COMPSTRUCT.2012.10.004>.
- [6] Camanho PP, Maimí P, Dávila CG. Prediction of size effects in notched laminates using continuum damage mechanics. *Compos Sci Technol* 2007;67:2715–27. <https://doi.org/10.1016/J.COMPOSITECH.2007.02.005>.
- [7] Greenhalgh ES. Failure analysis and fractography of polymer composites. Woodhead Publishing Limited 2009. <https://doi.org/10.1533/9781845696818>.
- [8] Irvine TB, Ginty CA. Fracture modes in notched angleplied composite laminates. *NASA Tech Memo* 1984;83802.
- [9] Arteiro A, Catalanotti G, Xavier J, Camanho PP. Notched response of non-crimp fabric thin-ply laminates. *Compos Sci Technol* 2013;79:97–114. <https://doi.org/10.1016/J.COMPOSITECH.2013.02.001>.
- [10] Huang C, Ju S, He M, Zheng Q, He Y, Xiao J, et al. Identification of failure modes of composite thin-ply laminates containing circular hole under tension by acoustic emission signals. *Compos Struct* 2018;206:70–9. <https://doi.org/10.1016/J.COMPSTRUCT.2018.08.019>.

- [11] Sihn S, Kim RY, Kawabe K, Tsai SW. Experimental studies of thin-ply laminated composites. *Compos Sci Technol* 2007;67:996–1008. <https://doi.org/10.1016/J.COMPOSITECH.2006.06.008>.
- [12] Lovejoy AE, Scotti SJ, Miller SG, Heimann P, Miller SS. Characterization of IM7/8552 thin-ply and hybrid thin-ply composites. *AIAA Scitech* 2019. Forum 2019. <https://doi.org/10.2514/6.2019-0773>.
- [13] Amacher R, Cugnoni J, Botsis J, Sorensen L, Smith W, Dransfeld C. Thin ply composites: Experimental characterization and modeling of size-effects. *Compos Sci Technol* 2014;101:121–32. <https://doi.org/10.1016/J.COMPOSITECH.2014.06.027>.
- [14] Arteiro A, Furtado C, Catalanotti G, Linde P, Camanho PP. Thin-ply polymer composite materials: A review. *Compos Part A Appl Sci Manuf* 2020;132:105777. <https://doi.org/10.1016/J.COMPOSITESA.2020.105777>.
- [15] Wu X, Fuller JD, Longana ML, Wisnom MR. Reduced notch sensitivity in pseudo-ductile CFRP thin ply angle-ply laminates with central 0° plies. *Compos Part A Appl Sci Manuf* 2018;111:62–72. <https://doi.org/10.1016/j.compositesa.2018.05.011>.
- [16] Fuller JD, Wisnom MR. Pseudo-ductility and damage suppression in thin ply CFRP angle-ply laminates. *Compos Part A Appl Sci Manuf* 2015;69:64–71. <https://doi.org/10.1016/J.COMPOSITESA.2014.11.004>.
- [17] Furtado C, Tavares RP, Arteiro A, Xavier J, Linde P, Wardle BL, et al. Effects of ply thickness and architecture on the strength of composite sub-structures. *Compos Struct* 2021;256:113061. <https://doi.org/10.1016/J.COMPSTRUCT.2020.113061>.
- [18] Camanho PP, Dávila CG, Pinho ST, Iannucci L, Robinson P. Prediction of in situ strengths and matrix cracking in composites under transverse tension and in-plane shear. *Compos Part A Appl Sci Manuf* 2006;37:165–76. <https://doi.org/10.1016/j.compositesa.2005.04.023>.
- [19] Mitrou A, Arteiro A, Reinoso J, Camanho PP. Modeling fracture of multidirectional thin-ply laminates using an anisotropic phase field formulation at the macro-scale. *Int J Solids Struct* 2023;273:112221. <https://doi.org/10.1016/J.IJSOLSTR.2023.112221>.
- [20] Reinoso J, Arteiro A, Paggi M, Camanho PP. Strength prediction of notched thin ply laminates using finite fracture mechanics and the phase field approach. *Compos Sci Technol* 2017;150:205–16. <https://doi.org/10.1016/J.COMPOSITECH.2017.07.020>.
- [21] Arteiro A, Catalanotti G, Reinoso J, Linde P, Camanho PP. Simulation of the Mechanical Response of Thin-Ply Composites: From Computational Micro-Mechanics to Structural Analysis. *Arch Comput Meth Eng* 2019;26:1445–87. <https://doi.org/10.1007/s11831-018-9291-2>.
- [22] Laux T, Gan KW, Tavares RP, Furtado C, Arteiro A, Camanho PP, et al. Modelling damage in multidirectional laminates subjected to multi-axial loading: Ply thickness effects and model assessment. *Compos Struct* 2021;266:113766. <https://doi.org/10.1016/J.COMPSTRUCT.2021.113766>.
- [23] Körbelin J, Goralski P, Köter B, Bittner F, Endres H-J, Fiedler B. Damage tolerance and notch sensitivity of bio-inspired thin-ply Bouligand structures. *Composites Part C: Open Access* 2021;5:100146. <https://doi.org/10.1016/j.jcomc.2021.100146>.
- [24] Oz FE, Mehdikhani M, Ersoy N, Lomov SV. In-situ imaging of inter- and intralaminar damage in open-hole tension tests of carbon fibre-reinforced composites. *Compos Struct* 2020;244:112302. <https://doi.org/10.1016/j.compositestruct.2020.112302>.
- [25] Kawai M, Arai Y. Off-axis notched strength of fiber–metal laminates and a formula for predicting anisotropic size effect. *Compos Part A Appl Sci Manuf* 2009;40:1900–10. <https://doi.org/10.1016/J.COMPOSITESA.2009.07.014>.
- [26] Corre T, Lazarus V. Kinked crack paths in polycarbonate samples printed by fused deposition modelling using criss-cross patterns. *Int J Fract* 2021. <https://doi.org/10.1007/s10704-021-00518-x>.
- [27] Takei A, Roman B, Bico J, Hamm E, Melo F. Forbidden Directions for the Fracture of Thin Anisotropic Sheets: An Analogy with the Wulff Plot. *Phys Rev Lett* 2013;110:144301. <https://doi.org/10.1103/PhysRevLett.110.144301>.
- [28] Williams JG. On the calculation of energy release rates for cracked laminates. *Int J Fract* 1988;36:101–19. <https://doi.org/10.1007/BF00017790>.
- [29] Krueger R. A summary of benchmark examples to assess the performance of quasi-static delamination propagation prediction capabilities in finite element codes. *J Compos Mater* 2015;49:3297–316. <https://doi.org/10.1177/0021998314561812>.
- [30] Murri GB. Effect of data reduction and fiber-bridging on Mode I delamination characterization of unidirectional composites. *J Compos Mater* 2014;48:2413–24. <https://doi.org/10.1177/0021998313498791>.
- [31] Catalanotti G, Arteiro A, Hayati M, Camanho PP. Determination of the mode I crack resistance curve of polymer composites using the size-effect law. *Eng Fract Mech* 2014;118:49–65. <https://doi.org/10.1016/j.engfracmech.2013.10.021>.
- [32] Camanho PP, Catalanotti G. On the relation between the mode I fracture toughness of a composite laminate and that of a 0° ply: Analytical model and experimental validation. *Eng Fract Mech* 2011;78:2535–46. <https://doi.org/10.1016/J.ENGFRACMECH.2011.06.013>.
- [33] Furtado C, Arteiro A, Linde P, Wardle BL, Camanho PP. Is there a ply thickness effect on the mode I intralaminar fracture toughness of composite laminates? Theoretical and Applied Fracture Mechanics 2020;107:102473. <https://doi.org/10.1016/J.TAFMEC.2020.102473>.
- [34] Vermes B, Tsai SW, Massard T, Springer GS, Czigan T. Design of laminates by a novel “double-double” layup. *Thin-Walled Struct* 2021;165:107954. <https://doi.org/10.1016/J.TWS.2021.107954>.
- [35] Braun M, Bischoff M, Ramm E. Nonlinear shell formulations for complete three-dimensional constitutive laws including composites and laminates. *Comput Mech* 1994;15:1–18. <https://doi.org/10.1007/BF00350285>.
- [36] Lekhnitskii SG. *Theory Of Elasticity Of An Anisotropic Body*. 1981.
- [37] Ting TCT. On Anisotropic Elastic Materials for which Young's Modulus  $E(n)$  is Independent of  $n$  or the Shear Modulus  $G(n, m)$  is Independent of  $n$  and  $m$ . *J Elast* 2006;81:271–92. <https://doi.org/10.1007/s10659-005-9016-2>.
- [38] Ting TCT, Chen T. Poisson's ratio for anisotropic elastic materials can have no bounds. *Q J Mech Appl Math* 2005;58:73–82. <https://doi.org/10.1093/qjmamj/hbh021>.
- [39] Zheng QS, Chen T. New perspective on Poisson's ratios of elastic solids. *Acta Mechanica* 2001;150:191–5. <https://doi.org/10.1007/BF01181811>.
- [40] Ting TCT. The Stationary Values of Young's Modulus For Monoclinic and Triclinic Materials. *J Mech* 2005;21:249–53. <https://doi.org/10.1017/S1727719100000691>.
- [41] Mencattelli L, Pinho ST. Ultra-thin-ply CFRP Bouligand bio-inspired structures with enhanced load-bearing capacity, delayed catastrophic failure and high energy dissipation capability. *Compos Part A Appl Sci Manuf* 2020;129:105655. <https://doi.org/10.1016/j.compositesa.2019.105655>.