ANALYSIS OF THE MATRIX TRANSVERSE DAMAGE IN A UD PLY OF AN UNBALANCED HYBRID PEEK-CARBON/GLASS COMPOSITE UNDER COMBINED STATIC LOAD

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Keywords: PEEK, carbon, composite, damage, transverse

Abstract
Assuming plane stresses, an unidirectional ply intra-laminar damage is the result of in-plane shear and transverse tension, mainly due to micro-cracks resulting with a stiffness loss. [1, 2, 4, 5, 6] However, damage due to the latter is difficult to study owing to its brittle behaviour, this premature failure [4] being not representative of its transverse behaviour in a laminate. Besides, transverse tensile tests give better results for an unbalanced woven fabric glass/epoxy 83/17 (83% of fibres in the warp direction, 17% in the weft). Indeed, their failure is not brittle as the 17% of fibres in the weft direction limit the cracks propagation to the whole specimen. [6] Therefore, a new unbalanced hybrid Carbon/Glass-PEEK composite 87/13 has been especially developed for this work.
For the model parameters identification, then the damage evolution, the performed tests are quasi-static tensile tests with loading/unloading cycles for the stiffness loss observation, the strain field measured by strain gages and Digital Image Correlation. Tensile tests on $[30°]_{12}$, $[45°]_{12}$, $[60°]_{12}$, $[67°]_{12}$, $[78°]_{12}$ and $[90°]_{12}$ laminates have been carried out on flat dumbbell-shaped specimens. Hence, for carbon fibres transverse tension load, this study leads to a better model parameters identification for the matrix transverse damage.

Excerpt from ISBN 978-3-00-053387-7

1. Introduction

The model used is developed by the LMA [2, 4, 5, 6] and based on [1]. Particularly, in the in-plane shear and transverse directions, an unidirectional (UD) ply under a static tensile load has a non-linear behaviour with damage. Assuming plane stresses, this intra-laminar damage is mainly due to micro-cracks directed along the fibres resulting in a decrease in stiffness. Thus, the identification of the model parameters is based on the observation of the stiffness loss during quasi-static tests with loading/unloading cycles.
For transverse load, tensile test on [90°] UD epoxy/carbon specimen in [4] shows an early failure at a very low strain level, leading to an incomplete identification of the model parameters. Moreover, this brittle behaviour is not representative of its transverse behaviour in a laminate. To prevent this, it has

been added in [4] elastic plies in glass fibre on both sides of the carbon/epoxy specimens, in order to allow the specimen to sustain larger strains and so, to delay the final failure.
Besides, transverse tensile tests give better results for an unbalanced woven fabric glass/epoxy 83/17 in [6] (83% of fibres in the warp direction, 17% in the weft). Indeed, this transverse failure is not brittle as the 17% of fibres in the weft direction do limit the cracks propagation to the whole specimen. Furthermore, for a thermosetting matrix such as epoxy, tensile tests carried out on [±67.5°] laminate in [1] show that the behaviour remains brittle. Whereas, for a thermosplastic matrix such as PEEK, tensile tests performed on [±67.5°] laminate in [3] showed a delay in the micro-cracks occurrence due to the higher ductility of PEEK compared to epoxy ; even if the mixed damage type, due to tension and shear, makes its identification more difficult.
Thus, a new unbalanced hybrid Carbon/Glass-PEEK composite has been developed especially for this work. The fibres ratio between the warp and the weft direction is 87/13, close to the one in [6]. Its weft fibre is a low lineic mass E-glass yarn chosen for its high strength on stiffness ratio enabling us to observe damage over a greater strains range. In this study, the performed tests are quasi-static tensile tests with loading/unloading cycles in order to observe the damage evolution. The strain field measurements are made by strain gages and Digital Image Correlation (ARAMIS Software).
Despite this new material, for pure transverse loading i.e. testing on $[90°]_{12}$ laminate, the behaviour remains brittle. Then, for the model parameters identification, off-axis tensile tests on $[30°]_{12}$, $[45°]_{12}$, $[60°]_{12}$, $[67°]_{12}$ and $[78°]_{12}$ laminates have been carried out on flat dumbbell-shaped specimens, with the added difficulty of a combined load state of in-plane shear and transverse tension. The overall evolution of specimens damage is found to obey to a non-linear law. Hence, by analysing those results and comparing them to the literature for transverse to the carbon fibres tension load, this study leads to a better identification of the model parameters for the matrix transverse damage.

2. Material and method

2.1. Material

The unbalanced hybrid carbon/glass weave composite material studied here is produced by combining a thermoplastic resin PEEK with carbon in the warp direction and glass in the weft direction.
The volumic warp/weft ratio is 87/13 (Fig. 1), a value chosen to be close to the 83/17 ratio in [6].
The warp carbon fibre, a High Strength fibre type, is T300J (3K carbon thread, 198 tex, sizing 1.2 %, shrinkage 0.25 %) and the weft glass fibre is the yarn EC9 68 Z40 PPG 1383 (68 tex, sizing 0.7 %, shrinkage 0.83 %). This glass fibre is exactly the same one used in the work of [5, 6].
The weave type is a plain weave, the warp and weft are aligned so they form a simple criss-cross pattern. Each weft thread crosses the warp threads by going over one, then under the next, and so on.
The matrix is Polyether-ether-ketone (PEEK), an organic semicrystalline thermoplastic polymer showing excellent mechanical, thermal and chemical resistance properties.
In terms of processing, the plates were consolidated via hot-pressing process (395°C, 11 bars).
The composite obtained by this way (Fig. 1) shows very good both thickness and volume fibre fraction stability, and a good repeatability in terms of C/Scan inspection. The plates are manufactured using 12 plies in order to achieve a 2 mm thickness plate, with a resulting fibre volume fraction $V_f = 54{,}5\%$.

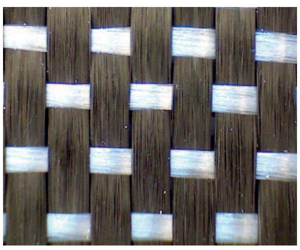

Figure 1. Unbalanced hybrid PEEK-Carbon/Glass Composite, manufactured by Porcher Industries.

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2.2. Specimens

Concerning the state of the art of methods for the transverse tension testing, standard tests exist. According to the ASTM D5450, the specimens are tubular-shaped, but it implies a certain level of difficulty for their manufacturing. Furthermore, the ASTM D3039 recommends rectangular flat test specimens with tapered tabs. But in that case, delamination that can occur at the tabs ends causes a a failure at a low strains level. In addition, the ASTM D5083 preconizes rectangular-shaped specimens with no tapered tabs, a sources of early failures with an under-estimation of strength due to a stress concentration in those areas. Finally, the specimen geometry used in previous works in [4, 5, 6] with good results are dumbbell-shape type, with the advantage of the no need of using reinforced tabs to prevent the occurrence of clamping effects.

Consequently, the specimen geometry type chosen for this work is a dumbbell-shape type and its geometry is shown in Fig. 2. As a result, all the tests presented here have their specimen failure occurred in the central zone of the specimen. In addition, the high radius of the specimens edge is chosen in order to avoid a non-uniform stress field in the gage length.
The specimens were subsequently machined to their final shape using a water-only jet cutter, an industrial tool capable of cutting a wide variety of materials using a very high-pressure jet of water at high speed, without the use here of added abrasives. It is the preferred method when the materials being cut are sensitive to the high temperatures generated by other methods.

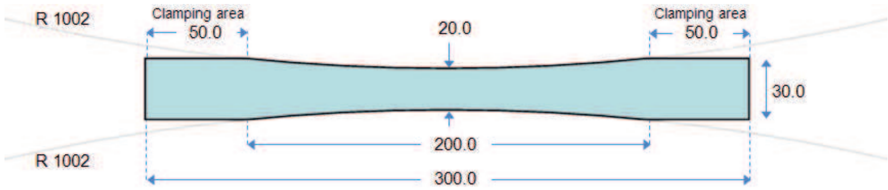

Figure 2. Quasi-static tensile test specimen geometry.

Static tensile tests were performed with loading/unloading cycles, using an MTS 100 KN machine. The specimens were fixed to the machine using hydraulic jaws. The displacement speed was 2 mm/min. Strain measurements were performed using HBM pre-wired 0°/45°/90° rectangular rosette.
The loading/unloading cycles were performed by applying strain variations, ranged between a force of 0N and strains of 0.2%, 0.4%, 0.6%, etc. up to failure.
Thus, the results for the $[30°]_{12}$, $[45°]_{12}$ and $[60°]_{12}$ laminate are shown in §3.2 - Fig. 7, 8 and 9.

2.3. Damage model and parameter identification

When a composite material is subjected to mechanical loading, different phenomena can lead to changes into its properties due to irreversible, numerous and complex damages (fibre break, cracks propagation,fibre/matrix debonding, delamination…). However, within the assumption of diffuse damage (no macro-cracks) and plane stresses (no delamination, no defects interaction), the predominant ones are fibre/matrix debonding and matrix micro-cracking.
This model is intended to describe the early damage mechanisms associated to these micro-cracks until the first ply failure. [1, 2, 4, 5, 6] Formulated at the ply scale (so-called meso-model) and based on Continuum Damage Mechanics (CDM), it uses a thermodynamic formalism for anisotropic material behaviour law where internal variables are associated with the stiffness loss of each ply. Plies are considered homogeneous, orthotropic and with a constant damage through the thickness.
The model takes into account the inelastic strain (mainly observed in shear) but also the couplings between tension and shear on the evolution of the damage. This coupling is defined by the tension effect on the shear failure behaviour of the material, and likewise, the shear effect on the failure

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behaviour in transverse tension. By that way, the progressive development of damage depends on the shear load as well as on the transverse tension load.
Hence, the evolution of damage is taken into account by defining two internal variables which reflect the effect of matrix damage on the shear stiffness (d_{12}) and on the transverse tension stiffness (d_2) and are corresponding to each ply stiffness loss. Thus, E_2^0 being the initial modulus before any damage occurs, the unidirectional modulus in the transverse direction E_2 is given Eq . 1:

$$E_2 = E_2^0\,(1-d_2) \qquad \Rightarrow \qquad d_2^i = (1-E_2^i/E_2^0) \qquad \forall\, i = unloading\ cycle \tag{1}$$

Indeed, this damage is measured on the stress-strain $(\sigma-\varepsilon)$ curves of quasi-static tensile test during the different unloading cycles i, knowing that the damage appears macroscopically by a decrease in the material stiffness. Thus, taking the case of [30°]$_{12}$ laminate of unbalanced hybrid PEEK-Carbon/Glass composite on Fig. 3 (same procedure for all the tests), it can be seen a typical stress-strain $(\sigma-\varepsilon)$ curve showing the evolution in the load direction of the stress (MPa) vs the strain (-).
This figure describes, in a more visual way, the evaluation of the macro-damage D in the specimen via the measure of stiffness loss during the different unloading cycles. Therefore, it is therefore possible to draw the evolution of the macro-damage D versus the strain (-) in §3.2. The material shows elasto-plastic damage behaviour owing to the damage processes occurring in the material with inelastic strain loading due to friction undergone by fibre/matrix cracks oriented off-axis.

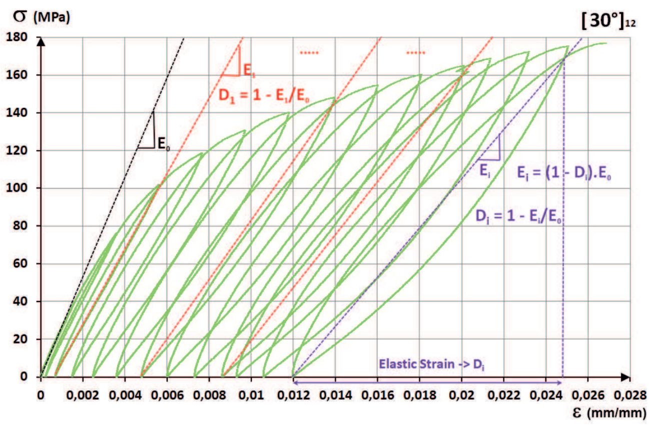

Figure 3. Quasi-static off-axis tensile test of [30°]$_{12}$ laminate - Stiffness loss measure for damage evaluation - Stress (MPa) vs. Strain (-).

3. Results and discussion

3.1. Transverse tensile tests analysis

The stress-strain $(\sigma-\varepsilon)$ curve on Fig. 4 presents some strains discontinuities (surrounded by red ellipses). This is reflecting the fact that macro-cracks appeared under the strain gage length and crossed the whole specimen width. Even if the glass fibre (same as [6]) ensures its function as a help to transfer the load to other fibres, allowing the test to go further in terms of strains, this test did not reach the strength shown in [6].
Here, a failure stress of 106 MPa at a failure strain of 1.25%, to compare respectively to 184 MPa and 2.24% in [6]. The reason is that the quasi-static tensile on a [90°] laminate in [6] does not macro-cracks let appear, leading to an earlier failure as in Fig. 4.

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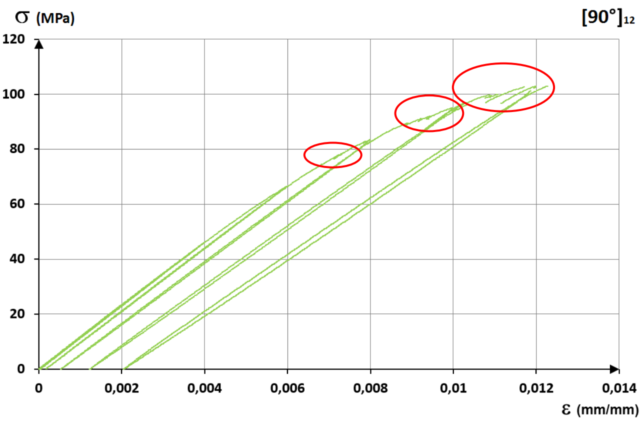

Figure 4. Quasi-static tensile test of $[90°]_{12}$ laminate - Stress (MPa) vs. Strain (-).

In Fig. 5, it can be seen the images of cracking just before final failure using ARAMIS Digital Image Correlation (DIC) Software for the $[90°]_{12}$ laminate.

ARAMIS is an optical analysis tool that uses the evaluation of sequential digital images for measurements of deformation/strain/displacement. It recognizes the surface structure of the measuring object in digital camera images by allocating coordinates to the image pixels. To enhance the image analysis, a random speckle pattern is applied using a spray paint.

The use of DIC and micrographics show that macro-cracks appear crossing the whole width of the specimen. ARAMIS allow us to see the macro-cracks but not the micro-cracks, the use of micrographic observations was then useful and necessary.

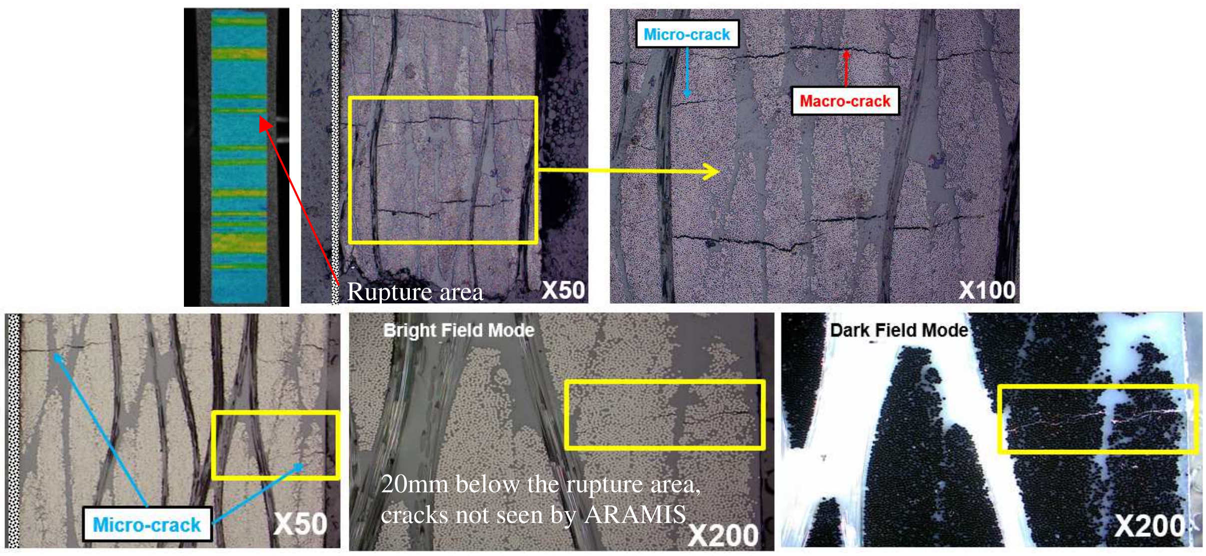

Figure 5. Quasi-static tensile test of $[90°]_{12}$ laminate - Micrographics close to the rupture zone and at 20mm far from it by binocular (x50 - x100) and bright/dark field (x200) optical microscopy.

Thus, Fig. 5 shows that, despite this new material, the behaviour remains brittle for pure transverse loading. Therefore, this test can not be chosen to identify the model parameters for the transverse tensile behaviour as it is outside our model field validity (no diffuse damage). [1, 2]

The $[90°]_{12}$ laminate has the advantage to have a pure transverse behaviour, the solution then is to perform difficult off-axis tensile tests. The orientation has to be chosen in order to limit shear and the brittleness of transverse specimens. That is to say, an orientation as close as possible to [90°] but without any macro-crack up to failure, only diffuse damage to be into the limits of our model. [1, 2]

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3.2. Off-axis tensile tests analysis

Fig. 6 shows the images of macro-cracks just before failure using DIC for the $[90°]_{12}$, $[78°]_{12}$ and $[67°]_{12}$ laminates of unbalanced hybrid PEEK-Carbon/Glass composite, respectively from left to right. For all, macro-cracks appear by crossing the whole width of the specimen i.e. no diffuse damage. Hence, they cannot be chosen to identify the model parameters for the transverse tensile behaviour. [1]

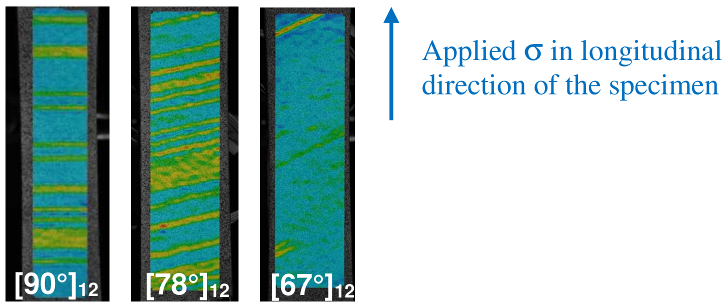

Figure 6. Quasi-static tensile tests of $[90°]_{12}$, $[78°]_{12}$ and $[67°]_{12}$ laminate - Macro-cracks DIC images.

Consequently, off-axis tensile tests have been carried out on $[30°]_{12}$, $[45°]_{12}$ and $[60°]_{12}$ laminates. Table 1 gives a summary of all their results: failure strain and stress, ratio between the stiffness just before failure and the initial one and ratio between the strain measure by ARAMIS and by strain gage.

Given that σ is the applied stress and knowing that an off-axis tensile test is subjected to a combined load state of in-plane shear σ_{12} and transverse tension σ_{22}, this table also gives their distribution as a function of σ for each laminate. Here, the $[30°]_{12}$ laminate shows the higher ratio of stiffness loss, with 75% of the applied stress resulting in shear. Finally, this tables shows that the $[60°]_{12}$ laminate exhibits the higher level of transverse tension (shear being only 25% of σ), resulting with the validation of its use for the model parameters identification of the transverse tension.

Table 1. Results summary for the $[30°]_{12}$, $[45°]_{12}$ and $[60°]_{12}$ laminates.

Laminate	$\varepsilon^{Failure}$ (MPa)	$\sigma^{Failure}$ (%)	σ_{22} (MPa)	σ_{12} (MPa)	$E^{final}/E^{initial}$ (%)	$\varepsilon^{ARAMIS}/\varepsilon^{Strain-Gage}$ (%)
$[30°]_{12}$	177	2.69	$\sigma/4$	$3\sigma/4$	55	3.4
$[45°]_{12}$	133	2.34	$\sigma/2$	$\sigma/2$	62	6.9
$[60°]_{12}$	123	1.73	$3\sigma/4$	$\sigma/4$	71	0.9

Fig. 7, Fig. 8 and Fig. 9 represent the longitudinal and transverse strains vs. the applied stress σ. They all show an important “apparent” stiffness loss, characteristic of damage increase within the specimen.

Moreover, it can be seen that the hysteresis loops are wider for the $[30°]_{12}$ laminate, typical of a higher friction phenomena (in-plane shear). And so, Table 1 shows that 75% of the applied stress σ is resulting in shear σ_{12} for this laminate.

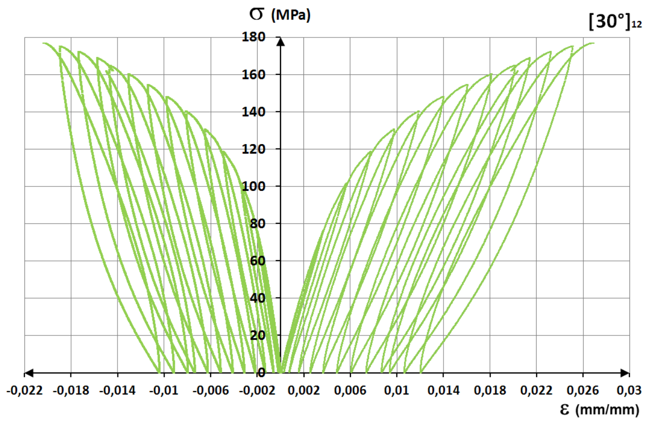

Figure 7. Quasi-static off-axis tensile test of $[30°]_{12}$ laminate - Stress (MPa) vs. Strain (-).

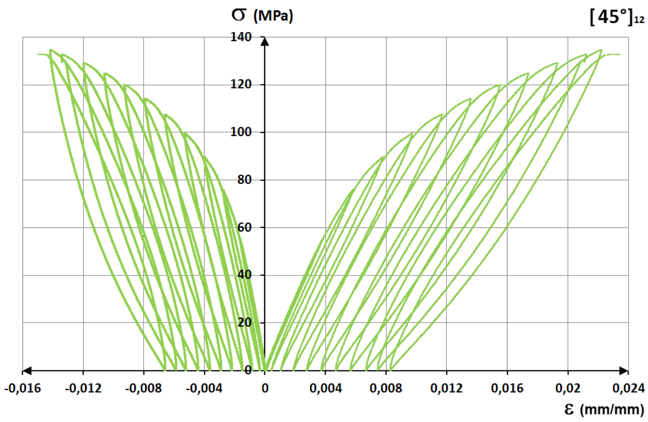

Figure 8. Quasi-static off-axis tensile test of $[45°]_{12}$ laminate - Stress (MPa) vs. Strain (-).

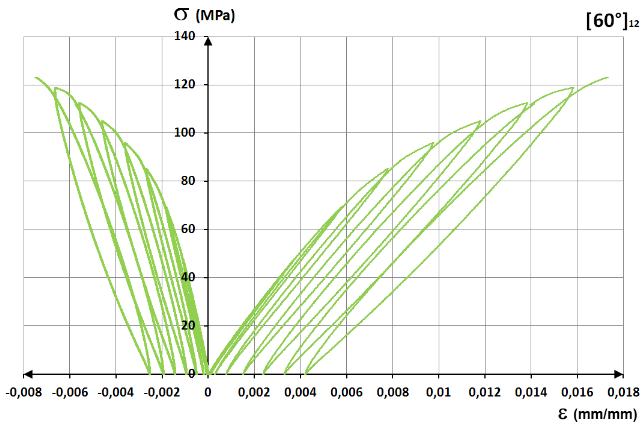

Figure 9. Quasi-static off-axis tensile test of $[60°]_{12}$ laminate - Stress (MPa) vs. Strain (-).

Finally, Fig. 10 shows the evolution of the specimen macro-damage D (-) vs. Strain (-) in load direction during a quasi-static tensile test of unbalanced hybrid PEEK-Carbon/Glass composite for $[30°]_{12}$, $[45°]_{12}$ and $[60°]_{12}$ laminates. As can be seen, the overall evolution of the specimen macro-damage D is found to obey to a non-linear law. [4, 5, 6]

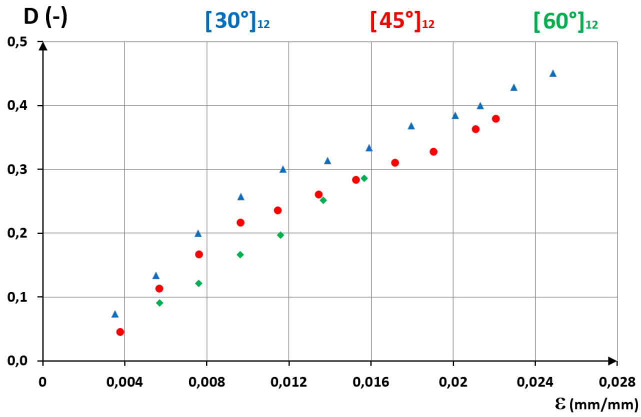

Figure 10. Quasi-static off-axis tensile test of $[30°]_{12}$, $[45°]_{12}$ and $[60°]_{12}$ laminates – Evolution of the specimen macro-damage D in load direction - Damage D (-) vs. Strain (-).

4. Conclusions

The model studied is based on CDM: assuming plane stresses, an UD ply intra-laminar damage is the result of in-plane shear and transverse tension. [1, 2, 4, 5, 6] But the transverse tensile behaviour is brittle, so its damage difficult to study, knowing that this premature failure [4] is not representative of its transverse behaviour in a laminate. Besides, transverse tensile tests give better results in [6] for an unbalanced woven fabric glass/epoxy as their failure are not brittle, the fibres in the weft direction limiting the cracks propagation to the whole specimen. Therefore, a new unbalanced hybrid Carbon/Glass-PEEK composite with its warp/weft fibres ratio close to [6] has been especially developed for this work. Given that the damage appears macroscopically in the material by a stiffness loss, quasi-static tensile tests were performed with loading/unloading cycles, the strain field is measured by strain gages and DIC. Tensile tests on $[30°]_{12}$, $[45°]_{12}$, $[60°]_{12}$, $[67°]_{12}$, $[78°]_{12}$ and $[90°]_{12}$ laminate laminates carried out on flat dumbbell-shaped specimens were presented. Thus, the $[60°]_{12}$ laminate has been validated for the transverse tension parameters identification. The overall evolution of the specimens damage is found to be non-linear. [4, 5, 6] Hence, for carbon fibres transverse tension load, this study leads to a better model parameters identification for the matrix transverse damage. On-going work is to simulate this material behaviour (MATHEMATICA).

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Excerpt from ISBN 978-3-00-053387-7