Contribution of damage mechanisms comprehension of interlock-reinforced composite materials

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ABSTRACT

Recent improvements of weaving tools in synergy with the evolution of the composite fields allow manufacturing of advanced woven composite. Thanks to these techniques, new generation of composite with a through-the-thickness reinforcement appears. This reinforcement offers a high delamination resistance and generates a strong capacity to dissipate energy by damage. However, using such composites involves, among other things, an understanding of the damage mechanisms. Thus, the aim of this work is to study the damage mechanisms at work in an interlock woven composite.

1. INTRODUCTION

Fibre reinforced polymer (FRP) composites are used in almost every type of advanced engineering structure, (aircraft, helicopters, spacecraft, boats, ships and offshore platforms, automobiles…). A key factor driving the increase of applications of composites over recent years is the development of new advanced generation of FRP materials. Thus, in the last 15 years, with the development of FRP composites reinforced with a three-dimensional (3D) fibre structure, a major stride has been made. The development of this new generation of materials reaches a commercial level and can be used in both traditional and emerging markets.
Studying these materials requires new experimental approaches in accordance with the complexity of their architectures. Indeed, considering the large dimensions of the volume representative element (VRE), strain measurements should be done with new measurement techniques and qualify them. Moreover, damage mechanisms in these materials are also complex and specific [1]. Therefore a crosschecking of several investigation techniques should be performed in order to understand their ruin process.
This article approaches the mechanical behaviour of an interlock graphite / epoxy composite.
The first part of the study will focus on validating the techniques of strain measurement comparing several approaches. The second part will analyze the damage mechanisms of these materials. We will present the step adopted as well as an example of ruin scenario in the case of uniaxial tensile tests.

2. MATERIAL PRESENTATION AND EXPERIMENTAL PROCEDURE

Three main types of interlocks exist, the layer-layer angle interlock, the layer to layer angle interlock, and the orthogonal interlock. The major advantages of these materials lie in their damage tolerance and delamination resistance. The materials investigated in this paper are graphite / epoxy balanced and unbalanced layer-layer angle interlock (Fig.1).

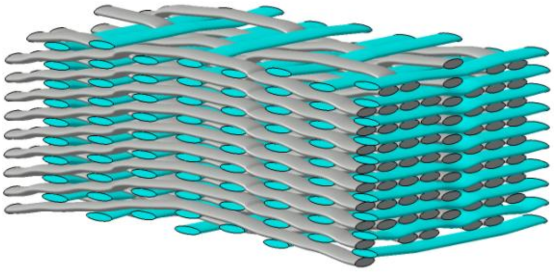

Figure 1: Example of an interlock composite using yarn paths from Wisetex (MTM-KUL)

Tensile, compressive and flexure tests are conducted on both warp and weft directions: In the tensile test case, a ± 45° test is added. On this paper, we will focus on the tensile test.
Due to size of the VRE (greater than 15mm in both warp and weft direction), the test piece dimensions are different from the ones usually used. The geometry was established using finite element approach, bearing in mind that one VRE should be present in useful area. Thus, all specimens are dog-bone shape with an adequate width, transition radius and 10 mm thick.
For the same reasons, strain measurement cannot be done with small gage. So, for this study, longitudinal strain gauges of 10mm, 20mm, 60mm and an extensometer with 50mm rage measurement were selected. For transversal strain measurement, the gage lengths used were 5 mm, 10 mm and 20 mm.
Strain field measurement technique from digital images [2] was used in complement.
Figure 2 illustrates a tensile test with an example of various gages and the extensometer placement on the specimen.

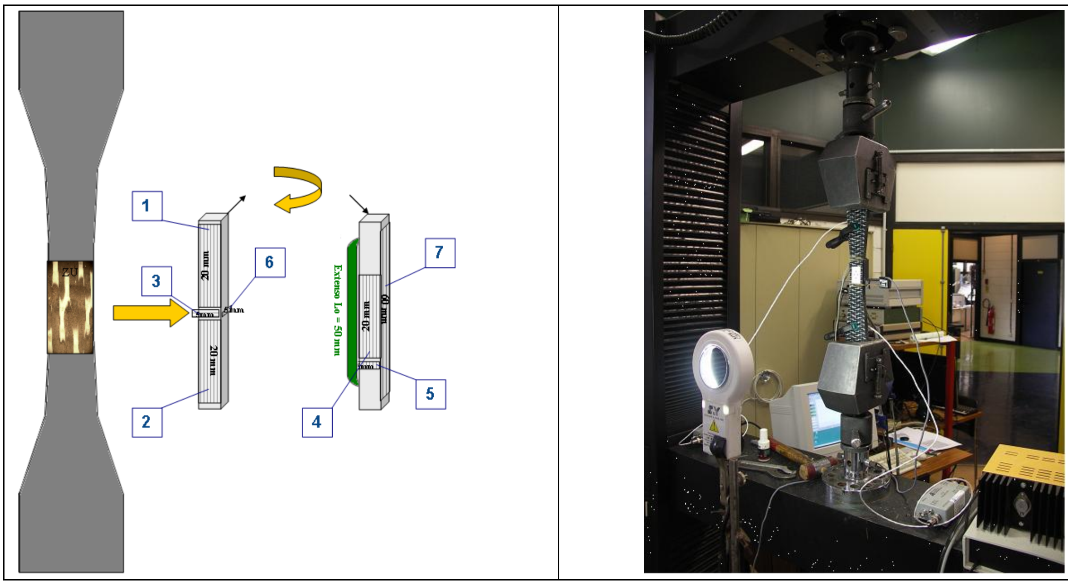

Figure 2: Example of a complex instrumentation (gauges of 10mm, 20mm, 60mm and extensometer) used for weft tensile test presented in figure 3.b

3. EXPERIMENTAL RESULTS

3.1 Reinforced experimental procedure

Figures 3a and 3b show the evolution of the different strain gages responses versus time for tensile tests along, respectively, warp and weft direction. During the tests, loading - unloading cycles with tensile dwell time were carried out.

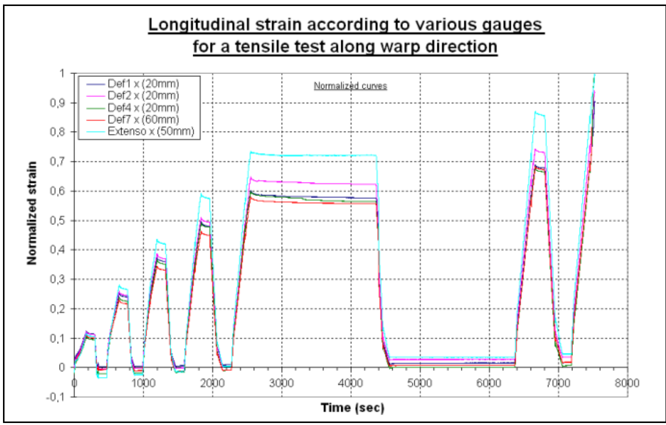

Figure 3.a: Results of a complex instrumentation for a warp direction tensile test

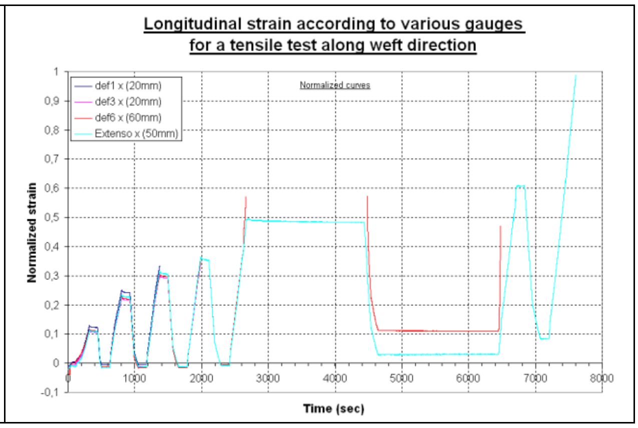

Figure 3.b: Results of a complex instrumentation for a weft direction tensile test

Considering the behaviour of the material in the warp and the weft direction, the straight part of curves for all gages are partially identical (comparable elasticity) except for the extensometer and the 60mm gage in the warp case (Fig. 3.a).
A difference is notable for the maximum values reached for all gages. For the warp direction, the lower and the upper value are reached with respectively the 60 mm gage and the extensometer. It should be noted that these two instrumentations are laid out on the side of the specimen.

In warp case (Fig. 3.a), the three same gages with 20mm length, indicates a rather close answer, but a difference persists. Effect of the gage site on the measured value highlight the heterogeneity of this type of material [3]. This phenomenon exists from the start of the tests [4] but becomes notable for significant deformations. That explains a limited assignment on the rigidity modulus.
During weft direction tensile test (Fig. 3.b), all longitudinal gages saturate prematurely (lower than 1 %). The signal of the gage is observable again in phase of discharge, probably due to the closing of the crack (60mm length gage in Fig. 3.b). Therefore, the saturation of the gages was due to the nature of the produced damage. The microscopic observations (fig. 4), carried out during the tests, confirm microscopic cracks presence under the strain gages. These microscopic cracks involve a local strain which produce a loss of the gage electric resistance and have no effect on the extensometer measurement.

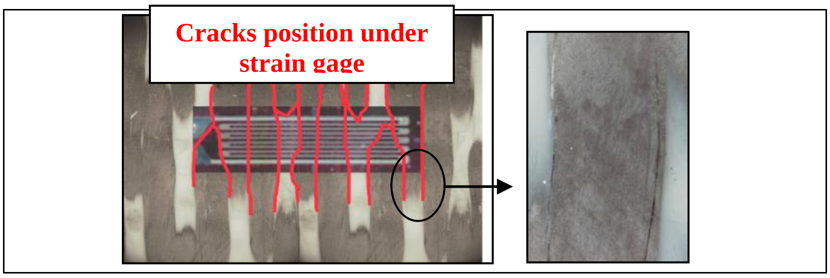

Figure 4: Microscope inspections of a weft tensile specimen

No general tendency could be done on the size and site of the gage. The position of the gage is very significant especially if its length is low. We have to be careful about the local deformation included in the measurement size. This point generates a reflection on the quantification of the local heterogeneity and its influence on the veracity of measurement.

3.2 Strain fields procedure

In order to avoid previous problems, crosschecking of the gages measurements with the strain fields analysis technique was required.

Figure 5 shows meshing deformation into the two directions of the woven. Supposed heterogeneities are confirmed and explain the disturbances previously observed. It is obvious that low-size gage will be strongly affected by local behaviour of material. At beginning of the tests, the same heterogeneity exists in the warp and weft direction. In a small strain case, noise couldn't be considered negligible and filtering was necessary [5].
The warp strain field results let appears a non linear deformation of the section. This phenomenon can explain the difference between 60mm length gage and 50mm length extensometer positioning on the side of the specimen.

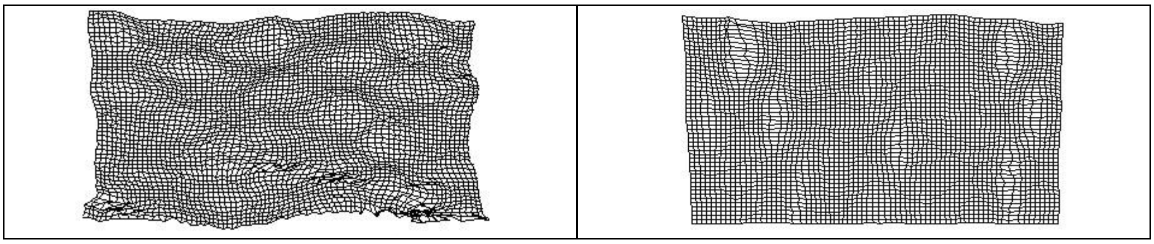

Figure 5: Meshing deformation of the face of sample during uniaxial tensile test along warp (left) and weft (right) direction

To check the veracity of the strain field measurement technique, a 20 mm length gage was placed under the strain field measurement area (Fig. 6). According to the dimensions of the real gage, virtual gage was calculated from the longitudinal strain field. Thus, comparison test of the two techniques on the same area containing same heterogeneities was performed.

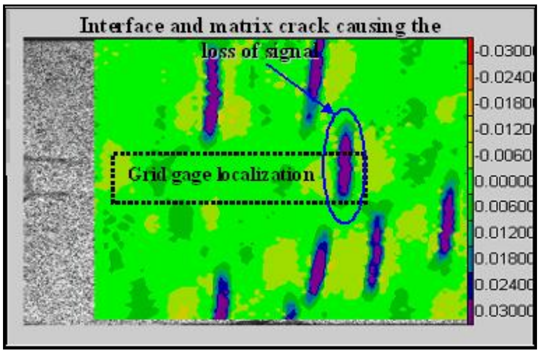

Figure 6: Longitudinal strain field and grid gage position

The figures 7a and 7b present results of the comparison test. The evolution of the real 10mm and 20mm length gage and virtual gage responses versus time was shown for tensile tests along, respectively, warp and weft direction.

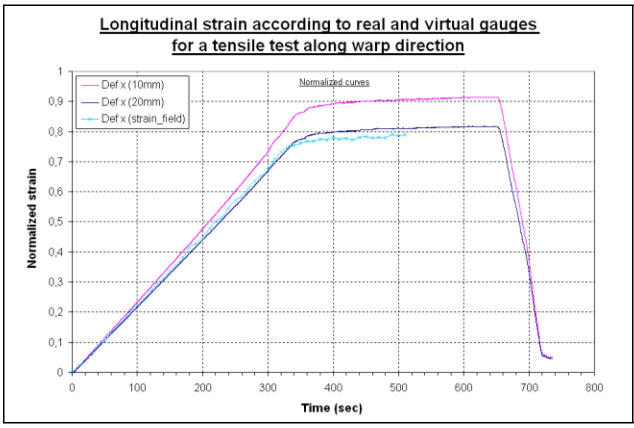

Figure 7.a: Warp direction tensile test

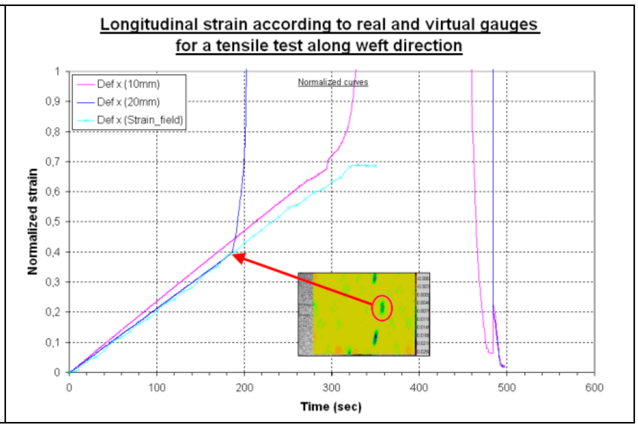

Figure 7.b: Weft direction tensile test

For the two tensile tests, the same responses for the two measurement techniques were observed all through the experiment.
The pink curves represent a 10mm length gage positioned on the other face of the specimen. In the first moments of the loadings, the whole strain measurement gages (real and virtual) are comparable. However, rather quickly, the 10 mm length gage shows a difference with two other measures due to its size and its localization in relation to heterogeneities.
The saturation of the 10mm length gage on the tensile test along weft direction (Fig. 7.b) was caused by interface crack illustrated on the figure 6. Loss of signal was correlated to the precise time where local strain was closed to 2.4%. The 20mm length gages used were limited by a longitudinal strain of approximately 2.5% (Data provides by the manufacturer).

3.3 Damage mechanisms

To study into detail the damage, a correlation involving several techniques like treatment by acoustic emission, in situ (video microscope) and post mortem (Scanning Electron Microscope) microscopic observations as well as the analysis of the strain fields have been investigated. In this paper, we focus on the weft damage scenario.

Previous studies [6] showed that amplitude ranges can be related to the various damages existing in composite fabric (Fig. 8). Thus, low amplitudes [35-50dB], corresponding to matrix crack, medium amplitudes [50-80dB] related to the interface failures, debonding and friction. Finally, high amplitudes [80-100dB] characterize fiber or/and yarn breaking.

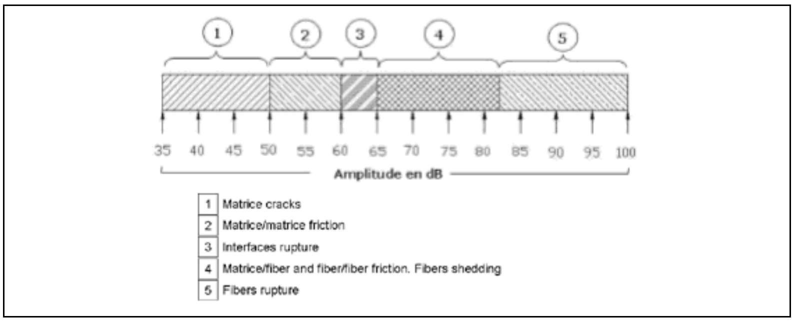

Figure 8: Amplitude ranges according to various damages

Acoustic emission treatment provides significant information concerning the nature of dominating damage in the material. For example, to determine shear modulus and characterize the viscoelastic behavior of the polymer matrix, 45° off-axis dwell time tests were performed. Compared to tensile tests in the weft or warp direction, the acoustic activity is mainly undertaken by amplitudes inferior to 60dB (Fig. 9). It is necessary to wait the last loading to see high amplitude acoustic emissions in the off-axis case. The differences in damage between these two tests were clearly illustrated by the technique.

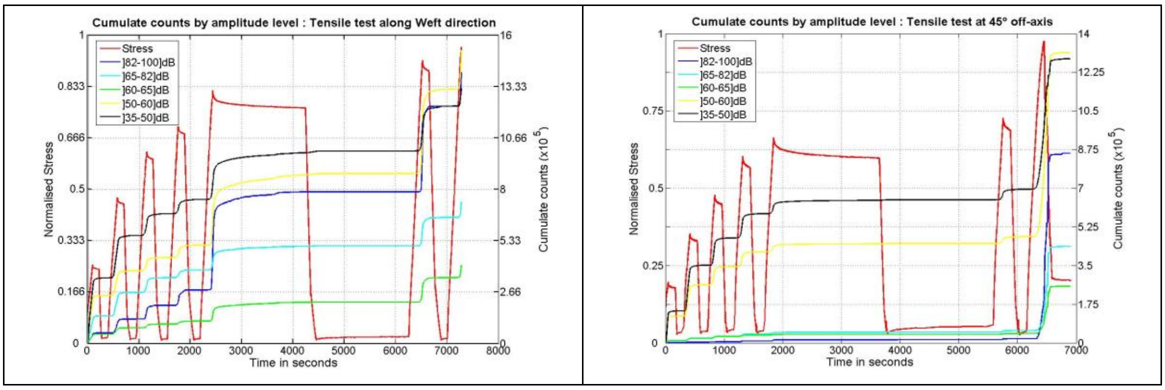

Figure 9: Acoustic activity during a tensile test in the warp direction (on the left) and at 45° off-axis (on the right)

With treatments considering counts, energy and amplitude, damage chronology could be established.
For a weft direction loading, all the amplitude ranges occur and increase from the start of the test. However, a significant growth of high amplitudes was observed from the fifth loading. These large fiber breakings generate a decrease of rigidity which hasn't been seen previously. Before that, matrix and interface damage manage the mechanical behaviour and have no effect on rigidity. For the weft direction instance, acoustic emissions of amplitude higher than 60dB didn't occur at the beginning of test. Different undulations between the tensed warp and the tensed weft yarns could explain that phenomenon.

The appearance of the first damages in the matrix and the interfaces was confirmed by in-situ fractographies (Fig. 10) and strain fields analysis overprinted with microstructure (Fig.11).

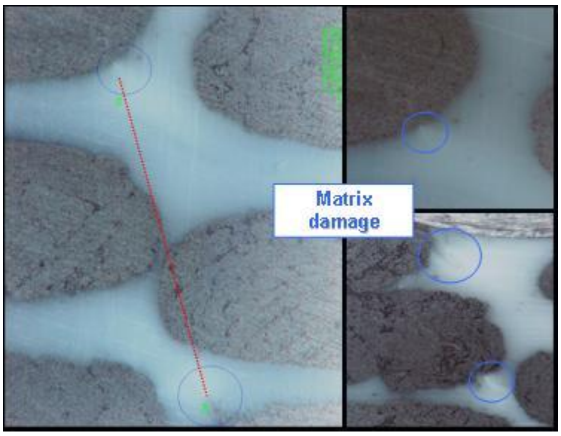

Figure 10: Example of matrix damages and cracks

Figure 11 informs on complexity and heterogeneity of strains during a tensile test on the side of the specimen.

Local shear and longitudinal strain (11.a and 11.c) occur in the whole thickness of the composite and produce inter-yarn cracks. Greater local disband (11.b) can be seen on surface due to its specific woven.

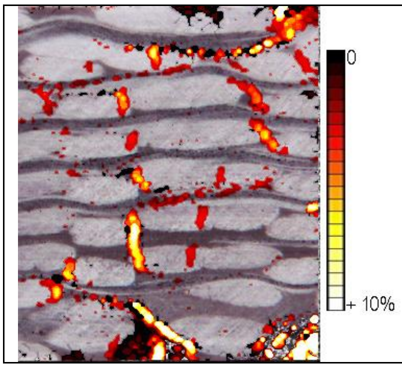

Figure 11.a: Longitudinal strain field for a weft tensile test

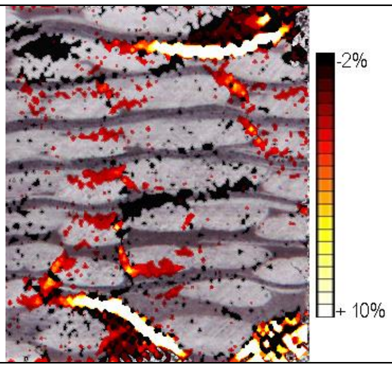

Figure 11.b: Strain field in the thickness for a weft tensile test

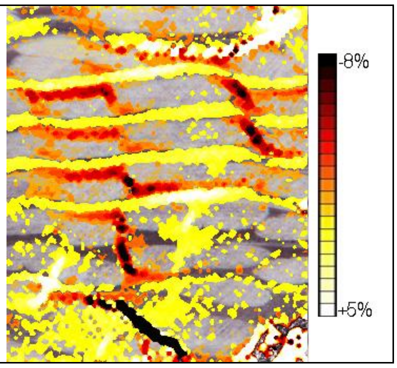

Figure 11.c: Shearing strain field for a weft tensile test

The delicate issue of the strain fields is about surface information. Indeed, damage mechanisms between the side and the core of the woven can be different. Moreover, the weave comprise different plane including or not weft fill (Fig. 12). For example, strain fields on figure 11 were specified in a plane confounded with the weft fill paths. In this location, matrix and interface rupture generate local disbond at the weft and warp strand interfaces. On a plan without weft tow, cracks and damage mechanisms are not deviated by these yarns.

That divergence generates different topographies of cracking between these plans illustrated by the figure 12.

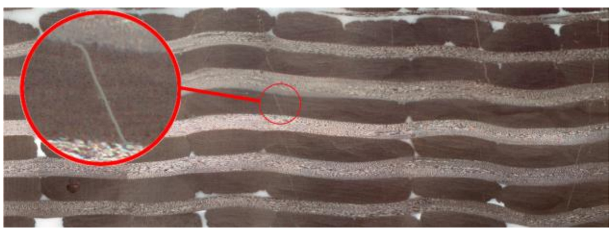

Figure 12.a: Fractography in a plan confounded with the weft tow column

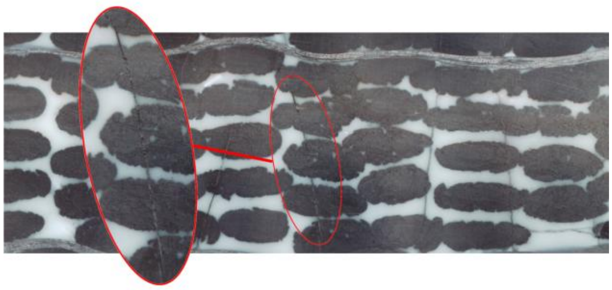

Figure 12.b: Fractography in a plan between two columns of weft tow

Post mortem scanning electron microscope observations allow a possible localization of the primary damages. It would seem that they occur at the interface yarn/yarn and inside yarn and generate thereafter matrix cracks and local debonding. A strain field analysis method at this scale is in progress to confirm that information.

Those different damages produce acoustic activity which covers all the amplitude ranges. Due to the complexity of the pattern, differences of stress levels and/or stress directions can be observed in the yarn. Thus, each fill having its own behaviour, damaged zone on matrix and interfaces are created and finally generate cracks. For a high damaged level of the interfaces and matrix, warp yarn columns have a movement compared to the other and only weft yarns absorb loading and began to break.
To ensure the validity of the study and confirm that final fracture at 90° of the specimen were caused by these damages, fractographic analysis on various plans was investigated (Fig. 13). Finally, cracks overprint corroborate that damages observed on the sides were similar to those in the core of the composite.

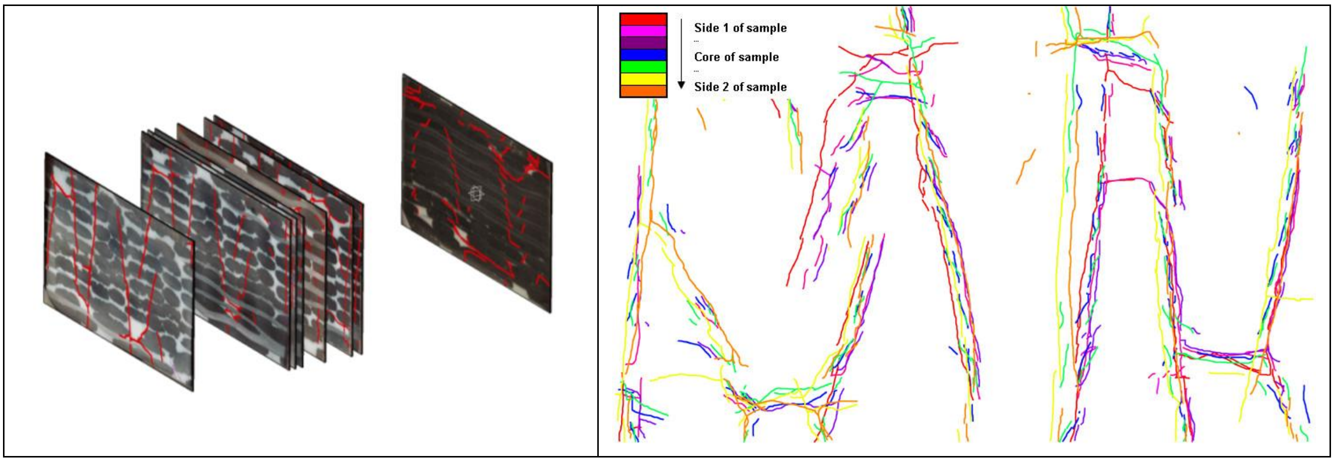

Figure 13: 3D and overprint representation of the various plans seen under microscope

According to acoustic emission, microscopic observations and strain fields analysis, a first damage scenario for a tensile test along the weft direction were realized for this interlock reinforced composite (Fig. 14).

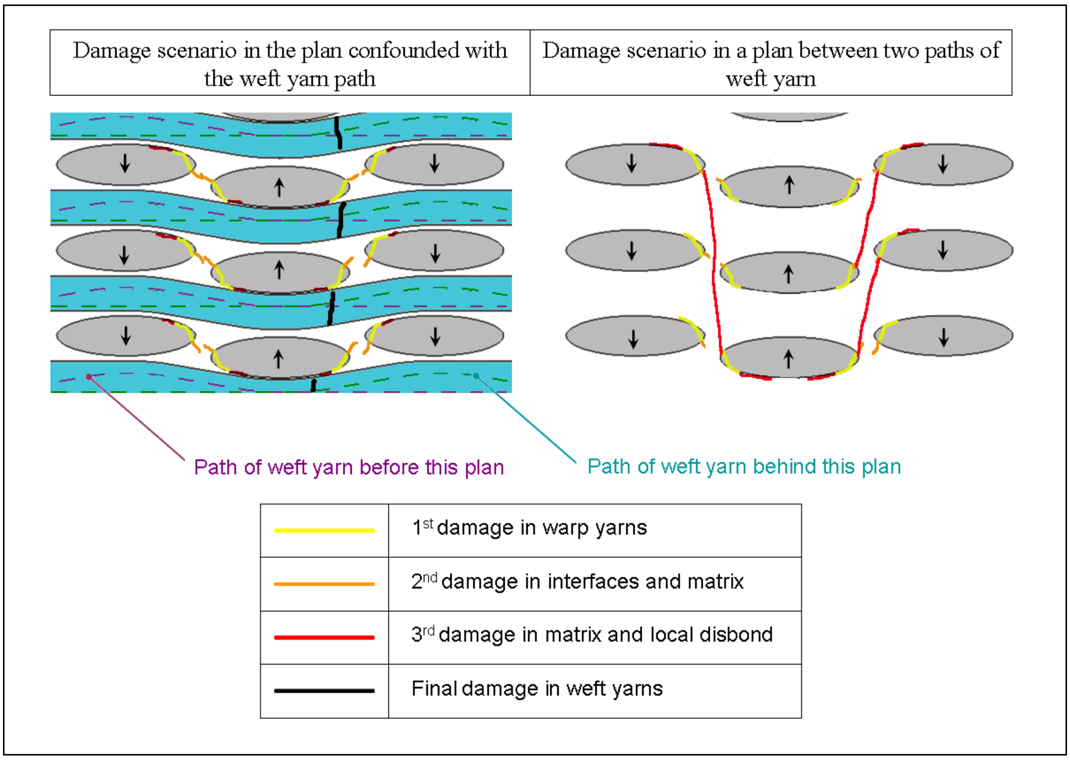

Figure 14: Damage scenario for tensile test along weft direction

4. CONCLUSIONS

The interest of the interlocks lies in the diversity of architectures. These architectures must be thought in order to fulfill the requirements of the design. Nevertheless, this step can be carried out only if the mechanical behavior of these structures is well understood.

The complexity of these architectures imposes a sophistication of the testing methods, and it’s necessary to keep in mind dimensions of the unit cell, to have an idea of the measuring device to set up.

Thus, acoustic emission, strain fields analysis, in-situ and post mortem microscopic observations are used together in order to understand the damage mechanisms.

The strain field analysis also highlighted the fact that using strain gages and extensometer with such composites could give a partial information on the damage mechanisms and even be useless depending on the stress level considered.

This study proposes a methodology of analysis of damage process of interlock reinforced composite materials, a scenario of ruin under tensile test along weft direction was thus proposed.

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