ON MULTI-INSTRUMENTATION TECHNICS FOR DAMAGE IDENTIFICATION OF 3D COMPOSITE MATERIALS

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Abstract: The development of new materials, in industry such as aeronautic, needs to acknowledge their behavior under loading. In order to achieve this objective, numerous testing are done and the data such as initial Young modulus or life for a certain fatigue loading are known. However, complex loadings existing in real life are not so easy to predict, so models have been developed to simulate such loadings. For quasi-static loading in 3D composites, a model has been created and uses damage accumulation as the main factor impacting mechanical properties. The accuracy of the model depends on the data that can be obtained through testing investigation. As we know, 3D composites have a really complex frame and the internal stress and strain can hardly be known without a sophisticated instrumentation. Investigation has been made during quasi static loading, hardly showing the links existing between damages and mechanical properties. This present work extends the quasi-static work to the fatigue loading problem. It focuses on extending the instrumental methodology developed previously on life testing. Thus, the measurement tools used for this purpose are DIC, Acoustic Emission, strain measurements, Infrared thermography, microscopy and micro-tomography. All these techniques are often used almost alone. This paper manages to present all this tools, their specific uses in this case, and the connections that can be done between them.

1 INTRODUCTION

The knowledge of the damage process is a key step for the development of this new generation of materials. The high heterogeneity combined with the complexity of the 3D weaving pattern need the mix of various techniques and to ensure the follow-up of the damage. Previous works focused on the determination of the ruin scenarios during quasi static loading (Schneider 2009). This paper aim is to show the different techniques and the methods that have been used to follow and analyze damages that occurred during fatigue loading. It describes mainly the purpose of each technique and the links between them. For this purpose, uni-axial tensile tests have been achieved. The monitoring of the tests is done with the combination of extensometry, strain field observation by digital image correlation (DIC), acoustic emission, Infrared thermography, post mortem microscopy (optical and SEM), in-situ microscopy (video-microscopy) and micro-tomography (Figure 1.). This multi-instrumentation aims at describing the ruin scenario in fatigue loading, identifying the key mechanisms at different observation scales and their evolutions with number of cycles in order to give sufficient elements for the set up of a phenomenological macroscopic model for fatigue loading.

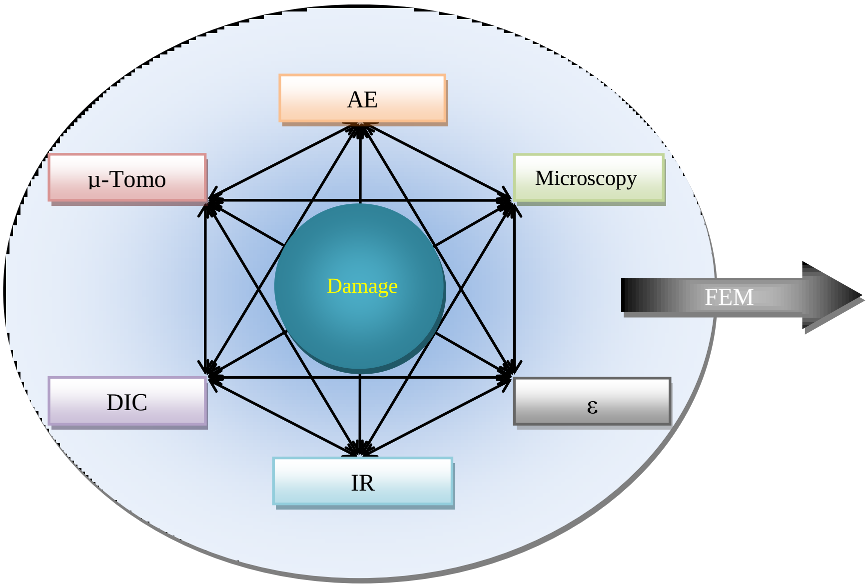

Figure 1. Multi-instrumentation around damage process.

2 METHOD

The rigidity evolution of a composite during uni-axial tension classically shows three different phases. During the first one, the Young modulus is decreasing drastically. The modulus then remains stable without high loss in the material rigidity, it is the second phase. The last step of this evolution is a sudden loss of the elastic properties which ends to damage the material until final failure (Figure 2).

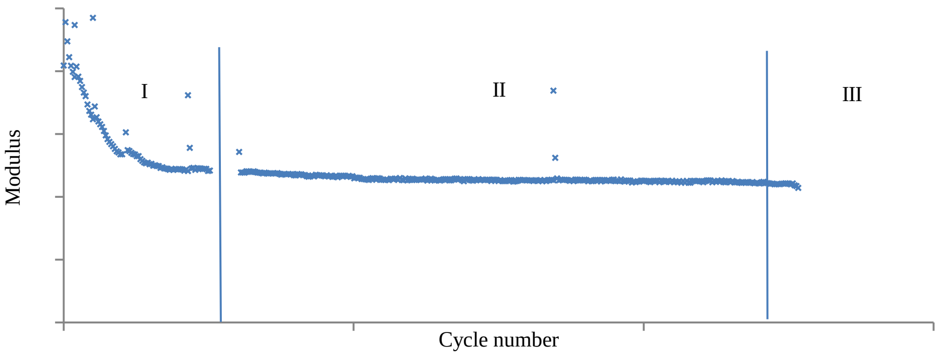

Figure 2. Typical elasticity evolution during fatigue testing for composite

The set up instrumentation for the entire test allows us to define the different phenomenon impacting each of the phases. Nevertheless, a distinction is made for these tools: the continuous analysis from which one can obtain the data during the entire testing process, and a discrete acquisition that needs to regularly stop the testing machine. Uniaxial tensile tests are performed by having a first quasi-static loading, where discrete acquisition takes place. During the cycling fatigue, the continuous instrumentation acquires the needed data. The testing machine is then regularly stopped for punctual acquisitions (Figure 3).

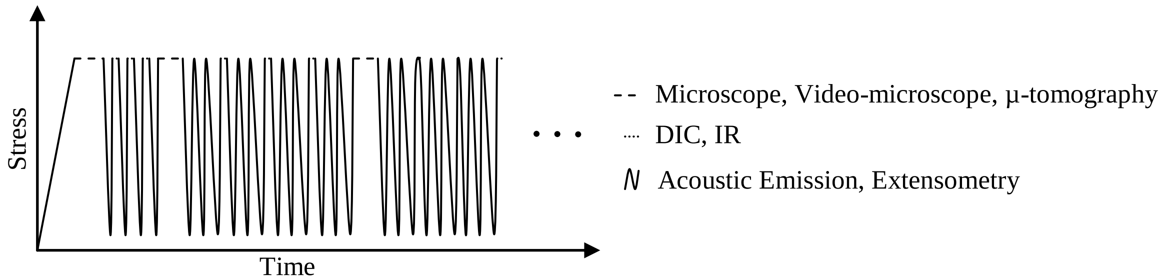

Figure 3. Schematic loading path for multi-instrumentation.

2.1 Continuous Acquisition

Continuous acquisition can be performed during fatigue loading with automation. The main idea is to take measurements on the sample to ensure that sufficient data are taken during the testing. Thus, a self heating process has been pointed out for high frequency testing (up to 5Hz) first with thermocouple measurement then with the use of an infrared camera.

2.1.1 Infrared Thermography

There are mainly two different ways to achieve the control of the temperature. The first one is to work with a lower frequency, increasing the testing duration. The second one is to find a way to cool the sample during loading without interfering with the instrumentation. It is the last one that has been chosen, the material is cooled with a cold air flow generated by a vortex tube. The vortex tube (or Ranque-Hilsh vortex tube) is an ingenious mechanical device that produces cold and hot streams from compressed air. It doesn't require any moving part which ensures good reliability (Figure 4).

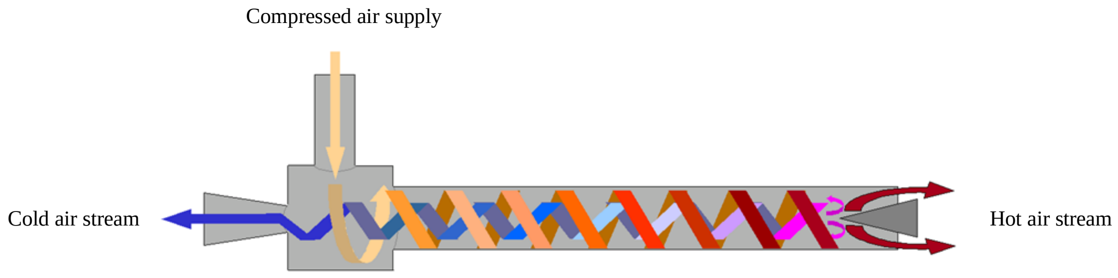

Figure 4. Schematic view of a vortex tube.

This cooling system doesn't inhibit the use of the infrared camera. As the sample is uniformly cooled around ambient temperature, it is still possible to observe local self heating area that define hard rubbing and so an advanced damage state. Basics operations can be performed on the temperature map obtained by IR thermography such as subtraction of two different images to enhance the new local overheating related to the weaving structure (Figure 5). It is yet possible to look for better description of the phenomenon of self-heating by some advanced calculation for heat source identification (Chrysochoos 2000). Nonetheless, Infrared tomography, by thermal conduction through the carbon fibers, gives clues on the damage state at the heart of the sample. Another technique that allows for obtaining data from non visible part of the sample is acoustic emission.

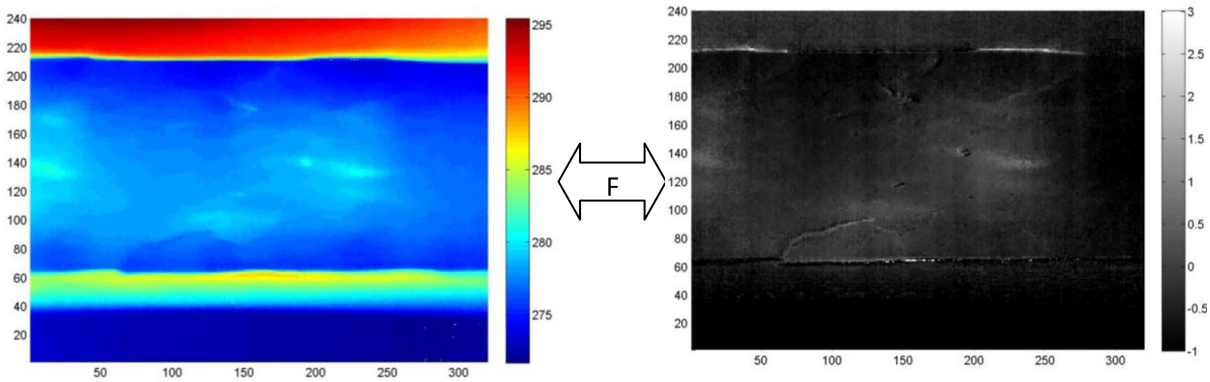

Figure 5. Temperature map of a cycle fatigued sample (left), with subtraction of an earlier temperature map (right).

2.1.2 Acoustic Emission

Acoustic emission acquires every sound signal that run through the composite when an event occurs. In fact every micro-failure emits a wave from the area it occurs. This wave travels the sample and is recorded by the acoustic acquisition system when exciting the microphone (piezo-electric captor); one calls this recorded event a hit. Due to the acquisition of an important volume of non-desired data, a spatial filter, using two captors, is performed along the entire acquisition. Thus all the signals from outside the two micros are not recorded. The wavelet is also not recorded to decrease the amount of data recorded, as well as any signal with amplitude below 55dB. We assume that damage impacting the mechanical behavior will have high energy as much as high amplitude. Although all this actions to reduce data, the hits recorded during one week of fatigue loading can exceed 1 million populations and the post-processing of such data requires computed assistance. A statistical approach via Noesis is used to ensure optimized data processing. The representation of the energy of each hit versus the counts show clearly two different trends. The work with Noesis has mainly focused at isolating the two trends with two classes from six hit parameters: amplitude, rising time, duration, frequency, counts and energy. This classification allows for the association of corresponding damage to each classe. For the first one, which is with the fewer counts, but higher energy, the trend is similar to signals seen during quasi static loading. As far as we know from previous works, all these signals stand for resin cracks, interfaces rupture, fibers pull-out and fiber breaking. As for the second class, it seems that rubbing causes such signals. The detailed analysis of the data with specific testing with higher loading ratio (R = 0.5), show that the second class is mainly made of signals from high amplitude loading (Figure 6.) and notably during unloading where localized compression can damage efficiently the composite (Henry 2011).

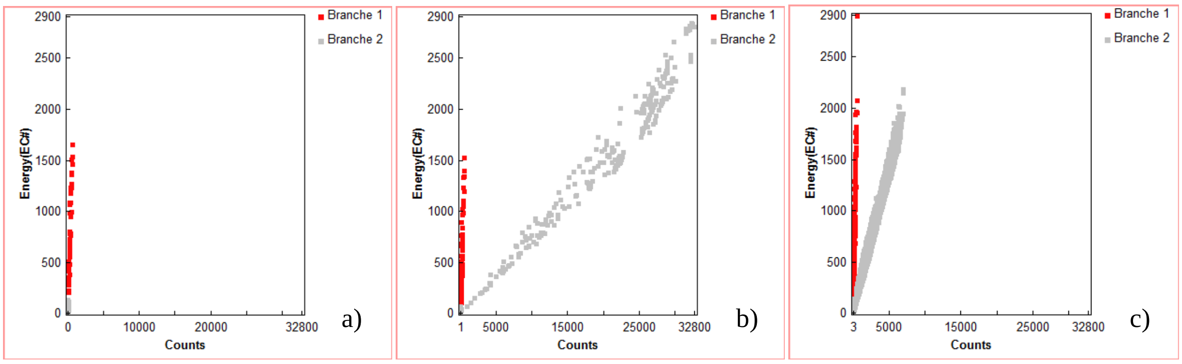

Figure 6. Energy vs counts for R = 0.5 (a), R = 0.3 (b), R = 0.05 (c).

2.1.3 Extensometry

In order to record global information about damage, an extensometer is used through all the life span of the material. This gives the strain of the sample from which, and with the applied stress, we can calculate the Young modulus in the loading direction. During its life, the sample elasticity of the specimen changes even for one cycle. One observes that with an advanced state of damage the behavior is far from pure elasticity and the ruin of the interface between tows and resin gives the strain-stress curve a banana shape (Figure 7).

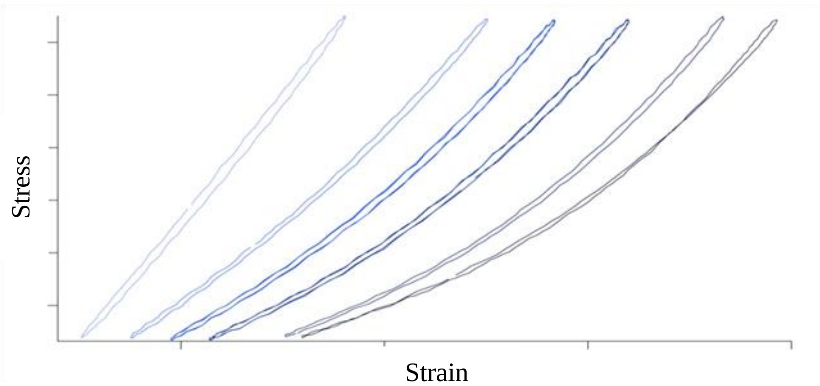

Figure 7. Cycle evolution for different moments in life span. From light to dark blue 0, 3, 7, 12, 60 and 95 % of life span.

2.1.4 *Digital Image Correlation*

As the evolution of elasticity is meant to obtain a reliable indicator for damage state, and not to produce reliable data for the model, one calculates the modulus with the minimum and maximum bounds for strain and stress. In order to detect early cracking, a full field strain measurement is performed on one face of the composite during loading. The testing machine software allows for the creation of complex loading. It is then possible to compute short stops in the cycling process to take pictures. If a speckle is paint on the face of the sample, with two different images, it is then possible to perform Digital Image Correlation (Correli_Q4 software). The result of the DIC is a displacement field which leads to the strain field with derivative calculation.

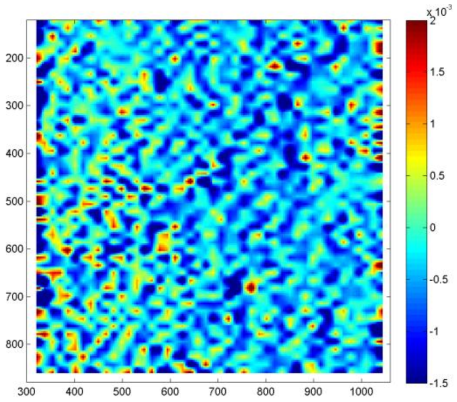

Figure 8. Strain field from DIC

However, as this method is used to detect early damages, the strain expected are low and localized. Despite all the care brought for the acquisition of clean images (alignment, cooled camera, contrasted speckle), there is always some experimental noise that is amplified by the derivative calculation. This noise can hide the local strain and it needs the use of filtering method to get rid of it. Lots of filters could do a proper job, whatever; the filter used for all of our DIC measurements is based on Diffuse Approximation. This kind of filter gives a weighted influence on the neighborhood of the filtered point. It has the possibility to run on the spatial field but on the time field too (for many images). Rx is the parameter for spatial distance and Rt the parameter for time distance. This allows obtaining a good filtering level with less apparent blur that the filtering with the same filtering level but just in the spatial field. The best couple of parameter Rx and Rt, is chosen through experimentation and depends on the size of ZOI (zone of interest) of the DIC measurements or the number of images (Feissel 2009).

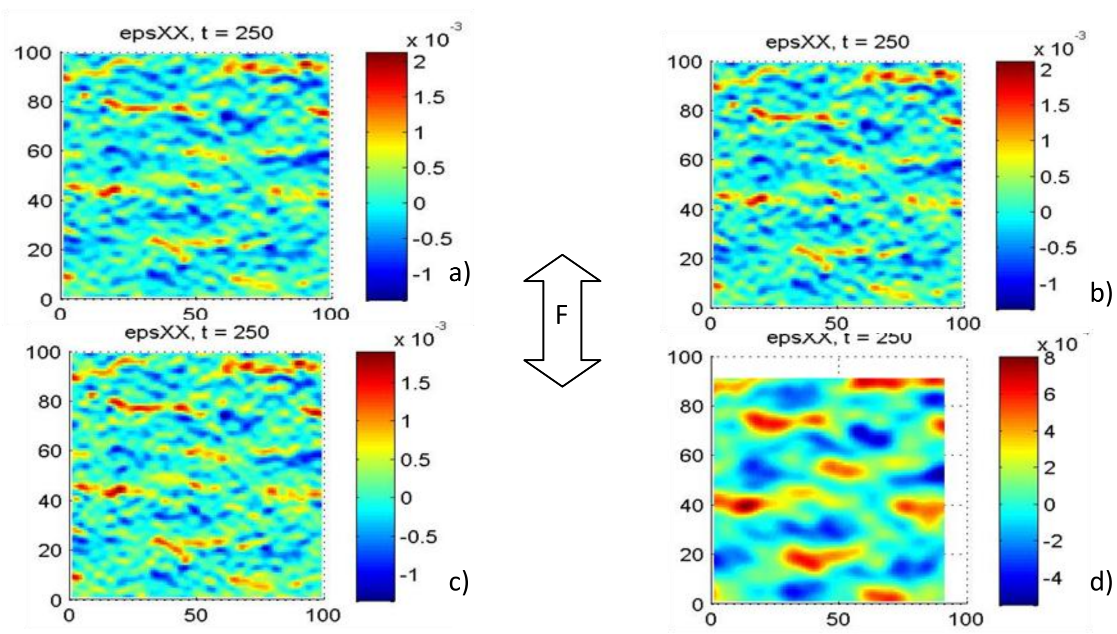

Figure 9. Strain field for different values of Rx and Rt. a) Rx = 20, Rt = 20, b) Rx = 20, Rt = 30, c) Rx = 20, Rt = 40, d) Rx = 40, Rt = 40.

All these different techniques are used during the entire fatigue loading with sometimes a small stop to acquire sharp images (for DIC and IR), thus allows to follow up the entire testing time and to have sufficient data. But other tools, that can't be used during cycling loading, are very useful for understanding the entire damage mechanic.

2.2 Discrete Acquisition

In order to use these devices, the testing machine has to be stopped enough time to perform proper acquisition. In this step, acoustic emission is no longer used due to Felicity effect. In order to optimize all of the stops, most of them are done during the first part of the life of the sample (during the first elasticity loss) (Figure 10.).

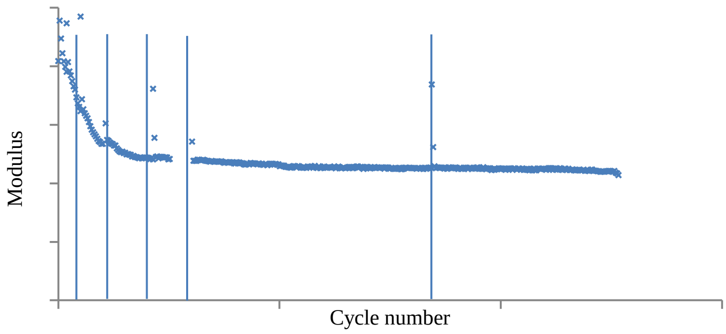

Figure 10. Example of stops positions during a fatigue test

2.2.1 Microscopy

DIC is not performed on the side of the sample because very early in the damage state, numerous cracks make the strain field very difficult to calculate, understand and interpret but this problem is limited to the face of the composite. Video microscopy and microscopy in general terms help interpreting the damage because of the direct view of cracks among the weave structure. It then helps to understand what is seen in DIC. On the side, video microscopy is helpful with detailed pictures of the sample for different instant during the cycling fatigue. In order to detect most of the damages with this device, the sample remains under tension during the acquisition (Figure 11. left)

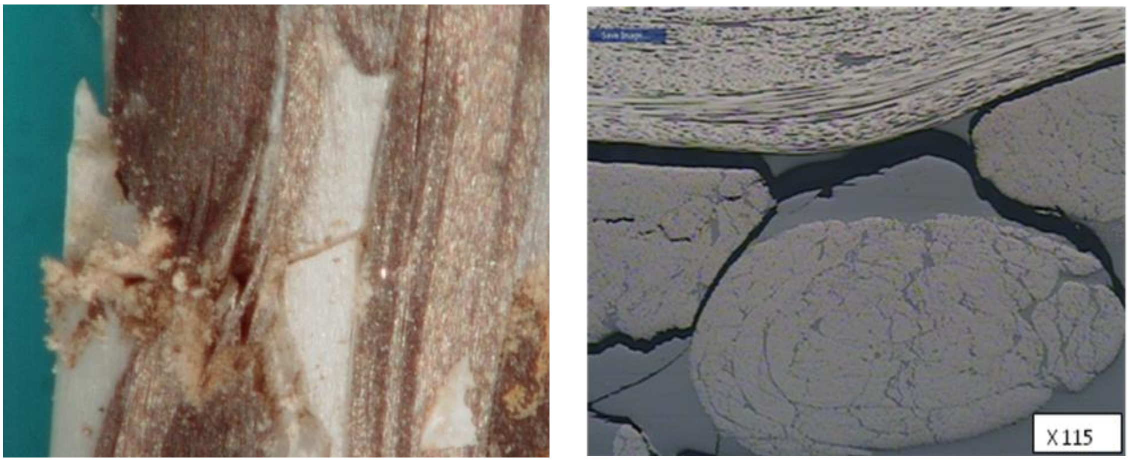

Figure 11. Damage pictures from: video-microscope (left), classical microscope (right)

One looks for precise picture of the damage, but the main usage is to picture the whole polished side of the sample. Then, we can directly see the damages on a few representative elementary volumes (REV) and the links existing between weaving pattern and damages. The video microscopy allows for the observation at mesoscopic scales from the width of the sample to the size of the tows. Any smaller observation is dedicated to classic microscopy with better quality pictures (Figure 11. right). The pictures can then be joined together to create a bigger image with high resolution and insight of the entire pattern (AutoStitch tool) (Figure 12.).

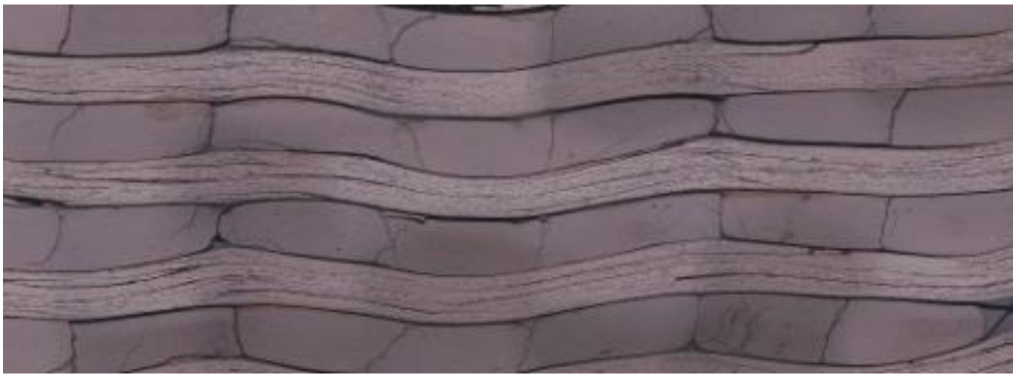

Figure 12. Stitched microscope pictures

The scanning electron microscopy as been used too, to get fibers information such as debonding and smaller resin cracks. It has a much better depth of field at this scale than classic microscopy (Figure 13.).

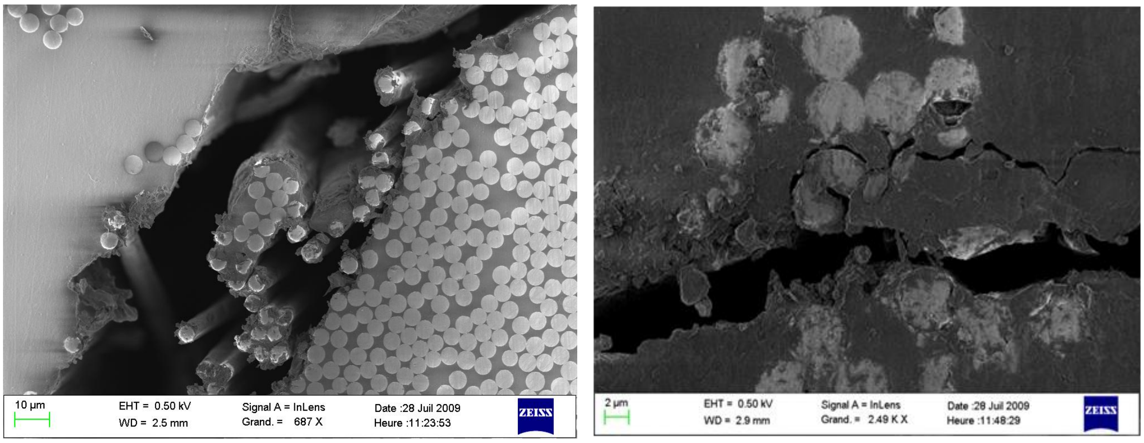

Figure 13. SEM images of tow interface (left) and isolated fibres (right)

The last two techniques bring very precious information on damages, however, these two needs a mirror polish surface and from time to time to cut the material in pieces for heart of the sample observation, or just to ensure to enter in the SEM vacuum chamber. So they are reserved for post-mortem (or post-testing) observation.

2.2.2 Micro-Tomography

To permit such observations at any moment during the life span, one can use micro tomography, a non destructive acquisition that represents the volume of the material with its weaving and cracks. The working principle of this device is to take X-ray pictures of the sample from different angles and then rebuild the entire volume per complex calculation. In Situ micro tomography is not so democratized yet, so the sample has often to be taken off from the machine. The results from such a method are dependant from the quality of the device. It is yet possible to distinguish warp and weft tows among the resin and above all to observe cracks (Figure 14.). As the material is not under tension during the acquisition, cracks are not too wide and hard to detect and the resolution of the technique doesn't allow one to see micro crack and fibers. Nonetheless micro-tomography is a very powerful tool that gives data any other device can't afford without damaging the structure of the specimen.

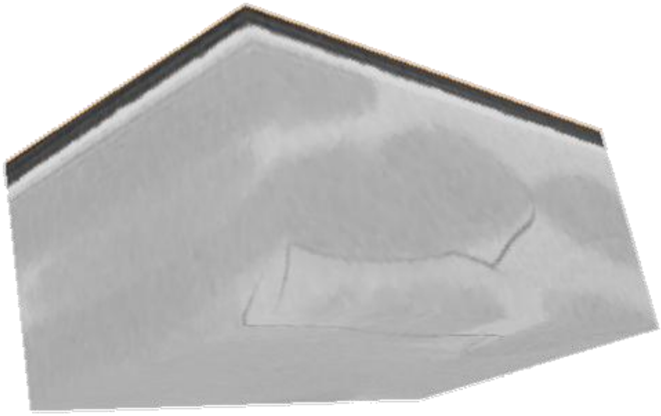

Figure 14. Micro-tomography picture of a crack through 3D composite

Each of this devices have their own function and when used alone can't help in finding out the damage scenarios. But together, every pieces of information from a device can be correlated with the other acquisition means and bring out reliable scenarios that can then be used in determining life span of complex loading.

3 CONCLUSION

Fatigue testing is a specific problem in material science that needs devices to ensure its follow-up through long tests. This paper has shown a complex instrumentation that is set up for every sample during their fatigue test. For each part of the global instrumentation, specifics data are obtained that help checking the validity of some results and interpreting other data. Thus, all of these techniques used together allow finding, for each damage phase and for complex material such as 3D weaving composites, the type of damage, their sequence of apparition and their impact on mechanical properties loss. The specific damage mechanisms are then added on the model to ensure that simulation is close to the real mechanical behavior.

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