EXPERIMENTAL INVESTIGATION OF THE IN PLANE AND THROUGH THICKNESS SHEAR DAMAGES ON 3D WOVEN CMC USING MULTI-INSTRUMENTED TORSIONAL TESTS

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Abstract

This paper relates the experimental study of the in plane and through thickness shear behavior of a 3D woven SiC/SiBC Ceramic Matrix Composite (CMC). Torsion tests were applied on rectangular bars to identify both initial in plane and through thickness shear modulus of the material. By the means of a mutli-instrumented approach, composed by tridimensional Digital Image Correlation (DIC 3D), Scanning Electron Microscope (SEM) observations and Acoustic Emission (AE) analysis, first damage and damage kinetics have been assessed for this type of solicitation. Results of this investigation demonstrate that damage mechanisms are primarily governed by the brittle properties of the seal coat. Above a certain level of damage, woven architecture appears to influence damage kinetics, particularly induced by out of plane shear stress.

1. Introduction

CMC have been developed in the early 1960th to provide good mechanical behavior at high temperature. Due to their low density comparing with metallic structures, its applications in aeronautical and spatial industry become more and more important. 3D woven preforms have been developed to increase mechanical properties in the third direction. In addition, new predictive numeric tools have been developed **[1] [2]**, including strong experimental knowledge. However, lack of information on the third direction necessitate further experimental investigation. This study, which investigates both in plane and out of plane shear behavior of this new material, fits into this framework. The aim is to quantify initial mechanical rigidity and to understand damage mechanisms induced by this type of solicitations. 3D woven perform leads to a very large size of the Representative Elementary Volume (RVE) compared with the 2D composites. Thus, structural tests, such as torsion tests, must be used to induce homogeneous shear stress on the whole RVE of the material. The extreme complexity of the CMC structure lead to complex damages mechanisms. Multi-instrumented approach, based on the overlap of several observation tools, such as DIC 3D, SEM observation and AE analysis, will be used to identify accurately these mechanisms and their kinetics.

2. Material and experimental procedure

2.1. Material

The material used in this present study is a 3D woven SiC-SiBC composite, which is manufactured by Herakles (SAFRAN group). At a mesoscopic scale, this CMC encloses three main parts: (i) The 3D woven structure, which is composed by SiC fibers and densified by self-healing matrix **[3]**, (ii) the macropores due to the high waviness of the 3D woven structure, and (iii) the surface layers composed by self-healing matrix called "seal-coat".

2.2. Experimental procedure

Torsion tests provide a complex state of stress, that is not simple to apprehend. Thus, adaptive testing methodologies must be developed to find out shear characteristics of the tested material. In our case, we firstly have defined a suitable method to measure in plane and trough thickness initial shear rigidity, in the elastic domain of the material. Secondly, a multi-instrumented approach has been used to identify damage mechanisms and their kinetics.

2.2.1. Initial shear modulus measurement

Torsion tests induce both in plane and through thickness shear stresses on rectangular bars. Distribution of these shear stresses is a function of the sample's geometry. By a judicious exploitation of the elastic theory of anisotropic body **[4]**, scientific community has developed a specific method to measure simultaneously in plane (G_{12}) and out of plan (G_{13} or G_{23} depending on the orientation of the samples) shear modulus **[5]**.This method is based on the use of at least three sets of bars having different sections. By the means of an interpolation, the linking of all torsional rigidities ($\boldsymbol{CL/\theta}$) issued from these sets, allows to access both in plane and out of plane shear modulus of the material (equation 1).

$$min_{G_{12},G_{13}}\left(\sum_{i=1}^{N}\left[\frac{C_iL_i}{\theta_i b_i {h_i}^3} - G_{12}ß\left(\frac{b_i}{h_i}\sqrt{\frac{G_{13}}{G_{12}}}\right)\right]^2\right) \qquad (1)$$

where "G_{12}" and "G_{13}" are respectively in plane and out of plane shear moduli. "b"," h","L" are respectively the width, the thickness, and the length of the test sample. "θ" is the angle of twist and "C" is the applied torque. "i" is one of the "N" different sets of section tested.

The accuracy of the method relies on the quality of the torsional rigidities experimental measurement. These values are influenced by the effects induced by the torque introduction. To avoid these effects, it is necessary to measure torsional response of the samples $\boldsymbol{\theta}$ on a restricted area, far away from the torque introduction zones **[6]**. Based on these considerations, an original experimental procedure has been developed to identify simultaneously in plane and through thickness shear modulus **[7]**. To measure properly the torsional angle of each sample, DIC 3D is focused on a restricted area comprised between 35% and 65% of the total length of the rectangular bars (Step 1,2 on Figure 2). The torsional angle is then calculated by geometrical transformation of positions and displacement fields measured by DIC 3D (Step 3). From this torsional angle and the applied torque, torsional rigidity is then identified by linear regression (Step 4). Different sets of section are chosen to finally proceed the interpolation (Step 5).

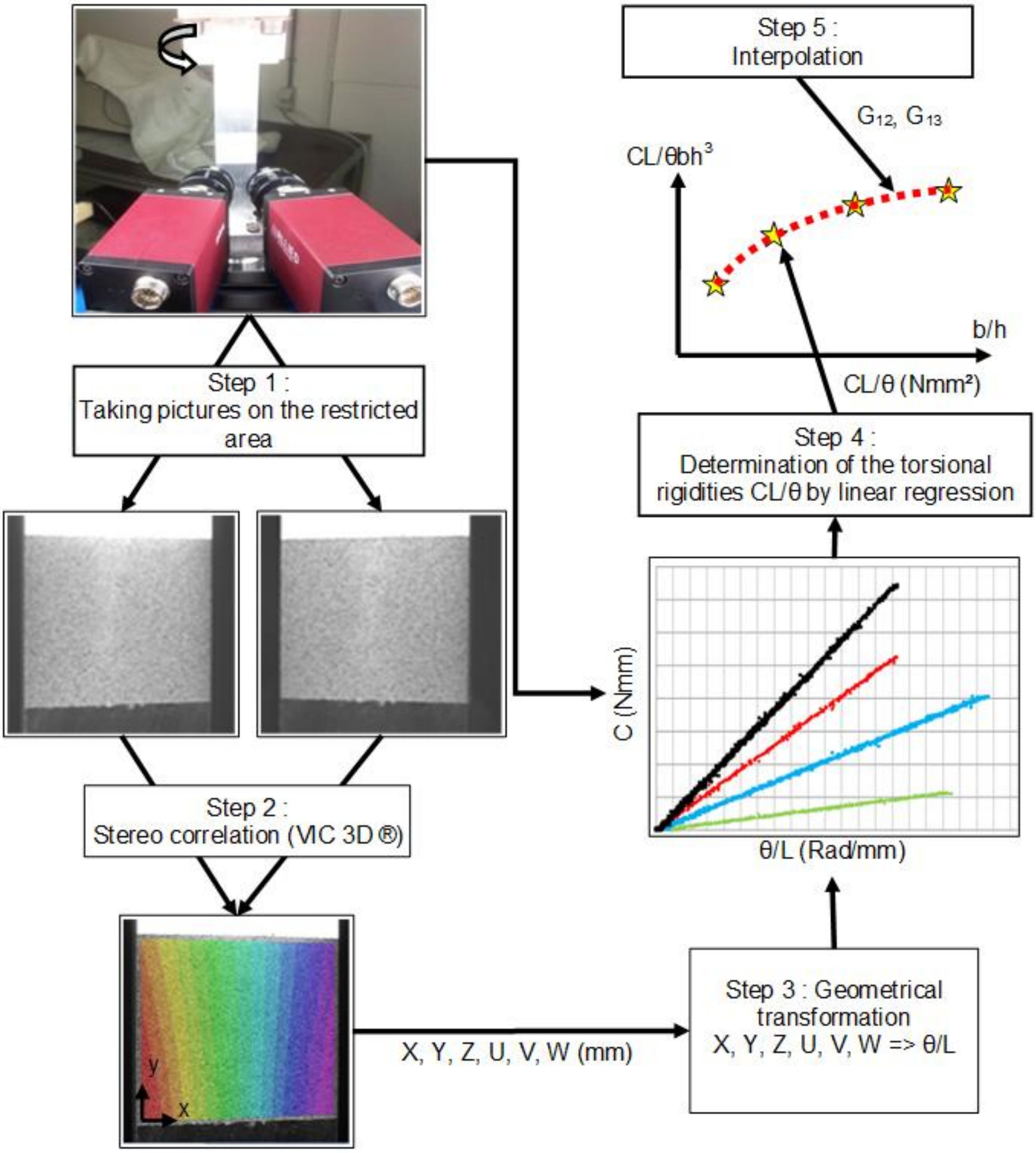

Figure 1. Description of the experimental procedure to measure simultaneously in plane and out of plane shear modulus by torsion tests (After [7])

.2.2.2. Identification of damage onset and kinetics

A specific torsion test protocol, based on several incremental loads, has been established to investigate the onset and the kinetic of the damage mechanisms (Figure 3.a). Tests have been multi-instrumented, using both DIC 3D, SEM fractography, and AE analysis (Figure 3 b).

DIC 3D is applied on both the front and the side of the tested samples, to acquire simultaneously in plane and through thickness strain fields. The samples' macroscopic response can be measured, thanks to vitual strain gauges applied on the strain fields. Due to fragile properties of their constituents, CMC provide very low strain levels. To reduce the noise component, which is relatively high comparing with this strain levels, these fields are first filtrated thanks to diffuse approximation **[8]**. This filtering approach enables to get high quality strain fields. From these filtered strain fields, localization of nonlinearity can be identified on the DIC 3D covered surface, by comparison between two fields measured at different time **[9]**. This method, called "method of local nonlinearity gaps", allows to detect potential local damages occurring at the material surface.

SEM fractographies are taken on the opposite faces of the samples (both front and side), after each incremental load, in order to study the evolution of the damages due to shear loading. The crack identification necessitates high resolution images, which do not cover up the totality of material RVE. To overcome this problem, mesoscopic maps are constituted with more than 4000 high resolution images. From these maps, damage kinetics can be observed, at the mesoscopic scale of the material.

Acoustic emission, resulting from torsional solicitation, is acquired and then analysed thanks to non supervised clustering **[10]**. Several cluster can be defined, using the similarity of the signals.

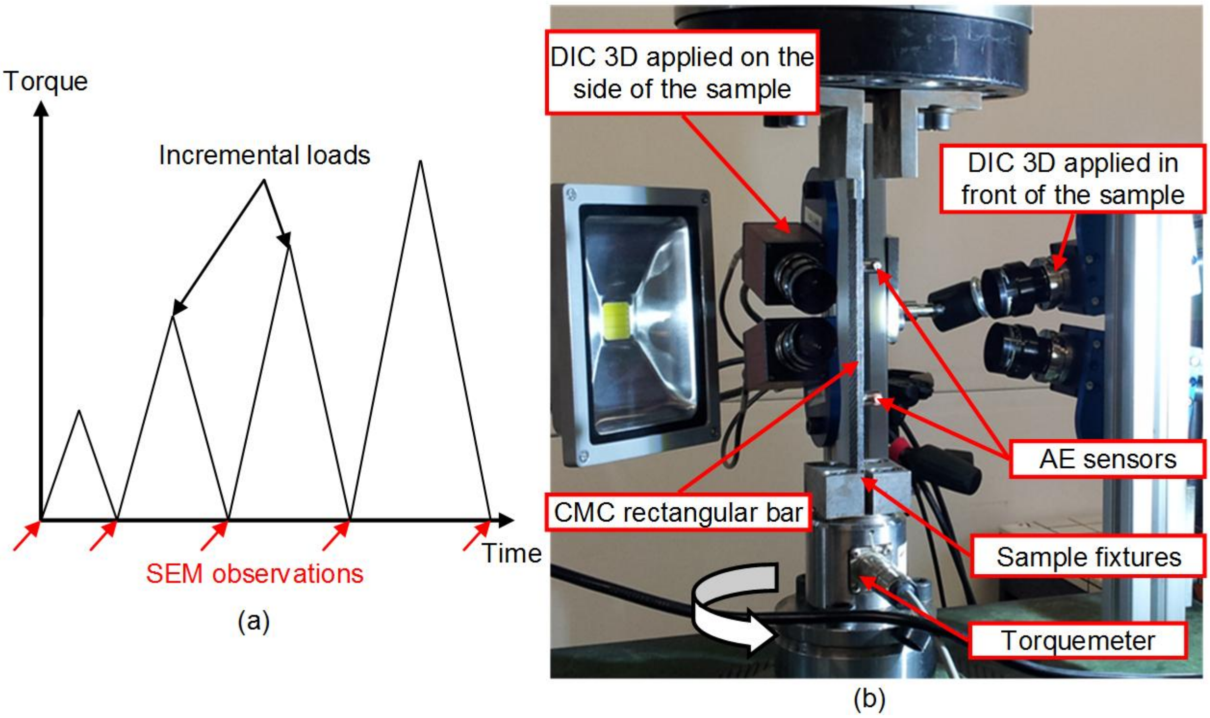

Figure 2. Illustration of the test protocol experimental procedure to measure evaluate simultaneously in plane and out of plane shear modulus.

3. Results and discussion

3.1. Elastic behaviour

Three different sets of section have been chosen to proceed the torsion tests on CMC. Figure 4 shows samples' normalized torsional rigidity versus their geometrical characteristic b/h. From these values, both in plane (G12) and through thickness (G13) shear modulus have been identified, using a constrained nonlinear optimization program (provided by Matlab ® software) to interpolate experimental data. To ensure that the results weren't local minimum of the function (equation 1), the optimization program have been launched several times using different initial conditions.

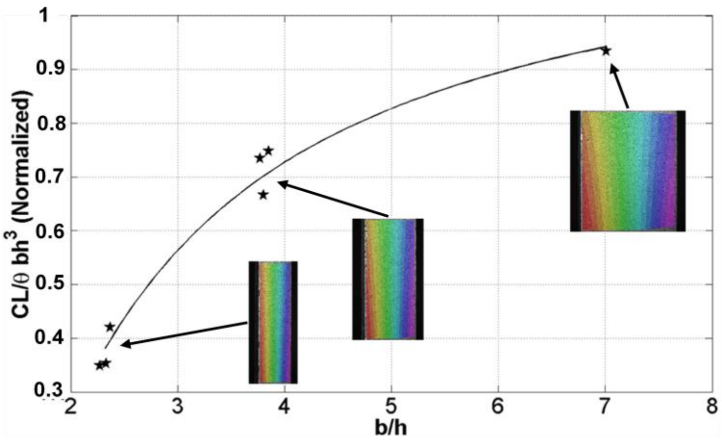

Figure 3. Torsional rigidities measured on the CMC samples and result of the interpolation process.

3.2. First damage

Several indicators have been checked out to identify the onset of the damage. The first one, which is a macroscopic damage indicator, consists on the measure of the global shear deformation, using virtual strain gauges on both the fronts and sides of the tested samples. After each incremental load, residual shear strains have been measured. As soon as these values appeared to be non zero values, corresponding maximum shear strains have been noticed. Following this procedure for all the samples tested, maximum shear strain values appeared to be about the same, regardless of the section and the surface (front or side) considered. From this consideration, all values have been averaged. The resulting normalized value, which is equal to 0,11, correspond to the in plane $\boldsymbol{\varepsilon_{12}}$ and through thickness $\boldsymbol{\varepsilon_{13}}$ shear strain level before the apparition of a macroscopic residual shear strain. The second damage indicator consist in finding out the initial cracks on the CMC surface, thanks to the SEM cartographies taken on both the front and the side of one tested sample, after each incremental load. The first cracks have been detected on the front of the sample for an applied load inducing in plane normalized shear strain $\boldsymbol{\varepsilon_{12}}$ equal to 0,12. On the side of this sample, first cracks have been identified for a through thickness normalized shear strain $\boldsymbol{\varepsilon_{13}}$ equal to 0,10. We can notice that these values surround the one defined thanks to the macroscopic damage indicator. To constitute another damage indicator, the method of local nonlinearity gaps has been applied to in plane shear deformation $\boldsymbol{\varepsilon_{12}}$ fields. Figure 5 shows fields resulting from the application of this method. Results shows that above an in plane normalized shear strain $\boldsymbol{\varepsilon_{12}}$ of 0,15, the first nonlinearity gaps (indicated by red arrows on the figure) appears. These first gaps indicate that potential local damages initiate at the material surface.

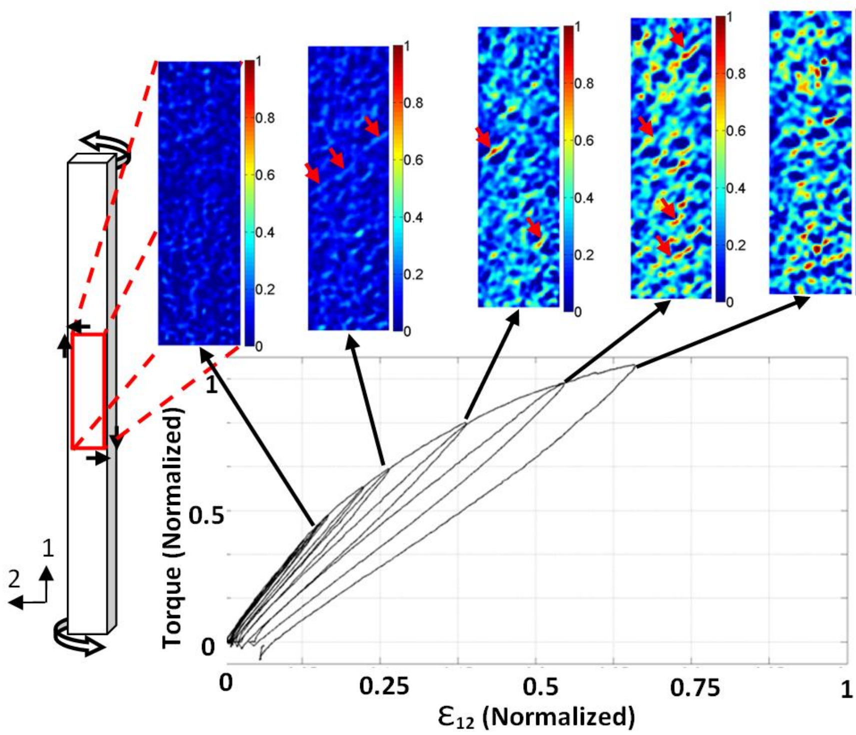

Figure 4. Illustration of the fields issues from the application of the method of local nonlinearity gaps.

Using the k-means unsupervised clustering algorithm on the acoustic signals, three different cluster have been identified. From these three clusters, one appeared to contain much more energetic signals than the two others (green cluster on Figure 6). In addition, this specific group respects the Kaiser effect **[11]**. These two remarks indicate that this cluster is directly linked with damages occurring on the material. Based on this consideration, the onset of the emission of this particular group constitutes an additional damage indicator of the CMC. We can observe that the emission of this cluster begins for normalized in plane shear strain $\boldsymbol{\varepsilon_{12}}$ equal to 0,12. Simultaneously, the normalized value of $\boldsymbol{\varepsilon_{13}}$ is equal to 0,10.

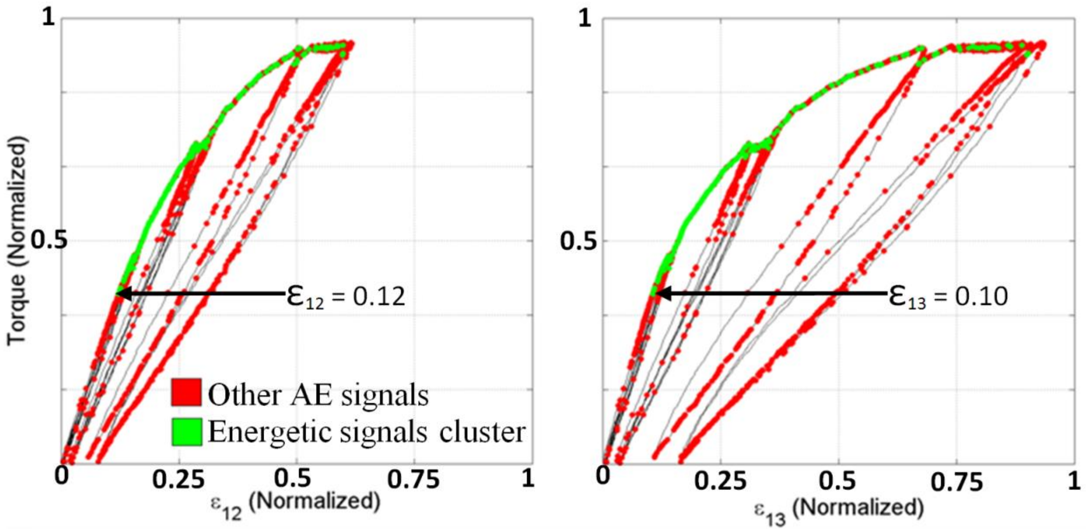

Figure 5. Acoustic emission acquired on a sample subjected to a torsion test.

Based on the crosscheck of these multiple results, we can admit that damages induced by in plane and through thickness shear solicitation initiate for in plane $\boldsymbol{\varepsilon_{12}}$ and through thickness $\boldsymbol{\varepsilon_{13}}$ shear strain normalized values comprised between 0,1 and 0,12.

3.3. Damage kinetics

Damage kinetics have been assessed thanks to both SEM mesoscopic maps and the shear deformation fields given by DIC 3D. SEM mesoscopic maps, illustrated in Figure 6, permit to observe that all the cracks were oriented at 45° with respect to first principal direction of the material coordinate system. This specific orientation can be explained by the isotropic brittle properties of the surface layers which compose the seal coat. The SEM map obtained on the side of the sample reveals that the majority of cracks connect open voids. This voids act as stress concentration zones, where cracks initiate.

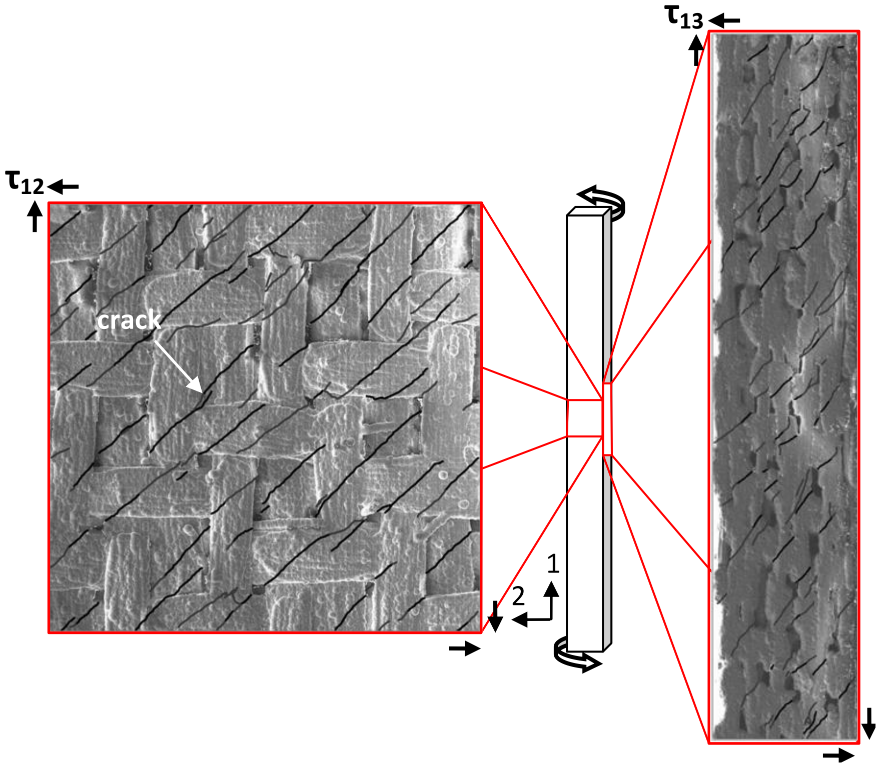

Figure 6. Observation of the damage kinetics occurring on a CMC sample surface (front and side) subjected to torsion test , through SEM cartographies.

Beyond a certain level of damage, the through thickness shear strain field, measured by DIC 3D, shows progressive apparition of high gradients, which describe a periodic pattern (Figure 7). This pattern has been linked with the 3D woven architecture of the CMC. Thus, 3D woven structure plays a major role on damage kinetics, as soon as surface cracking are sufficiently developed to allow relative yarn displacements into the woven structure.

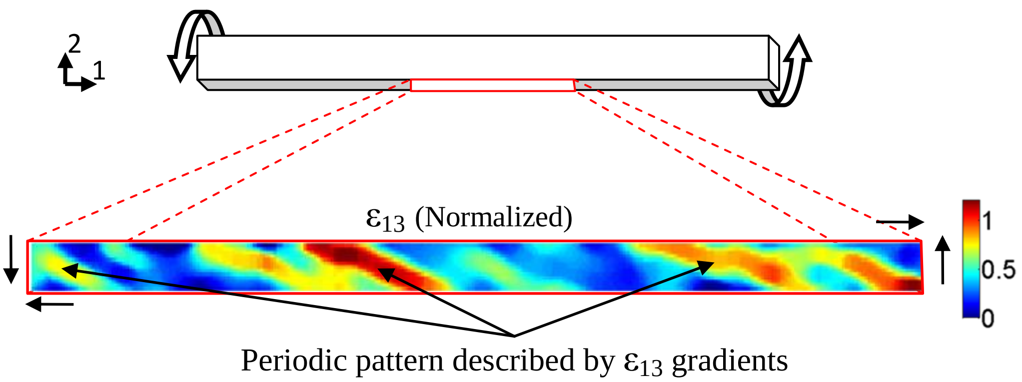

Figure 7. Periodic shear strain pattern issued from DIC 3D field on the side of a sample subjected to torsion test.

4. Conclusion

In this work, torsion tests have been applied to a complex 3D woven CMC material, to increase the comprehension of its in plane and through thickness shear properties. In the first part of the study, an original methodology, based on the use of DIC 3D, has allowed to identify its initial shear rigidities. Secondly, damages occurring on CMC have been investigated thanks to multi-instrumented tests. Onset of damage has been identify by the crosscheck of several damage indicators, resulting from all the investigation tools (DIC 3D fields, SEM cartographies, AE analysis). Damage kinetics have been studied through SEM mesoscopic maps and though thickness shear strain fields. The results of this investigation demonstrated that the early damage mechanisms were cracks whose orientation are governed by the brittle properties of the seal coat. Above a certain level of damage, it has been shown that woven architecture influence damage kinetics too. This new mechanism appears as soon as cracks are sufficiently developed to allow relative yarn displacements into the woven structure.

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