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Comparing Methods to Detect the Formation of Damage in Composite Materials

V. Couty¹, J. Berthe^{1,2}, E. Deletombe^{1,2}, P. Lecomte-Grosbras¹, J-F. Witz¹, M. Brieu³

There is a significant need for tools to detect damage in composite materials, whether for the development of models, the characterization of materials or the validation of structures. However, many different methods are available, each with its own advantages and drawbacks, making the choice difficult when setting up tests. This paper will present multi-instrumented uni-axial tests on $[0_{2},90_{2}]_{s}$ carbon-epoxy samples at 0°, 90° and 45°. These tests feature DIC, thermography and acoustic measurements with a standard microphone in order to explore the capabilities of each of these methods. The processing is detailed and the information extracted from each method will be discussed in order to provide an overview of the uses for each method.

Composite. Cross-ply laminate, Thermography, DIC, Damage

Introduction

Composite materials such as Fiber Reinforced Polymers (FRP) offer excellent specific properties, making them ideal for aeronautical applications. But the mechanical properties of FRP can be altered by damage. If the occurrence of damage can sometimes be harmless to a system, it may also lead to an alteration of the properties of a part and even lead to a failure. Consequently, understanding damage is of critical concern to properly and efficiently design composite parts. Damage is often represented by a decrease in the stiffness of the material. This phenomenon is the consequence of a degradation of the material at the microscopic scale. In order to quantify damage at the local scale, one can either observe locally the consequences on the material or directly detect the events leading to this degradation when it is possible. It may be done thanks to the energy dissipated by these events.

V. Couty victor.couty@centralelille.fr When the energy is released under the form of heat, the temperature increase caused by alterations of the material can usually be picked up using infrared thermography, a commonly used Non-Destructive Testing (NDT) technique to detect damage in composites [1–4]. The heat fluctuations caused by thermoelasticity can also be detected, which is commonly used to study fatigue [5–7]. Active thermography is a technique used to extract information from the heat conductivity of the material by recording the transient behavior of a sample [8].

The energy released by the internal phenomena leading to damage can also be mechanical. This induces mechanical waves that can be picked up by accelerometers using the passive acoustic emission method. This technique is commonly used in composite testing [9–15]. It is not to be confused with active acoustic emissions, where the waves are generated using transducers (classically in the ultrasonic range) and the response of the material is measured to detect anomalies in the propagation of the waves due to an alteration of the material [16–21]. This method can detect local alterations of the material and the presence of porosity.

Damage can also be detected by its kinematic signature: the local evolution of the material properties will cause a reorganisation of the structure. Using an adequate model of the material, this signature can be detected using surface displacement measurement techniques. Several methods such as holographic interferometry, moiré interferometry, the grid

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method or many others [22–24] can be used to measure the displacement fields on the surface of the sample. Digital Image Correlation (DIC) has become the most common full-field kinematic measurement most likely because of the simplicity of the setup. It is now possible to measure pixel-wise displacements and strain fields with a very high sensitivity, allowing the detection of very faint phenomena, making DIC a viable candidate for damage detection and measurement [25]. Evolution of the microstructure in the bulk of the material can be detected using X-ray imaging by radiography, laminography or tomography [26–29], often revealing damage under the form of cracks and delamination in the case of composite materials.

In this paper, the capability of DIC and thermography to detect damage will be studied and compared. Additionally, the use of a non-contact condenser microphone to detect acoustic emissions will be explored and compared to the other methods. It should be noted that in this study, the thermography measurements will not be interpreted quantitatively. No effort was made to extract the temperature of the surface or quantify the amount of thermal energy released from the sample. Instead, the raw images will be processed directly in order to detect short variations of emission. It will be assumed that these events correspond to irreversible phenomena such as cracking and that they are linked to damage formation in the material. The goal of this study is to compare the capacity of these different measurement techniques to detect damage during a tensile test on carbon-epoxy samples. All three measurements are performed simultaneously during the tests. They are performed on T700-M21 laminate samples, the layup, $[0_2, 90_2]_{c}$, is tested at different orientations. The measurements will be processed offline to extract information about the state of the material and the mechanisms of damage will be investigated and compared to the literature.

Materials and Method

Two series of uniaxial tensile tests were performed on samples of laminated carbon-epoxy at different angles.

Samples Preparation

The composite plates used to cut the samples count eight layers of unidirectional plies of prepreg carbon-epoxy with a thickness of 0.25mm, the layup is $[0_2,90_2]_s$. The layers were cut and laid out manually and cured at 180°C and 7 bars of pressure for 4 hours followed by a cooling ramp of 3 hours.

Each test was performed with an angle of 0° , 45° and 90° between the direction of traction and the fibers of the surface plies. The dimensions of the samples are shown in Fig. 1. The samples were prepared with 50mm long



Fig. 1 Dimensions of the samples of the first series (a) and the second series (b). The only difference is the presence of the hole in the center of the ROI

glass-fiber pads glued on each side of the ends of the sample, with a 45° chamfer to limit strain localisations near the grips of the machine, meaning that the Region Of Interest (ROI) is 150mm long. The samples of the second series are prepared with a 3mm hole in the center of the ROI drilled using a drill press with a carbide tip 3mm drill bit. The goal is to cause non homogeneous strains near the singularity and compare the observed mechanisms to the strain fields of the first samples.

The samples were cut using a water jet cutter. Tests were performed on scrap plates to find the best cutting parameters and avoid delamination. It is crucial for the water jet to enter the plate by a side or a pre-drilled hole to avoid delaminating the composite. The parameters used to cut the samples were a pressure of 1000 bars, 170grams/min of abrasive silica and a speed of 250mm/ min. The hole of the nozzle is 0.35mm. The plates were clamped to a thin wooden plate secured to the working area of the machine.

Experimental Protocol

The testing procedure consists in a loading phase at constant speed of 2mm/min until a prescribed strain is reached and unloading at the same rate until the force is 10N. The strain steps are gradually increasing by 0.25%. An example of loading is shown on Fig. 2. The strain is measured using real time global DIC [30].

Hardware Description

The test is performed on an Instron 5882 tensile machine equipped with a class 0.2 load cell rated for 50 kN. A picture of the setup can be seen in Fig. 3. The machine is controlled using CRAPPY, a Python module designed specifically to control setups involving multiple sensors and actuators. The



Fig. 2 Example of longitudinal strain applied to a sample: the strain increases by steps of 0.25% and the sample is unloaded until the force is 10N (strain is not necessarily 0% at the end of a cycle)

Fig. 3 Picture of the setup with the main camera (**a**), the side camera (**b**) and the microphone (**c**). The IR camera is out of the image (**d**)

integrated DIC is performed directly on the images from the front camera. The rigid body motions and homogeneous strains are extracted and the strain along the direction of traction is used as a criterion to control the cycles of the test. All the cameras are synchronized and recording at 5 frames per second and all the images are saved in full-resolution without compression for post-processing, including pixelwise full-field DIC using the OpenCV implementation of DISflow [31]. The force and position of the machine are saved at 1 kHz. The acoustic pressure is recorded using a T-bone SC500 condenser microphone at a samplerate of 192kHz in 24 bits mode. The microphone was placed as close as possible to the sample without direct contact. Even if this method is probably less sensitive than attached piezoelectric transducers, it is much more cost-effective, requires no preparation time and does not alter the sample. Since the room where the tests are performed cannot be completely silent, the ambient noise is removed in post processing using the spectral noise gating technique implemented in the Audacity ®;software [32]. This noise is caused mostly by the fans of the machines and by the Stirling cooler of the IR camera. Once the signal is free from the ambient noise, the acoustic pressure is averaged over a window of 10ms. This signal is differentiated and spikes are detected and counted as an event. The next spike can only be counted if the derivative has reached a negative value in between. This avoids counting the same event twice, especially since the sound is subject to reverberation in the room and shows a significant decay period during which the acoustic pressure can stay above the threshold.

In all of the tests, an infrared camera monitors one face of the sample, a high-resolution camera monitors the other face of the sample and a third camera monitors the side of the sample with a macro lens. The side of the sample was polished prior to the test to give a clear view of the plies.



Optionally, in only one series of tests the side camera was moved to the front of the sample to provide a closer look at the events on the face of the sample. The IR camera is a FLIR X6580sc camera with a 50mm lens, the images resolution is 640x160 pixels, with a pixel size of 160µm and the integration time is 3ms. The main camera is monochromatic camera Ximea CB500 8k camera recording images at a resolution of 7920x1600 pixels with a pitch of 20µm, an exposure time of 150ms and a Canon EF 100mm USM lens. The side camera is a monochrome Ximea MC124MG-SY with a Laowa 25mm macro lens which records images of the side of the sample at a resolution of 4112x3008 pixels, a pixel size of 0.96µm and an exposure time of 120ms. The lightning is aided by led rings placed around the lens of both optical cameras. In the tests where the side camera is moved to the front, the lens is a Zeiss Makro planar ZF T* 100mm lens. It records an area that covers the entire width of the sample and a 30mm of height. The pixel size is 9.9µm and the exposure time is 100ms.

To quantify the strain error introduced by the DIC algorithm used for post-processing, a study was performed on rigid body motions with the setup and each sample used during the test. A vertical motion was applied to the sample by actuating the machine without clamping the lower end of the sample. Images were taken at 0.01mm, 0.05mm and 0.1mm. The standard deviation, 95th and 99th percentile of the strain were computed. Since the strain is not supposed to vary, this method provides an estimation of the error in the strain measurement using this method. The Table 1 sums up the deviation of the measurements.

Table 1 Deviation on ϵ_{xx} and ϵ_{yy} on rigid body motions (μ strain)

Series	STD	95th percentile	99th percentile
1st series (plain)	146	281	405
2nd series (with a hole)	186	352	591

Results

Macroscopic Behavior

The $[0_2,90_2]_s$ and $[90_2,0_2]_s$ samples show very similar behaviors. This is expected as in both cases, half of the fibers are vertical (in the direction of traction) and the other half are horizontal, only the order of the plies is different. In these tests, the stress-strain curve showed a nearly elastic behavior as shown in Fig. 4. This is despite the clearly visible damage of the horizontal plies. The only major difference in the macroscopic behavior is the ultimate strain as the $[90_2,0]_s$ sample breakage occurred at 1.45% which is higher than the $[0_2,90_2]_s$ at 1.22%. The former therefore performed one additional unloading/loading cycle at 1.25% strain. The moduli are close for these two orientations, with 68.6 GPa for the $[0_2,90_2]_s$ and 69.2 GPa for the $[90_2,0_2]_s$ sample.

The samples at 45° showed a significantly different behavior. At the macroscopic scale, damage is clearly present as shown on the stress-strain curve in Fig. 5. The stiffness of the sample is decreasing after each cycle, which is expected for this layup. For every orientation, the samples showed behaviors similar to those in [33].

Observations on $[0_2,90_2]_s$ and $[90_2,0_2]_s$

Even though the macroscopic behavior is almost perfectly elastic in these configurations, numerous events suggest that the samples were actually subject to damage. DIC detects major events on the $[90_2,0_2]_s$ samples, suggesting an alteration of the 90° layer. The (Fig. 6a) shows the strain along the traction axis revealing some of these events on the $[90_2,0_2]_s$ sample. The lines on (Fig. 6b) are actually discontinuities but the DIC algorithm reveals them as strain spikes because of the regularization. For comparison, (Fig. 6c) shows the strain fields on the $[0_2,90_2]_s$ sample where no events are



Fig. 4 Stress-strain curve of a test on a $[0_2,90_2]_s$ (left) and a $[90_2,0_2]_s$ (right) plain sample



Fig.5 Stress-strain curve of a +/-45 sample on the third series of tests

easily visible. The sudden discontinuity parallel to the fibers and forming instantly on the $[90_2, 0_2]_s$ sample appears to be transverse matrix cracking. To confirm this, micrographies of the sample were performed and the presence of cracks like the ones shown on Fig. 7 at the locations of these events confirmed this hypothesis.

Thermography detects many events on the $[90_2,0_2]_s$ sample, they are likely caused by the heat released by the formation of the same type of cracks. These events show a sudden increase of temperature along a line over the width of the sample followed by a dissipation period of a few frames. Figure 8a shows the IR signature of these events. The $[0_2,90_2]_s$ samples show the same pattern (see Fig. 8b)

but with a lower amplitude. This could be the manifestation of the same mechanism, transverse matrix cracking, but occurring in the inner layer of the sample like observed in [29, 34, 35].

During the test, clicking sounds can be distinctly heard and are easily captured by the microphone. Most of these short sound bursts seem to coincide with the formation of a crack on either thermography or DIC. However, there are a few other acoustic events that do not coincide with the formation of a crack. These event have in average a lower amplitude and happen mostly at the higher strain levels. They are likely the manifestation of another type of event such as premature fiber rupture or delamination.

These observations lead to believe that the main damage mechanism observed in these tests is transverse matrix cracking in the plies oriented at 90° whether they are on the surface or in the bulk of the sample. The first cracks appeared at a global strain level of around 0.4% in every test and can be detected by thermography, DIC and the microphone.

The cracks appear to propagate through the entire width of the plain samples in a single frame. Given the frame rate of 5 fps, this implies that the cracks take less than 200 ms to propagate. The propagation is actually much faster: the audio recordings show that most events are a few milliseconds long and several paper with similar configurations show almost instantaneous propagations [34, 36, 37].

IR images show distinctly the formation of the cracks. For an easier processing, the difference of two successive images is considered instead of the images individually. On the $[90_2,0_2]_s$ samples, the crack occurring on the face are clearly visible. On the $[0_2,90_2]_s$, the crack occur in the bulk



(a) $[90_2, 0_2]_s$ sample



Fig. 6 Strain field on the face of the plain samples at different levels of macroscopic longitudinal strain

Fig. 7 Micrography of the side of a $[90_2,0_2]_s$ sample after testing showing a crack in the 90° surface layer





(b) $[0_2, 90_2]_s$ sample

Fig. 8 Signature of a transverse matrix crack on IR thermography

of the sample but the heat signature is still detectable thanks to the diffusion through the top layer. The signatures of a crack for both orientations are shown on Fig. 8. They are constituted of a localized IR emission increase in a single frame, followed by a return to the average temperature in 3 to 5 frames, inducing a negative spike on the differences of images. On the $[0_2,90_2]_s$ samples, the phenomenon is less clear as it is affected by the dissipation through the top layer.

In order to follow the evolution of the crack density, an algorithm was developed to detect and count the cracking occurrences on the IR and visible images and compute the number of cracks per mm. The method used to process the IR images consists in a detection of local increases of the emission of the sample. The goal is not to quantify the amount of energy dissipated directly, or measure the temperature of the sample but simply detecting and locating the occurrence of such spikes of emission. The formation of a crack results in a temporary increase of the emission. Because the cracks propagate through the entire width in a single frame, a method taking advantage of this was developed to detect and count the cracks reliably. This is done by making the pixel-wise difference between two successive images, and summing them along the width of the sample, resulting in a 1D array. This method helps reducing both noise and the amount of data to process. When a crack occurs, a positive spike in this 1D array can be detected at the appearance of the crack followed by a negative spike that progressively flattens and spreads out as the heat dissipates. Figure 8a and b show the signature of the cracks on 0° and 90° samples and the graph of the sum used to perform the detection. Projecting this 1D diagram over time constitutes a 2D image on which the instant and localization of each event can be visualized simply as shown in Fig. 9. The events can be easily recognized by the short bright line followed by a dark gradient. On 0° samples, since the cracks do not form



Fig. 9 History of the difference of digital levels from the IR camera summed over the width of the sample for both orientations

on the surface, only the heat dissipating through the top layer can be detected. The signature is significantly attenuated, but can be detected in the same way.

A similar approach is applied to process the fields extracted from DIC: an estimation of the longitudinal strain is obtained by computing the gradient of the displacement in the traction direction. This field is summed along the width of the sample. Using this method, DIC can detect very clearly the spikes caused by the discontinuities induced by the cracks. This is illustrated in (Fig. 6a). These events are very distinct, indicating that DIC performs well to detect events occurring on the surface of the sample. It should be noted that this method can be applied to the strain fields, but also to the residual between two successive images. When a crack opens on the surface, the texture is altered and a line of higher values will distinctly appear on the location of the crack. Section "Evolution of crack density" discusses further the evolution of the number of cracks.

On the tests at 0°, this method can still detect a very faint signature on the surface even though the cracks occur in the 90° plies at the core of the sample. To be able to detect these events of very low magnitude and filter out previous events, the DIC is performed between two successive images instead of keeping the unsolicited state as the reference. The displacement fields therefore contain only the motion that happened in the last 200ms. This method allows the detection of roughly one third of the cracks detected by thermography in the 0° orientation. The strain variation on the surface when a crack occurs in the inner transverse plies is about 0.02%, which is really close to the sensitivity threshold of the DIC

algorithm, making it unsuitable for a reliable detection in this scenario. The fibers along the direction of the traction present a rigidity orders of magnitude higher than the rigidity of the matrix so the very low amplitude of the strain on the surface was expected.

In this scenario, the apparition of the crack is accompanied by a very distinct clicking sound. The microphone can pick up these events easily. The detection is not a problem, however an accurate counting is not easy to perform as the noise spike caused by some events can take up to 100ms to fade entirely. This is partly due to the wave taking time to dissipate in the sample, but also due to echo in the room. This may induce overlaps of successive events so the use of a simple level threshold is not sufficient. To overcome this, an algorithm has been developed that computes an "average acoustic pressure" over windows of 2ms. It is considered that an event occurred if a high threshold is reached on a time window. Until the lower threshold is reached, new events are only registered if they show an increase over the previous window. It is like a cooldown period, but still registering events in the case of a sudden increase during the cooldown. Upon visual inspection of the results, this method has shown to be very robust. In the presented tests, all of the events detected by DIC and thermography are also detected with the microphone. However, there are events detected with the microphone and not the other measurements. This is discussed more in depth in Section "Evolution of crack density".

The force sensor is sensitive enough to pick up slight drops in the signal caused by some of these events. However, less than 25% of the cracks detected by DIC and thermography are detected by this method. The Fig. 10 shows the events detected as damage for all of the sources on a single graph on the 90° case. Each marker represents an instant when damage was detected, different markers refer to different methods. It shows that acoustic measurements pick more events that any of the other methods. Thermography and DIC are comparable and the analysis of the force sensor measurements is the least sensitive.

Fig. 10 Graph showing the evolution of the strain and markers on detected events for each measurement method. The markers were offset vertically to improve readability







(b) Zoom on the red region of figure a

Observations on [45₂,- 45₂]_s Samples

On the $[45_2, -45_2]_s$ samples, the transverse matrix cracking is not present like on the other samples. This is compatible with the observations from [38]. Even if the macroscopic damage is much more apparent on the stress-strain curve in this configuration than the 0° and 90° cases (see Fig. 5), thermography could only detect a few events. Local damage did not occur as clearly during the loading phases and the only events that could be detected occurred at high strain levels, shortly before the rupture of the sample. This is because this configuration does not favor the instantaneous propagation of cracks. Instead, shear bands appear progressively as the strain level increases without creating local increases of heat that can be detected using thermography. The observed mechanisms are different and they do not have an IR signature as distinct as transverse matrix cracking.

Thermography can also be used to monitor the global variations of temperature of the sample: a global decrease in emission can be noted during the loading phases, particularly on the first cycles with a smaller amplitude. Using thermoelasticity to detect variations of behavior is therefore possible. However, the ambient noise is close to these fluctuations due to the low strain rate of this test. This analysis is more appropriate for tests with a moderately higher strain rate. Also, the lightning required for the DIC may be inducing heat flux altering the interpretation of this method in this test.

Strain fields show localizations on lines in the direction of the fibers. They form irregularly spaced lines of higher strain in the directions of the fibers of both the face and the inner plies as shown on Fig. 11. These shear bands decrease in amplitude during the unloading but they are still present between the cycles when the force has returned to 0N. This means that they have an elastic and a permanent component. This form of permanent alteration appears progressively, therefore they are not accompanied with a sudden release of heat. This is why they can not be observed using IR thermography. The strain fields also show bands perpendicular to the fiber of the surface. These bands are caused by the same phenomenon occurring on the inner layers and showing through the surface plies.

In this scenario, the microphone captured the first event at $\epsilon_{xx}^{macro} = 0.31\%$. Then, the microphone captured new events every time the sample underwent levels of strain never reached before. However, more events occurred between 0.3 and 0.6% of strain and before failure at about 1.75 %. Figure 12 displays the number of events that were detected in each range of .1 % of strain. It shows that there are less events between 0.7 and 1.3 % of strain.



Fig. 11 Longitudinal strain field extracted from DIC on $[45_2, -45_2]_s$ layups during load at different levels of global strain

Impact of the Singularity

0° and 90° samples

In real applications, composite parts are rarely subject to a uniform strain state. The apparition and localisation of damage is usually caused by geometrical aspects and the nature of the solicitation of the sample. This is why some tests were performed on samples with a hole. Also, the use of rivets is common in the aerospace industry, further stating the need for open-hole tensile tests.

In the uniform sections of the sample, these tests showed all the behaviors observed previously. Transverse matrix cracking in particular is omnipresent, as described in Section "Observations on $[0_2,90_2]_s$ and $[90_2,0_2]_s$ ". However, the area near the hole showed new behaviors: slow transverse cracking can be observed on the 90° plies of the samples at 0° and 90°. Instead of an instantaneous propagation through the entire sample like in the previous tests, some cracks showed a slow progression starting from the hole and growing towards the edge of the sample as shown





in Fig. 13. This can be explained by the non uniform strain state that is not favorable to an instantaneous propagation.

On the 0° plies, a shear crack can be observed growing from the side of the hole in the direction of the fibers. The Fig. 14 shows the strain field of these samples at different levels of strain during loading on which this behavior can be observed. This shear crack also occurs on the 0° plies of the 90° sample, but is less clear as it is seen through the 90° layer. Figure 15 shows the shear strain to illustrate the progression of the shear crack.

On the 0° and 90° scenarios, most of the phenomena observed on the IR images appear to be transverse matrix cracking, just like the plain samples. One difference is the formation of some cracks that do not propagate over the entire width of the sample in the area near the hole due to the non-uniform stress in this region.

The measurements from the microphone are very similar to the plain samples. The microphone picks up many events in the loading phases. They show frequent distinct clicking sounds starting at 0.4% during the loading phases for the 0 and 90° samples

45° samples

On the 45° samples with a hole, the stress concentration induced by the hole favored the apparition of shear bands in the direction of the fibers, causing peak strain levels on an X-shaped region, with the hole in the center which is consistent with other studies in similar configurations [39–41]. This

is illustrated in Fig. 16. The region around the hole being subject to a higher strain, the rupture occurred in the center of all of the samples. The uniform regions of the sample showed a behavior similar to the previous tests with lines of shear strain on the direction of the fibers of both plies. The lines decrease in amplitude when unloading but the strain localization on the lines intersecting with the hole are still visible. This can be observed on the strain fields of the sample after unloading.

On the $[45_2, -45_2]_s$ samples, no localized events were detected by the IR camera except emission around the hole just before the final rupture. This is just like the tests on plain samples: these thermography measurements bring almost no information about localized energy dissipation on the sample on this layup.

Just like the other orientations, the measurements from the microphone do not show a different behavior than the plain samples. The events on the 45° sample are quieter than the 0° and 90° samples, but still very clear, especially the first events around the 0.5% level of strain and the ones just before rupture.

Discussion

Evolution of Crack Density

Getting back to the tests on the plain $[90_2,0_2]_s$ samples, the cracks can be detected and counted using the method

Fig. 13 Longitudinal strain on the $[90_2,0_2]_s$ sample, showing cracks growing from the hole towards the edge of the sample



described in Section "Observations on $[0_2,90_2]_s$ and $[90_2,0_2]_s$ ". Since thermography and DIC detect the cracks on two different faces, the time and localisations cannot be compared directly. However, the crack density on each face is expected to be similar for the same levels of strain. The Fig. 17 shows the evolution of the crack density as a function of the strain for each method. The number of cracks on each face is similar as expected, even though they are not identical because of the statistical effects of this phenomenon.

Since the events detected with DIC and thermography all appear to be matrix cracking, they are all expected to be detected by acoustic measurements. The Fig. 18 shows the cumulated events of both thermography and DIC on two different faces versus the events detected by the microphone.

This figure shows that the number of events detected by the acoustic measurements is almost equal to the number of events detected by both DIC and thermography at strain levels below 0.8%. Beyond this level, this method appears to detect other events that could not be observed on either thermography or DIC. These events are probably an other type of damage. The classification of the events based on their spectral signature as in [42] could probably provide more information on the type of events, but the acquisition frequency of the microphone of 192kHz is not high enough to perform this kind of study.

In the case of the samples oriented at 0°, DIC cannot detect reliably the cracks in the inner layer but IR images can be processed just like in the 90° case, using a lower threshold. Once again, acoustic measurements pick up more events than thermography, particularly when the strain level passes 0.8%. This is illustrated in Fig. 19.

These observations show that even if the dominant damage mechanism is transverse matrix cracking in this scenario, it is not the only mechanism since the microphone detected extraneous events at higher strain levels that were not detected by the other measurements. All the events picked up by DIC and thermography were detected by the acoustic measurements, meaning that this technique is the most sensitive. However, it gives little information on the event. A deeper analysis in the frequency domain could probably allow a classification of the events but providing a qualitative interpretation is delicate and the location of the event is inaccessible with a single microphone. The sensitivity of DIC and thermography appear to be similar for this





(b) $[0_2, 90_2]_s$ sample

Fig. 14 Strain field on the face of the samples with a hole

type of events, however DIC cannot detect events in the inner layers in some scenarios. Thermography can detect events in the bulk since the heat dissipates through the top layer. However, it is not expected to be the case with much thicker samples, since the signature was greatly attenuated by the top layers of prepreg. Also, a quantitative interpretation of the thermography measurements could bring information about the amount of dissipated energy. DIC can bring a lot of information by describing the kinematic fields, allowing not only to detect but also to describe to some extent the phenomena. The following section uses the measurements from the DIC to describe the transverse matrix cracking.

Investigation of the Damage: Matrix Cracking and Delamination

Then a particular attention was paid to the description of the events. As detailed in Section "Observations on $[0_2,90_2]_s$ and $[90_2,0_2]_s$ ", most of these events are transverse matrix cracks.

The question of whether these cracks cause delamination is explored. The impact of the cracks on the thickness of the sample is monitored using the secondary optical camera placed on the side of the sample. Even in this configuration, with a large magnification and the absence of an artificial speckle pattern on the side of the sample, DIC can be performed to compute the displacement fields caused by the formation of a crack in the 90° layer [43]. The Fig. 20 shows the displacement along the direction of traction caused by the formation of a transverse matrix crack in the 0° case and the 90° case.

On 90° samples, the cracks cause a distinct opening of the surface plies but appear to have no impact on the other layers. The stress relief around a crack causes the top plies to shear in the plane normal to the crack direction, resulting in lower measured strain on the surface around the crack. To determine if delamination occurred, the shear strain ϵ_{xz} is plotted along a line of the sample near the crack. This graph is shown in Fig. 21. The shear strain **Fig. 15** ϵ_{xy} (%) on the [0,90]_s sample, showing shear cracks growing from the hole in the direction of traction at different levels of macroscopic longitudinal strain



0.4% 0.8% 1.2% 2.00 - 1.75 - 1.50 - 1.25 § . inerts [emphilication of the second o

Fig.16 Longitudinal strain field on the $[45_2, -45_2]_s$ sample with a hole

spike between the 0° and 90° layers shows that delamination occurred between the 0° inner plies and the 90° cracks top ply.

Using the additional measurements from the zoomed camera on the face of the sample, the formation of the crack was captured more closely. The amplitude of the displacement of the surface and the relative strain along the direction of traction on the region around a crack is shown in (Fig. 22a). The value of the displacement is taken along the middle line of the sample. Several lines were inspected at different locations and along different cracks and the figures are all very similar both in shape and amplitude. These observations lead to the conclusion that these openings are 20 to 25µ m wide after their formation under load. A region of about 2mm on both sides of the crack is affected by the strain relief. The effect of this zone is also illustrated in (Fig. 22b) which shows the gradient of the displacement. It should be noted that in this case, the gradient of the displacement is not the strain because the displacement is computed between two successive images. The reference image is not the sample at rest, so this quantity could be called a "relative strain". Therefore negative values do not depict compression but a decrease in tension. Figure 22b shows that the value of this "relative strain" decreases in the area close to the crack and the discontinuity created by the crack is interpreted as a spike by the DIC algorithm. This is because the field measured by DIC is convoluted by a characteristic length, resulting in a smoothing of the field. The "relative strain" reaches 30% but this value is meaningless as it is the manifestation of a discontinuity in the field. The average strain level when this crack occurred was 0.73 %.





Fig. 18 Number of cracks detected by the microphone and by either DIC or thermography

When the crack density increases past $0.2 mm^{-1}$, the regions subject to delamination tend to join each other. The face of the sample is then constituted of almost independent patches subject to little to no strain at all. This can be seen in (Fig. 6a) where the strain of the surface between the cracks actually decreases as the number of cracks rises because the patches of the surface plies are almost completely detached from the inner plies. Many of these regions were ejected of the sample after the failure of the specimen, supporting that

the bond with the rest of the sample had weakened during the test.

On 0° samples, the cracks appear in a similar way and propagate through all the thickness of the 90° plies as illustrated on Fig. 20. Previous observations (notably thermography) showed that the crack also propagates instantly through the entire width of the sample. The crack causes relaxation of the material on both sides of the crack, but the ply being constrained by the 0° plies on the side, the





Fig. 20 Displacement field caused on the side of the sample by a transverse matrix crack in the 90 ply°



detached from the sample after the failure of the sample just like the 0° case.

affected area is smaller than the free surface case, with about 1 to 1.5mm affected by the crack on both sides. This length was estimated based on the displacement fields from the DIC on the side camera. Delamination also appears to be present as many pieces of the 90° ply were

As discussed in Section "Observations on $[45_2, -45_2]_s$ samples", the behavior is fundamentally different on the $[45_2, -45_2]_s$ samples. In this orientation, matrix cracking





Fig. 22 Plots illustrating the impact of the formation of a transverse matrix crack on the surface of a 90° sample

(a) Relative displacement along X over a (b) Gradient of the relative displacement line normal to the crack along X averaged over the width of the sample

is also the main damage mechanism, but instead of an opening, the cracks are the result of in-plane shear. As a consequence, the cracks appear progressively and do not open instantaneously like in the tensile mode. DIC shows that the amplitude of the displacement of each side of the crack grows when loading, but also diminishes during unloading. This means that the sides of the shear crack slide on each other during loading and unloading, possibly explaining the energy dissipation observed on the stressstrain curve on Fig. 5.

The tensile tests on plain samples show that when the entire sample is submitted to the same level of stress, the occurrence of damage is dictated by the uneven material properties or defects in the material. This is why it is impossible to predict the apparition of the local events such as transverse cracks.

Confronting Observations with Models

Local DIC showed a complex behavior with many local strain peaks caused by damage phenomena. The nature of these fields with such a discontinuous strain seems in opposition with the commonly used approach for modelling such materials by assuming that damage can be represented as an homogeneous quantity. In order to confront these observations with this assumption, simulations of the test on the samples with a hole were performed. The kinematic fields from the simulations were compared to the dense fields measured with DIC. Because DIC can now measure displacements at a high frequency and spatial resolution, this comparison is expected to illustrate the strengths and weaknesses of these models. The simulations were performed on samples with a hole and 3 different orientations. Finite element simulations were performed using the Z-set suite software. The meshes were generated using the pre-processing interface of the Z-set suite. Ruled meshes were generated with a higher density of elements near the central hole of the plate. Only one element in the thickness of a ply has been considered, leading to 8 elements for the total thickness of the plate. Finally, a total of 68000 linear elements have been used to performed the numerical simulations leading to 910440 degrees of freedom. Regarding the material behaviour law, the ONERA progressive failure model has been used for these simulations [44]. The material properties used for the simulation are the same than those used in [44] except for the viscoelasticity which has been neglected in this study.

The simulated strain fields show patterns very similar to the ones observed on the measured fields around the holes for every orientation. On the 45° samples, the strain localization induced by the hole is similar between the simulations and the measurements as illustrated on Fig. 23. However, the strain in the uniform sections differs significantly because of the heterogeneity of the material. This illustrates clearly why the question of a representative volume is critical when using uniform models on composite materials.

In the case of the 0[°] sample, the shear cracks in the direction of the fibers and tangent to the hole are present, even though the amplitude is smaller. As shown on the Fig. 24a, the simulated and measured fields are very similar even though the amplitude of the phenomena induced by the hole are underestimated.

The shear cracks tangent to the hole are also present on the 90° samples, just as observed on the experimental fields. However in this orientation, the two fields are completely different as shown in (Fig. 24b). This is almost entirely due to the numerous transverse matrix cracks that occur in the surface layer. Also, on the 45° scenario, the shear cracks and heterogeneities in the shear modulus that cause the strain localisations on lines in the direction of the fibers are totally **Fig. 23** ϵ_{xx} on the $[45_2, -45_2]_s$ sample, at 0.8 (%) global strain



absent of the simulations, also resulting in much smoother fields in the homogeneous sections of the sample. We can see the impact of the underestimation of the shear cracks around the hole and the multiple matrix cracks.

Based on these observations, the damage mechanisms can be classified into two categories: some phenomena are dictated by the geometry of the structure. Their location and amplitude may be predicted by simulations as their occurrence is deterministic. On the other hand, some phenomena are caused solely by the local fluctuations of the material properties and their occurrence follows a seemingly random pattern. This is the case of the transverse matrix cracks in 0° and 90° tests and the shear bands in the + / - 45° tests. Their macroscopic density is linked to an internal variable that can be estimated, but the instant and location of their formation is not predictable.

This is why simulations should not be interpreted as a representation of the reality. They cannot be compared directly to experimental measurements as they do not intent to predict such behavior. Even if these tools can predict accurately strain concentrations, rupture and give insights on the behavior of a structure, this does not mean that the resulting displacement or strain fields are close to the real behavior of material.

The intent of these observations is not to discredit the model or method used by the simulation, but rather to illustrate that models developed for simulation at the macroscopic scale cannot be used to accurately represent the local state of the sample. This is why direct comparisons between simulations and real strain fields are not straightforward, even with realistic models. The occurrence of these cracks cannot be predicted as they are seemingly random, but their macroscopic impact is taken in account in the form of a continuous damage variable. The actual impact of the shear **Fig. 24** ϵ_{xx} in % on the $[0_2,90_2]_s$ (left) and $[90_2,0_2]_s$ (right) samples with a hole at 0.8 % global strain



(a) Measured field (left) and simulated (b) Measured field (left) and simulated field (right) on $[0_2, 90_2]_s$ field (right) on $[90_2, 0_2]_s$

cracks on the global behavior of the sample is extremely low in this scenario since the modulus of this material in the transverse direction is much lower than the fibre direction. The same observations can be made for the shear localisations on the 45° sample, particularly the uniform regions: the simulation show a continuous strain whereas the measured field shows localized shear bands.

Conclusion

The choice of an experimental method to detect damage events in composite materials heavily depends on the material, structure and setup. The three methods compared in this paper showed very different detection capabilities. Thermography can detect energetic events such as cracks opening. Through diffusion, it can detect events that are located below the surface, making it a strong candidate when damage is expected to occur beneath the surface of the sample, as long as it is relatively close to the surface. Thermography is not limited only to these observations: with an adequate calibration and setup, it can also be used to quantify the dissipated energy and monitor thermoelasticity. However, thermography failed to detect slow progressive damage. Also, it requires expensive equipment and a complex setup procedure for accurate measurements. A low-cost option with a good sensitivity is the microphone. Acoustic measurements have been used for a long time to detect damage in composite materials (either passive or active). However, these measurements were usually performed using piezoelectric transducers and high-frequency conditioning units. This equipment can be costly, requires a preparation phase and necessarily alters the sample. This study showed that the use of a conventional microphone is more sensitive than both DIC and thermography. This is a low-cost alternative that requires almost no preparation, leaves the sample untouched and can detect damage during loading. The drawbacks of this method are the lower acquisition frequency, the impossibility to locate the event unlike the field measurement methods, and the sensitivity to ambient noise, implying the necessity to control the acoustic environment of the test. Finally, DIC is able to detect faint phenomena as long as they impact the observed surface of the sample. The capability to detect events in the inner layers depends on the stiffness compatibility of those layers. For example, the shear bands in the inner 45° plies are visible on the surface but the 90° cracks are not visible on the 0° plies. The benefit of DIC is to bring not only the count and location of the events, but also many additional information such as the width of the opening, its persistence after unloading, the direction, etc... The resulting fields can be interpreted in numerous ways, making DIC a rich tool to analyze damage phenomena. The main drawbacks are the necessity to present a texture with strong gradients for accurate results, often needing the use of an artificial speckle pattern and the high computational cost. It can be balanced by a hybrid use of DIC as performed in the presented tests: real-time integrated DIC to drive the test and slower pixel-wise algorithms in post-processing to extract further information on the local phenomena. DIC can also be used to detect existing damage by locating its kinematic signature upon loading, just like thermography can be used to locate existing damage using the active method. However, it was demonstrated that simulated and measured displacement fields may be very different making a direct comparison impossible.

Interpreting all the results from these sensors independently is a rather basic approach and since they are complementary, an interesting extension of this work would be to explore a way to fuse these sources of information together for a more accurate and sensitive detection of damage. Also, the field measurement methods may fail to detect events in the bulk of the sample. X-ray micro-tomography and laminography are 3D field measurement techniques that do not face this constraint. Using the intrinsic texture of the composite, it is possible to perform Digital Volume Correlation as shown in [45]. This allows the computing of the displacement in the bulk of the sample. In-situ testing could therefore bring more information than the presented methods and investigate damage in the bulk of the sample.

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