DAMAGE MECHANISM IN OPEN HOLE CARBON TEXTILE REINFORCED EPOXY COMPOSITES

Valter Carvelli[1], Kazuya Okubo[2], Toru Fujii[2]

[1] Department ABC, Politecnico di Milano, Piazza Leonardo Da Vinci 32, 20133 Milan, Italy
Email: valter.carvelli@polimi.it

[2] Department of Mechanical Engineering and Systems, Doshisha University, Kyoto, Japan
Email: kokubo@mail.doshisha.ac.jp; tfujii@mail.doshisha.ac.jp

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Abstract

In this experimental investigation the damage mechanisms and the damage evolution were observed during tensile quasi-static and cyclic loadings of open hole carbon balanced plain weave reinforced epoxy laminates. The initiation and propagation of the damage in open hole (diameter 5 mm) notched specimens were studied measuring the full field strain by the digital image correlation (DIC) and observing damage modes by X-ray micro-CT. The DIC maps of the strain components and the X-ray micro-CT observations highlighted similar damage concentrations and damage mechanisms for both loading conditions. In the beginning of the fatigue life (about 10%) and for a static load of almost 70% of the strength, the damage was localized between three different strained zones and limited in a very narrow area at the edge of the hole. A slow increase of delamination was observed from the hole edge up to 90% of the fatigue life and for a static load approaching 90% of the ultimate stress. Finally, the fast diffusion of the strain concentration and delamination led to the complete failure of the tows at the hole edge.

1. Introduction

The strength of notched composite materials was investigated extensively over the past three decades due to its importance in several industrial applications where joints and bolts are unavoidable.
Studies have been mainly focussed, in the authors' knowledge, on the quasi-static and fatigue behaviour of open hole non-woven laminates [1]. Some works have been dedicated to the characterization of open hole textile reinforced composites and few of them on their fatigue performance ([2], [3], [4]).
The objective of this investigation was to compare the damage during tensile quasi-static and cyclic loadings in carbon balanced plain weave reinforced epoxy laminates. The initiation and propagation of the damage in open hole (diameter 5 mm) notched specimens was experimentally studied measuring the evolution of the full field strain by the digital image correlation (DIC). Moreover, X-ray micro-CT observations of the internal damage were useful to highlight the damage mode close to the notch.
The warp quasi-static tensile loading shows a distribution of the strain component in the load direction with a subdivision in three almost uniform zones. One low strain zone in the centre having width as the hole diameter and two side regions with the highest concentration of deformation (similar distribution was recorded in [4]). This strain separation generates the initiation of longitudinal cracks at the edge of the hole caused by warp tow straightening and debonding near the hole due to stress concentration in this region. The evolution of the shear strain highlights the propagation of such cracks increasing the load. The concentration of the deformation at the edge of the hole does not reveal a development of transverse damage (delamination orthogonal to the load) for almost 85% of the failure load, while the longitudinal damage at the boundary of the different strained regions increase in length. A consistent

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growth of the strain (namely stress) concentration at the hole free edge is recorded at the latest loading stage close to the failure with a very fast increase leading to failure along the transverse cross-section in the specimen centre. This peculiar damage evolution is observed also during the tensile-tensile cyclic warp loading with an increase of the longitudinal damage increasing the number of cycles. The latter damage mode does not lead to complete failure after one million cycles considering a maximum stress level in the cycle higher than 85% of the quasi-static ultimate stress. For those load levels, the stress concentration near the hole edge did not generate an increase of the transverse damage responsible of the delamination and of the fibres fracture and, therefore, does not cause the material failure.

2. Composite material and experimental features

The composite material under investigation is an epoxy matrix reinforced with a carbon fabric. The reinforcement is a balanced carbon fibres plain weave textile (Pyrofil TR-3110-MS, Mitsubishi Rayon Co. Ltd., Japan, areal density 200 g/m^2, warp and weft count 4.87 ends-picks/cm). Warp and weft yarns have 3 thousand fibres (Pyrofil TR30S3L Mitsubishi Rayon Co. Ltd., Japan).
Epoxy resin is used as matrix (E-828, Japan Epoxy Resins Co. Ltd., Japan). The curing agent is modified aliphatic polyamine (JER cure-113, Japan Epoxy Resins Co. Ltd., Japan).
Eight layers of carbon fibre plain weave textile were stacked and laminated by hand lay-up impregnation on a heating system keeping the temperature of 50-60 °C to reduce the viscosity of the matrix. The mould was cured in a hot press machine at 80 °C for 1 hour, and then 150 °C for 3 hours keeping a pressure of 2 MPa. The resulting laminates had thickness of 1.98 ± 0.13 mm and fibre volume fraction of 56.3 ± 1.3%.
Specimens were cut out from the laminates on the warp direction of the reinforcement, assuming the same behaviour in both the principal directions. The same geometry was adopted for quasi-static and cyclic tensile tests.
Specimens had geometry similar to the suggestion of the standard ASTM D5766. In particular: total length 200 mm, gage length 100 mm, width 25 mm. The hole, drilled in the specimen centre, had a diameter of 5 mm (ratio width to diameter of 5). Glass fibres reinforced polymer tabs of length 50 mm were glued at both ends in the gripping zones.
All tests were performed using a hydraulic testing machine with a load cell of 50 kN.
The cross head speed was set to 1 mm/min for the quasi-static tensile loading. The full field strain was measured on the external surface of some specimens by means of the correlation of subsequent digital images (DIC) taken during static loading using a Nikon D3100 digital camera. The strain maps were obtained by the Vic2D software [5].
Cyclic tests were performed under constant stress amplitude, sinusoidal wave-form tensile-tensile loading and assuming the ratio $R = 0.1$ (ratio of the minimum to the maximum stress in the cycle). The frequency was set to 5 Hz. Some cyclic tests were assisted with a high speed digital camera (Memrecam fx K3) acquiring frames at a frequency of 250 Hz with a resolution of 1280 × 1024 pixels. The images post-processing allowed the measurement of the full field strain on the external surface of the specimen during cyclic loading by the digital image correlation technique, as for the quasi-static tests.
For the strain maps measurement purpose, the centre of the specimen, for a length of about 50 mm, was speckled with white and black acrylic paints.
The damage imparted after some loading cycles was observed by X-ray micro computed tomography (micro-CT) using a SkyScan 1172 system.

3. Results and Discussion

The mechanical behaviour and the damage observation of the considered open hole carbon textile reinforced composite was experimental investigated with two consecutive experimental phases. In the first phase, quasi-static tensile tests, up to complete failure, provided the tensile static strength needed for setting the fatigue test stress levels and showed the evolution of the damage up to complete failure with the DIC strain maps. The second phase was dedicated to the cyclic tensile-tensile tests assuming

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three loading levels Three or five specimens for each load level were cyclically loaded up to failure or after one million cycles, if complete failure did not occur. The evolution of the damage in those specimens was observed on the external surface with DIC strain maps. Other two specimens, for each load level, were fatigued for predefined numbers of cycles to observe the damage imparted by micro-CT images.

3.1. Quasi static tensile tests

Average strength of the open hole composite was $\sigma_u = 459.9 \pm 23.2$ MPa (average and standard deviation of six tests).
Here and the following the stress was calculated as the force divided by the net cross-section area.
For the sake of comparison the strength of the unnotched composite was 624.4 MPa.
The tensile stress vs. strain behaviour of the open hole composite was linear up to failure (Figure 1a). The average longitudinal strain in Figure 1a was measured by DIC on a 2 cm length portion of the surface above the hole. All specimens had a sudden and fragile failure in the centre at the smallest cross section (Figure 1b), as expected.

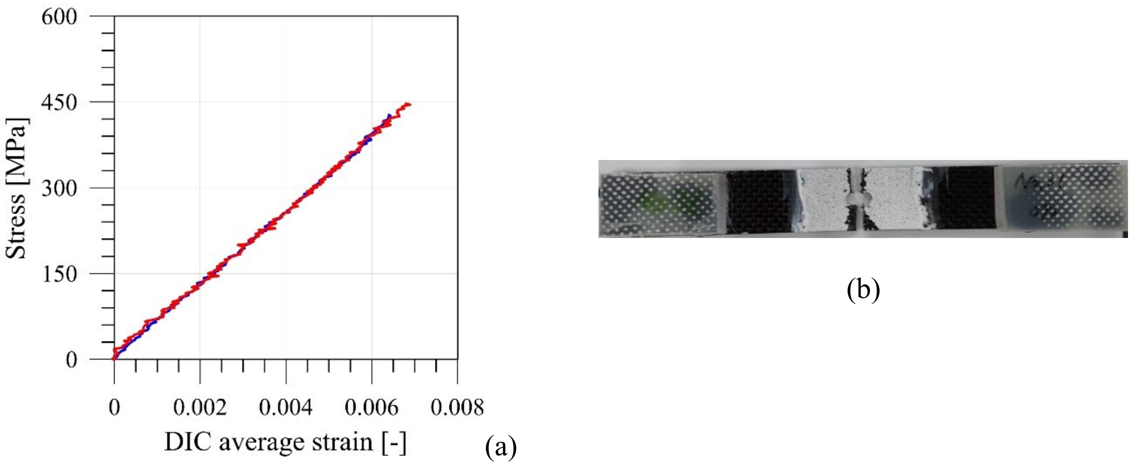

Figure 1. Quasi static tensile tests. (a) Two typical stress vs strain curves and (b) typical failure mode of the open hole composite.

The damage evolution during quasi-static loading was judged considering the DIC analyses resulting in maps of the three strain components on the external surface around the hole.
The maps in Figure 2 highlight an increase of the strain component (ε_{yy}) in the load direction in the two portions of surface beside the hole, while in the central strip above and below the hole, this strain component was almost negligible. The separation of the surface in three zones with different longitudinal strain concentration had as consequence a concentration of shear strain component (ε_{xy}) at the two separation zones.
The transverse strain component (ε_{xx}) did not have a relevant variation up to almost 70% of the ultimate stress (σ_u), e.g. see the load level 300 MPa in Figure 2 for a specimen whose σ_u was 448.1 MPa. The strain components evolution highlighted a delamination area initially developing along the separations of the three different strained zones and limited in a very narrow area at the boundary of the hole. Approaching about 90% of the ultimate stress, the longitudinal and transverse strain components had a relevant increase at the boundary of the hole (see load level 400 MPa in Figure 2). As consequence, the delamination increased in the transverse direction in the smallest cross section zone, where finally the damage had a sudden concentration leading to the breaking of the tows from the hole free-edge.

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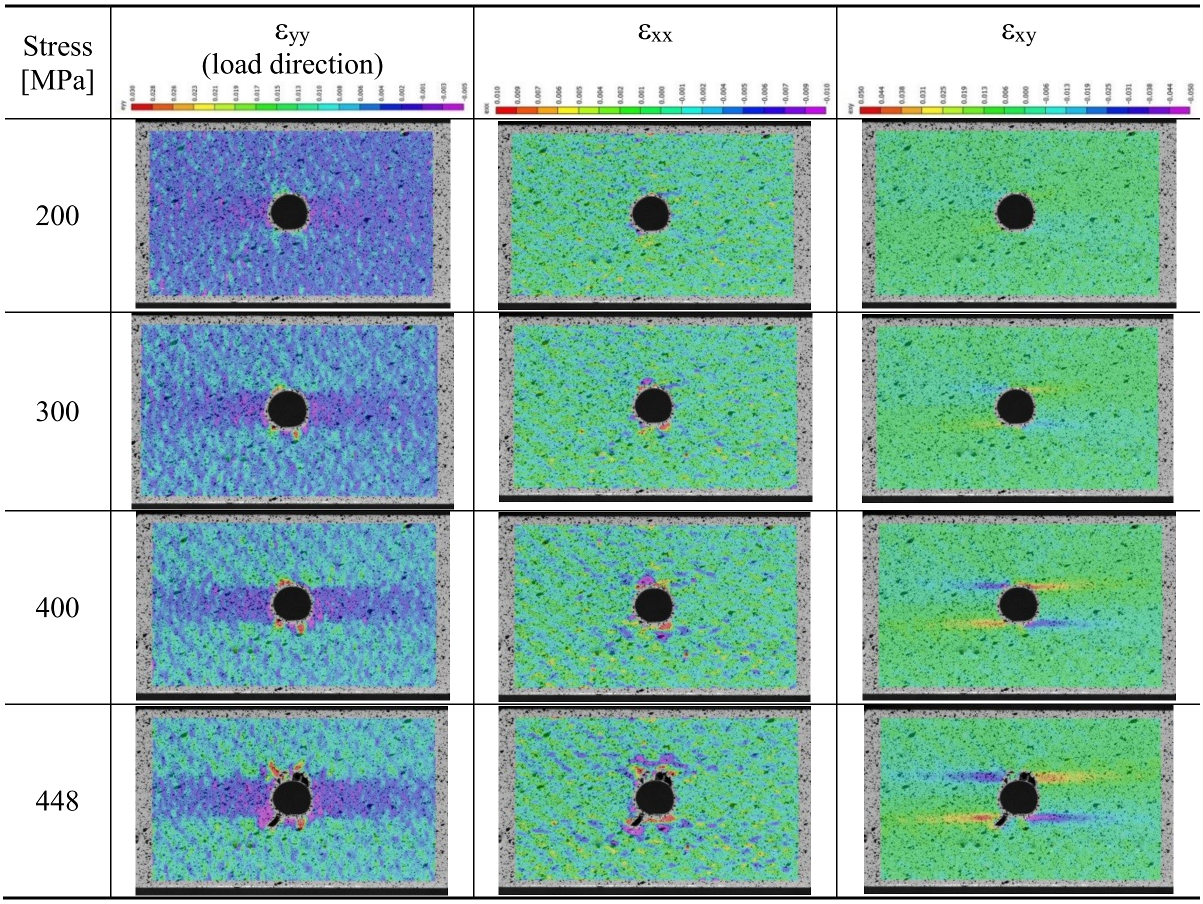

Figure 2. Quasi static tensile tests. Map of the strain components for different stress levels.

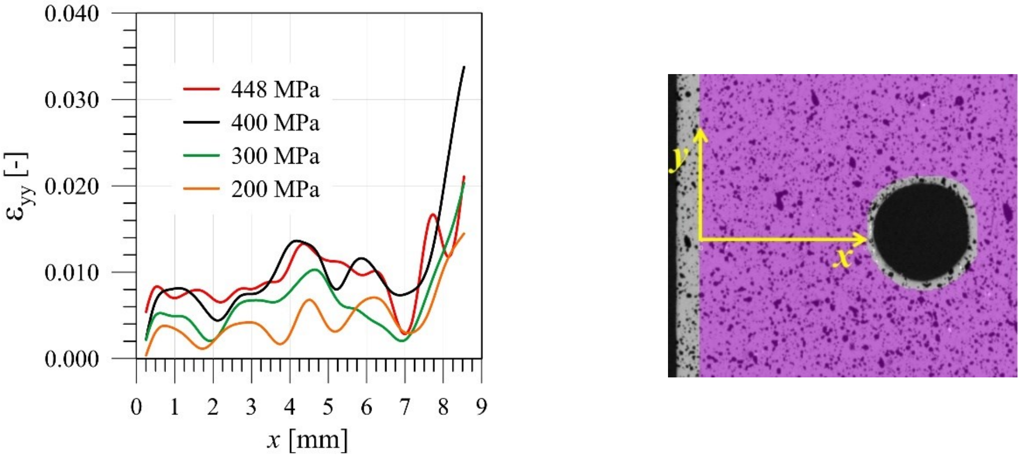

Figure 3. Quasi static tensile tests. Distribution of the stain component in the load direction (y) along the segment (x) for different stress levels.

The distribution of the longitudinal strain component (ε_{yy}) on a segment at the smallest cross section is shown in Figure 3 for different load level. As expected, the strain got the maximum approaching the hole edge for all load levels. The undulation of the strain moving from the external side to the hole reflects the internal geometry of the textile reinforcement (the tow width is almost 2 mm). For each load level the tows had similar strain levels except the one at the hole edge, where the highest value was recorded. The strain had a maximum, in that position, for the load level close to the 90% of the ultimate

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stress (see load level 400 MPa in Figure 3). Above that level, the delamination and the breaking of some fibres at the hole edge generated a redistribution of the stress and, as consequence, a reduction of the strain level (see load level 448 MPa in Figure 3). The mentioned evolution of the strain pointed out that the damage is mainly concentrated in very narrow strips at the hole edge having almost the width of one tow, up to 90% of the strength. Only above this load level the delamination starts to spread in the width of the smallest cross section and the highest stress concentration generates a sudden rupture of the tows at the hole edge and the complete failure.

3.2. Fatigue tests

The fatigue tests performed in the considered stress range (three stress levels) enable for depicting a fatigue life (Wöhler-type) diagram. The diagram in Figure 4 represents the number of cycles to failure for all the valid tests of the three maximum stresses (σ_{max}) considered. The stress level for which failure did not occur before one million cycles was 85% of the ultimate static stress (σ_u).
The fatigue damage development in composite materials may be described at the macroscopic scale by empirical metrics [6]. One of the main adopted damage metric is the stiffness degradation. In the present investigation, two metrics were adopted: the slope of the segment passing through the points of maximum and minimum of the stress-displacement cycle curve (cycle slope), and the energy dissipated in the cyclic loading, i.e. the area contained in the stress-displacement cycle curve. As observed in [7], stiffness and cycle slope evolution provide analogous qualitative information on the damage imparted during cyclic loading.

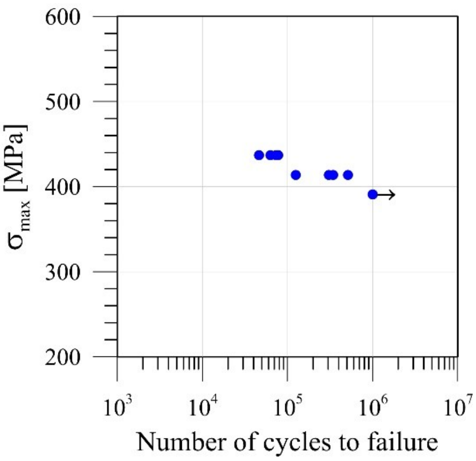

Figure 4. Fatigue tensile tests. Fatigue life diagram, i.e. maximum stress in the cycle (σ_{max}) vs. number of cycles to failure. '→' means no failure after one million cycles.

The diagrams in Figure 5 show the evolution of the slope and energy of all cycles for two load levels. In Figure 5a, for a maximum stress of 95% of σ_u, the cycle slope indicates a fast decrease in the beginning of the cyclic loading (initial 10% of the fatigue life), than a continuous almost linear slow decrease up to 90% of the fatigue life and finally a faster reduction up to failure. The behaviour of the energy dissipated in each cycle follow a similar scheme in the same ranges of the fatigue life: an initial fast increase (high energy dissipation), a continuous slow increase in the following 80% of the fatigue life and a final rapid increase of energy leading to failure (Figure 5b). Those trends show three stages of the damage development: an initial fast development, a slowest diffusion and a final rapid spread of the damage until failure.
Considering the load level 85% of σ_u (Figure 5b), for which the notched composite did not fail after one million cycles, the cycle slope and the dissipated energy have similar to the previous shape of the initial curves (almost 10% of the fatigue life), but with completely different range of slope reduction and energy increase, meaning reduced amount of damage imparted. In the remaining fatigue life up to one million

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cycles, the cycle slope had a slight reduction, while the dissipation of energy had a slight fluctuation around the maximum value at the end of the initial stage. This means a very slow diffusion of the damage contained in a reduced portion of the specimen.

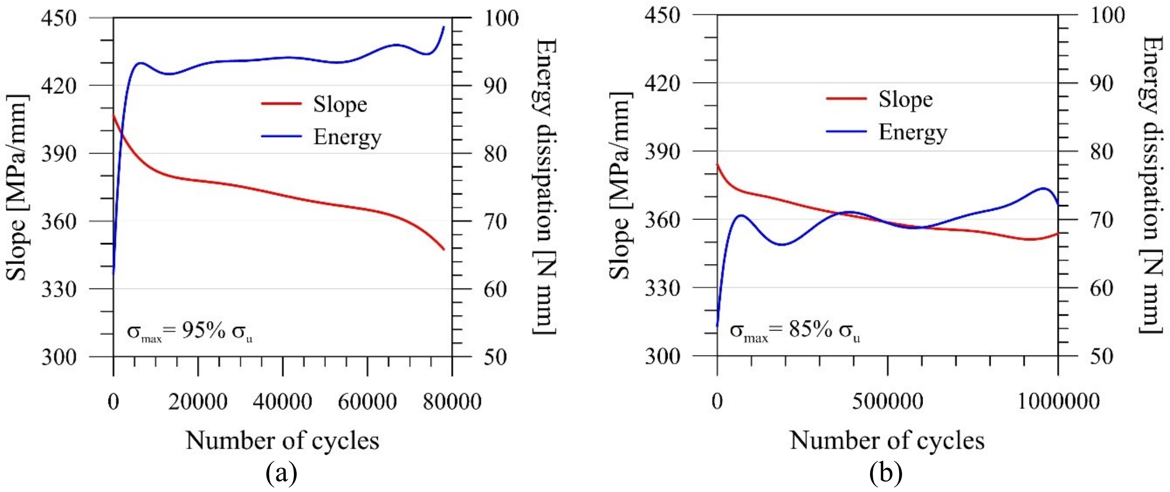

Figure 5. Fatigue tensile test. Cycle slope and dissipated energy vs. number of cycles for load level (a) 95% σ_u, (b) level 85% σ_u.

The damage evolution during cyclic loading, discussed above at the macroscopic scale, can be locally observed considering the DIC maps of the strain components on the external surface around the open hole. In Figure 6, the map of the strain components are detailed for a specimen cyclically loaded with a load level of 95% of σ_u. The maps refer to the strain distribution at the maximum stress in some cycles through the complete life of the specimen (63230 cycles). The same distribution of the strain in three zones was observed as for the quasi-static loading (Figure 2).

In the initial part of the fatigue life (about 10%), the longitudinal (ε_{yy}) and the shear (ε_{xy}) components had the highest concentration (see Figure 6 for two and ten thousand cycles), while the transverse component (ε_{xx}) remain almost negligible. This shows that the damage was localized between the three different strained zones and limited in a very narrow area at the boundary of the hole. In the second part of the fatigue life (up to 90%), a slow increases of the transverse and longitudinal strain component concentration was observed, meaning a diffusion of the delamination from the hole edge toward the area with the smallest cross-sections (see Figure 6 for thirty and forty thousand cycles). Finally, in the last 10% of the fatigue life, the fast diffusion of the delamination around the hole and the strain (i.e. stress) concentration at the hole edge (see Figure 6 for sixty thousand cycles) led to complete failure.

The supposed damage mechanisms, discussing the strain components mapping, were observed inside specimens loaded for a predefined number of cycles with the X-ray micro-CT.

In Figure 7, the micro-CT pictures of the three reference planes (*z* is the load direction, *y* is the thickness direction, *x* is the radial direction along the smallest cross-section) show the damage imparted in the centre of a specimen cyclically loaded with stress level of 95% of σ_u after 40 thousand cycles. The delamination was detected between several layers at the edge of the hole where the maximum strain concentration was measured (see maps for 40k in Figure 6, and Figure 7 picture $y=0$). After the considered number of cycles, the delamination was mainly limited in the two zones of smallest cross sections with an extension of less than the width of two tows, i.e. 4 mm, (see Figure 7 picture $z=0$). Moreover, some initial delamination was observed at the hole boundary in the radial direction parallel to the load one (see Figure 7 picture $x=0$) where a strain concentration was also measured by DIC (see maps for 40k in Figure 6).

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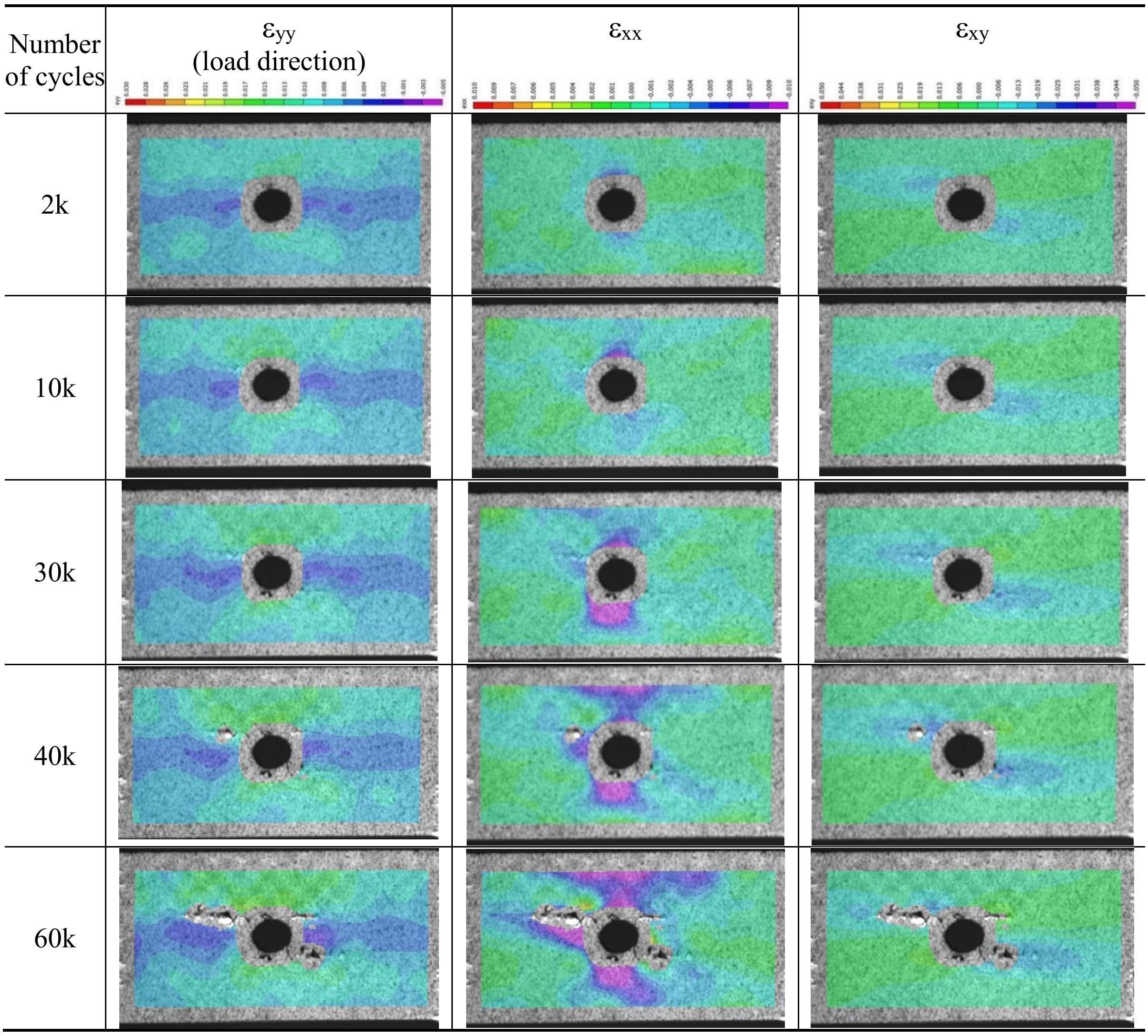

Figure 6. Fatigue tensile test, load level 95% σ_u. Map of the strain components at the maximum applied stress in some cycles (k means thousand).

4. Conclusions

The experimental study was focused on the mechanical behaviour and the damage observation during tensile quasi-static and cyclic loadings of open hole carbon balanced plain weave reinforced epoxy laminates.

The DIC maps of the strain components and the X-ray micro-CT observations highlighted similar damage concentrations and damage mechanisms for both loading conditions. In particular, considering tensile-tensile loading with a maximum stress of 95% of σ_u:

- The initial strain showed a concentration in three zones.
- In the initial part of the fatigue life (about 10%) and for a static load up to almost 70% of the strength, the damage was localized between the three different strained zones and limited in a very narrow area at the edge of the hole.
- In the second part of the fatigue life (up to 90%), and for a static load approaching 90% of the ultimate stress, an increases of delamination (strain) was observed from the hole edge toward the area with the smallest cross-sections with an extension of less than the width of two tows.

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– Finally in the last 10% of the fatigue life, and above 90% of the static strength, the fast diffusion of the strain concentration and delamination led to the complete failure of the tows at the hole edge.

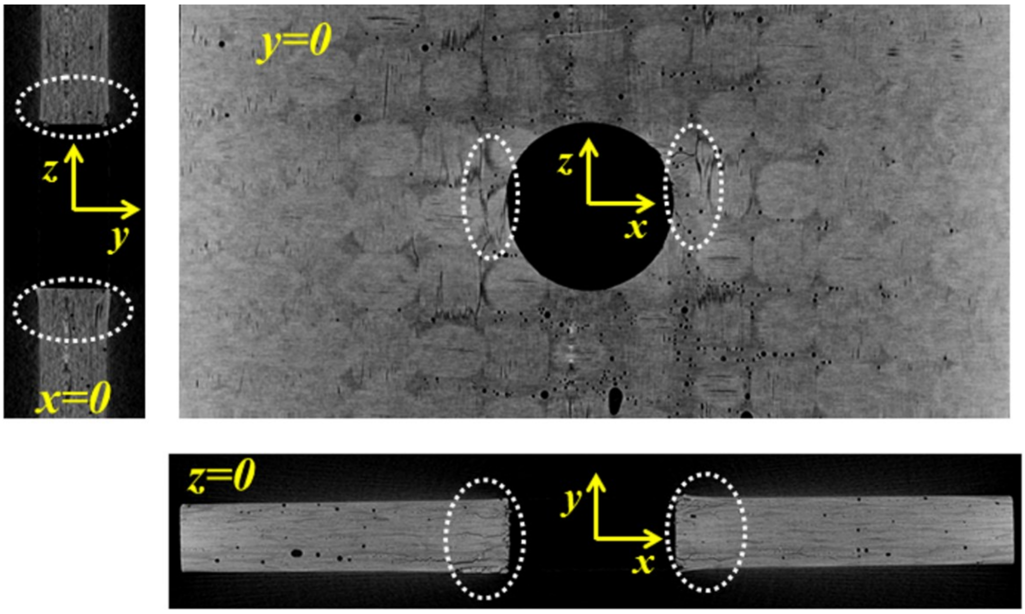

Figure 7. Fatigue tensile test, load level 95% σ_u. X-ray micro-CT picture of a specimen after 40 thousand cycles. Ellipses highlight the extension of the damage.

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