SIMILARITIES AND DIFFERENCES IN MICRODAMAGE MECHANISMS DURING TENSILE QUASI-STATIC AND CYCLIC LOADING OF NCF COMPOSITES

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Abstract

A comparative study of damage mechanisms governing the mechanical behavior of a $[-45/90/45/0]_s$ HTS40/RTM6 NCF laminate under quasi-static and tension-tension cyclic loading was performed. Intralaminar cracking in 90˚-layers is described assuming the Weibull distribution of transverse cracking initiation strength. Based on the assumption that the non-uniform fiber distribution is the reason for strength variation, the fatigue model parameters are determined using the crack density in a quasi-static tensile test and in a cyclic test with just one stress level. A triggering mechanism was observed when the cracking which starts in the 90˚-layer leads to immediate cracking in the neighboring off-axis layers even if the average stress there is low. In the quasi-static test, delaminations are small even at high strain levels. At low fatigue strain level, a similar behavior was observed, however in high strain cyclic tests, the delaminations are growing faster at the edges and inside the composite. The delamination length is the largest at the edge and it decreases towards the middle of the laminate. The rate of the decrease depends on the interface and the fatigue strain applied. Delaminations which have propagated inside the specimen increase the opening and the sliding displacements of the intralaminar cracks thus causing much larger stiffness reduction than cracks without delaminations.

1. Introduction

During their service life, composite laminates are subjected to various loadings which often lead to the deterioration of their mechanical properties and therefore of their structural integrity. This deterioration may be manifested in various damage modes. There are basic damage mechanisms in composite materials as a result of quasi-static or fatigue loading: intralaminar cracking, delamination, fiber breakage… The earliest damage mode in layers is intralaminar cracking (called also matrix or transverse cracking); the first intralaminar crack is created in the weakest position. The number of cracks increases with increasing the applied load in quasi-static loading or with increasing the number of cycles in the case of tension-tension cyclic loading. The cracks run parallel to fibers in the layer and they generally cover the whole thickness of the layer and are arrested at the interface with a different fiber orientation layer. They grow through the width of the specimen when stress and available energy conditions are satisfied. Local delaminations are often initiated at the crack tip of the intralaminar crack because of the high out-of-plane shear and tensile normal out-of-plane stresses. Edge delamination can also take place where no crack is observed. It is mainly due to edge effects where some stress singularities of the out-of-plane stresses are developing. Delamination could occur far from the edges due to incomplete curing, for example, or from close matrix cracks in two neighboring

layers which propagate and could be linked to each other by a delaminated area at the interface between the layers. The onset and growth of the delamination is important because it reduces considerably the capacity of the laminate to support further loads and is indirectly responsible for the final failure of the structure. In both quasi-static and fatigue loading, the different damage modes combined with structure anisotropy and complex stress fields limit the ability to define the real behavior of the laminate, to understand the damage mechanisms and to predict their effect on the mechanical properties.
Non-crimp fabrics (NCFs) is a very interesting class of composite reinforcements. They can be seen as a compromise between UD prepregs and woven fabrics which makes them attractive materials for use in high-performance composite structures. The damage development in these materials during quasi-static and fatigue loading and the influence of fatigue cycling on the residual properties have been investigated in many papers. For example, Mattsson et al.[1] investigated the effect of stacking sequence on the mechanical properties of cross-ply NCF composites and their damage behavior under tensile loading. Mikhaluk et al.[2] also investigated the tensile testing effect on the initiation and the evolution of damage in quasi–isotropic NCF composites, and developed a FE model to predict damage development. Correlation between the damage zones and the resin-rich zones created by stitching pattern was observed. Vallons et al. [3] studied the static, fatigue and post-fatigue behavior of a bi-axial NCF composite. The cited researches are examples among others revealing the importance to understand the damage mechanisms of NCF composites, their development under different loading, to determine their effect on the integrity of the material properties. There is a difference in the damage growth between quasi-static and cyclic (fatigue) loading conditions due to different mirco-mechanisms governing each loading type [4]. The fatigue testing is time consuming, therefore being able to predict the behavior of the composite under fatigue loading based on simple and quick quasi-static testing has been the subject of several researches, Reference [5] is an example. Damage initiation and growth characterization in both quasi-static and fatigue loading is required to develop efficient and less time-consuming testing methodology for statistical fatigue damage behaviour. This work is an overview of some similarities and differences observed in the damage behavior of NCF composites in quasi-static and tension-tension fatigue loading.

2. Experimental procedure

2.1. Material

The composite used in this study is NCF carbon fiber HTS40/RTM6 with quasi-isotropic $[-45/90/45/0]_s$ lay-up. The reinforcement is a unidirectional weave consisting of 12K fiber bundles with a density of 242 g/m^2 manufactured at 180 ℃. Some mechanical properties of the UD are given in Table 1.

Table 1. Mechanical properties of the unidirectional NCF CF/EP laminate

Property	E_L (GPa)	E_T (GPa)	G_{LT} (GPa)	γ_{LT}	α_L $(\cdot 10^{-6} 1/℃)$	α_T $(\cdot 10^{-6} 1/℃)$
UD	120	9.18	9.94	0.311	0.32	31.6

180 mm-length specimens were cut from the 2 mm thick plate. Edge polishing was performed using sand papers (P240, P600, P1200, P2500, P4000) followed by liquid diamond slurry (from 9 micron to 0.25 micron). The width of the specimens, after grinding and polishing, was approximately 10 to 12 mm for fatigue specimens and around 9 mm for quasi-static specimens. The dimensions of the specimens used for crack density monitoring were chosen so that the specimens width is about three bundle-width (one bundle width = 3.5 mm). GFRP end tabs were bonded onto each specimen by Araldite 2011 2-component epoxy adhesive, so that the final gauge length was 100 mm.

2.2. Quasi-static loading

Tensile tests with displacement rate 2mm/min were performed at room temperature and carried out on an Instron 3366 universal testing machine (Instron, America) equipped with a load cell of 10 KN and pneumatic grips. During the displacement controlled tensile test, load and longitudinal strains were recorded. Measurements of the longitudinal strain were performed using an extensometer with a gauge length of 50 mm. The load was increased by step of 0.1% of strain and after each increment of strain edge replicas of the specimen were taken to determine the state of the damage without removing the sample from the machine. In this manner, the laminate stiffness and the corresponding crack density/ delamination length were found after each load increment. The average longitudinal modulus for undamaged specimens was 43.7 GPa, a value which compares well with the analytical approximation 46 GPa when using CLT and the UD elastic properties in Table 1.

2.3. Cyclic loding

For fatigue testing, stress controlled cyclic loading with 5Hz frequency and R = 0.1 was carried out in an ElectroPulsTM E10000 Linear-Torsion machine with 10 KN load capacity. The fatigue testing was performed at several maximum initial strain levels (0.4; 0.45; 0.5; 0.55 and 0.6%) and the damage state dependency on the number of cycles N was investigated with the replica technique. The laminate stiffness was measured after each fatigue step.

2.4. Damage observation

At least 3 specimens were used for each level of the initial strain in case of fatigue loading in addition to the three specimens used for quasi-static loading. Evaluation of crack densities and the resulting stiffness reduction were performed using a stepwise loading sequence with increasing maximum strain level or number of cycles in each step for quasi-static and fatigue testing respectively.
A replica technique was used to reproduce the surface topography of the specimen allowing the microscope investigation of to the damage accumulation after each loading step when the mechanical testing was finished. The respective number of cracks n_i over a distance L of 50 mm on the middle of the specimen edge was counted and the crack density in each layer was calculated as: $\rho_i = n_i/(L.\sin\theta)$; where θ is the fiber orientation in the layer considered.
The delamination length was defined as the total length of all delaminations observed in the gauge length. The initial Young’s modulus was measured within the strain interval 0.05-0.25%. After each loading step, it was measured again in the same strain region, where the material shows linear behavior and does not undergo any additional damage.
The crack-density in the different layers and the delamination length (l_d) data for the specimen edges may be not-representative of the damage state inside the specimen. To evaluate the microstructural deterioration inside of the material, a procedure of grinding and polishing one edge of the specimen was used. Then the damage behavior was observed in detail with a microscope. This method is destructive and, therefore, it was done after the final loading step.

3. Results and discussion

The replicas were taken when the specimen was loaded to 0.2% of strain. The damage state for the last step of fatigue for all specimens was not analyzed using replicas but inspecting the specimen under microscope when it is subjected to thermal stresses only. Figure 1(a) shows an example of the different damage modes observed in the laminate. In both quasi-static and fatigue loading, the first damage sites coincide with the stitching positions in the 90°-layer. The ´stitch´ related cracks as the one shown in Figure 1(b) were not taken into account for the 90°-layer crack density results.

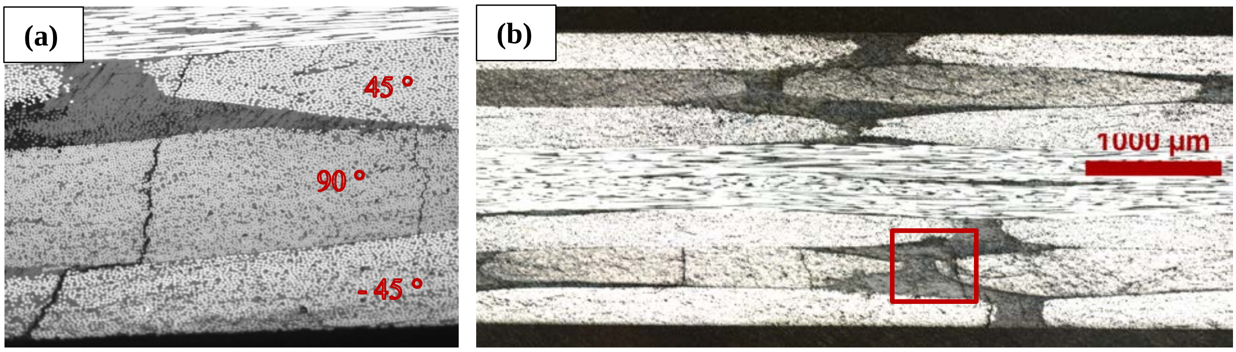

Figure 1. (a) Example of damage state after 1M cycles at 0.4% of maximum strain. (b) Stitch related crack in the 90°-layer.

3.1. Sequence of damage modes in quasi-static and fatigue loading

Inside of the composite, the crack planes in the 90°- and ± 45°-layers when propagating during loading could be crossing each other forming delamination as Figure 1(a) shows. At the first stage of fatigue testing, transverse cracks were initiated in the 90°-layers. Afterwards the delamination initiates at the interfaces between the 90°-plies and their surrounding layers and cracks in ±45°-layers are initiated from the tip of transverse cracks in the 90°-ply or from the delamination or from the stress concentration that a stitch on the off-axis layer could create (see Figure (a)). Then the transverse cracks of the off-axis layers propagated along the fiber direction and the delamination propagated from the edge to the middle of the laminate (y –direction). Similar sequence was observed for CFRP $[45/0/-45/90]_s$ in [6].

3.2. Transverse cracks in 90°-layer

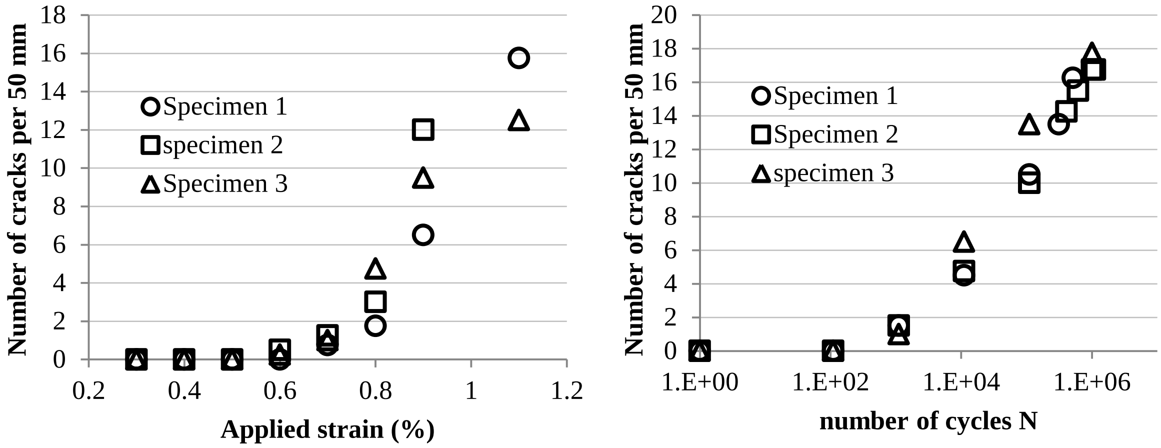

Figure 2. Dependence of the number of 90°-layer cracks over 50 mm length on the applied strain in quasi-static and on the number of cycles in fatigue loadings at 0.5% of max strain respectively.

This section is an overview of the previous research study of the authors [5]. Large tensile transverse and in-plane shear stress components lead to crack initiation in random positions. The weakest position was assumed to be the same in the tensile quasi-static and in the cyclic test. Figure 2 shows the similarity in the overall growth shape of 90°-layer crack density for quasi-static and cyclic loading.

Based on Weibull´s failure resistance distribution, intralaminar cracking was analyzed in the laminate-90°-layers where the crack initiation causes its immediate propagation. It was suggested to describe the probability of crack initiation dependence on the number of cycles and on stress by a power function. The Weibull probability of intralaminar cracking in the damaged layer P_{in} in a quasi-static test is modified to describe the distribution of residual strength after N cycles at the maximum stress in the cycle σ_T^{fat} , and it is written as: $P_{in} = 1 - exp\left[-N^n\left(\frac{\sigma_T^{fat}}{\sigma_{00}}\right)^m\right]$; Where parameters σ_0 , n, and σ_{00} are unknown material constants.

For the used NCF composite, in the range of the thermo-mechanical transverse stress in the 90°-layer used in cyclic tests, the stress dependence of the scale parameter was not significant and, hence, it could be neglected. Therefore, only one stress level at different number of cycles in fatigue tests in addition to the quasi-static tests performed to determine the Weibull shape parameter is necessary for this material to predict 90°-layer cracks.

3.3. Off-axis layer cracks

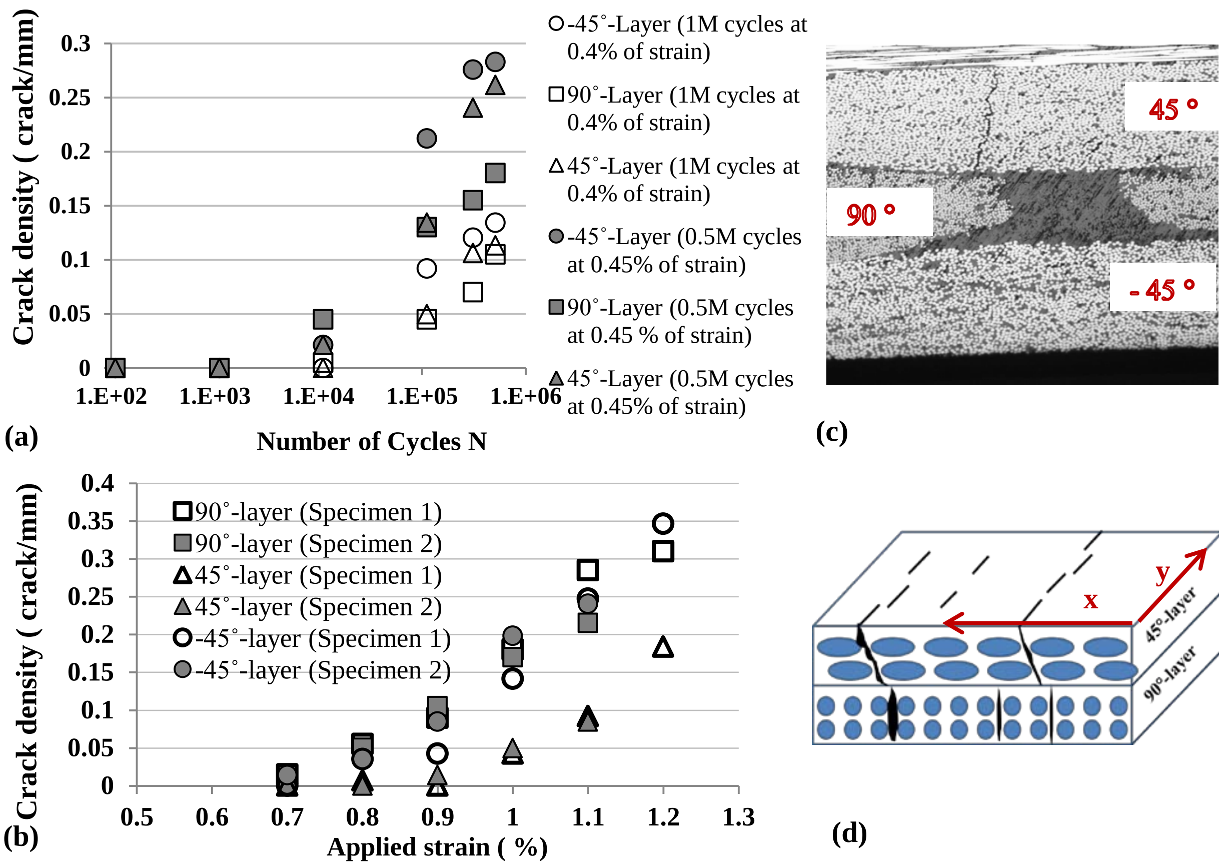

Figure 3. (a) Average transverse crack densities at the different layers of CF/EP [-45/90/45/0]s NCF at two different cyclic loading levels. (b) Average Transverse crack densities in the different layers of CF/EP [-45/90/45/0]s NCF subjected to quasi-static loading. (c) example of an edge 45°-layer crack where no other damage mode is observed. (d) Schematic view of 45°-layer crack.

Intralaminar cracks were equally observed in ±45°-layers for both quasi-static and fatigue loading. Polishing down the specimen and following those cracks inside of the laminate proved that they are not long tunnels even for high maximum strain fatigue loading; they are more like a system of parallel intralaminar cracks each with length 0.2-2 mm depending on the strain level and the number of cycles. A 90°-layer crack leads to immediate local crack initiation in the neighboring off-axis layers even if the average stresses in the off-axis layer are low. This phenomenon is defined as a triggering mechanism. At the same load cracks are very seldom initiating in off-axis layers of the same orientation if the layer is not in contact with the cracked 90˚-layer area, or in regions that are far from a stitch stress concentration zone (see Figure 3 (c)). The ±45˚-layer crack density increases with the 90°-layer crack density and it is accompanied with the initiation of delamination.

3.4. Delamination

Delamination on the neighboring interfaces of the 90°-layer is the second damage mode observed at the edges of the laminate subjected to quasi-static or fatigue loading. The delamination at the 45°/0° layer interface was rarely detected and it was small even at high strain level in quasi-static loading (above 1.1%) but it increased in large cycle tests with high maximum strain level (0.55% and more). In the case of quasi-static or low strain fatigue loading delamination between 90°/45° layers (or -45°/90°) prevents initiation and propagation of delamination at the other interface of the separating layer (Figure 4(a)). At high strain levels of fatigue (0.55% and above), the delamination could appear at both interfaces in the same region as shows Figure 4(b); but the growth of the delamination in x- and y- directions is not the same. That could be explained by the interaction between the multiple present delaminations, since the presence of another delamination change the value of the strain energy release rate at the delamination [7].

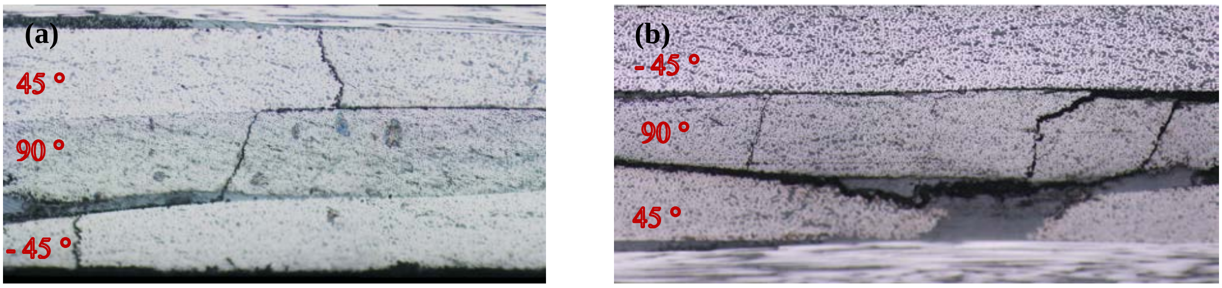

Figure 4. (a) Delamination migration at the inerfaces after 1% strain of quasi-static loading. (b) Delamination at both interfaces after 0.5 M cycles at 0.55% of max strain at fatigue.

Figure 5(a) shows the increase of delamination length on the edge with the number of fatigue cycles and the strain level. These values are higher than those found in quasi-static testing where l_d increases with increasing the applied strain. At low strain levels, the interlaminar damage takes place close to the edge and this behaviour is similar to the quasi-static test. At high strain, the delamination is not an edge effect: the delamination is propagating partially through the whole width of the sample as shows Figure 5(b). The propagation rate of the delamination inside the material ($l_d(y)$) depends significantly on the strain level. l_d is generally larger at the 90°/+45° interface and persists more in through the width of the laminate than at the -45°/90° interface. The ±45°-layer crack densities could not explain the delamination growth difference between the two interfaces: some cases were found where the crack density in the -45° layer is higher than in the 45°-layer. O'Brien [8], based on fracture mechanics principles found that the edge delamination crack growth can be a combination of different ratios of mixed modes (I, II and III) depending on the laminate lay-up and the loading conditions. The stitches´ structure combined to the damage state and the interaction between the different damage modes could be the reason of this difference. The delamination between the 90°/+45° layers could affect more the stiffness degradation of the composite which is another reason to investigate more the reason behind the difference of the delamination growth between the two interfaces. FEM based modelling could explain this effect.

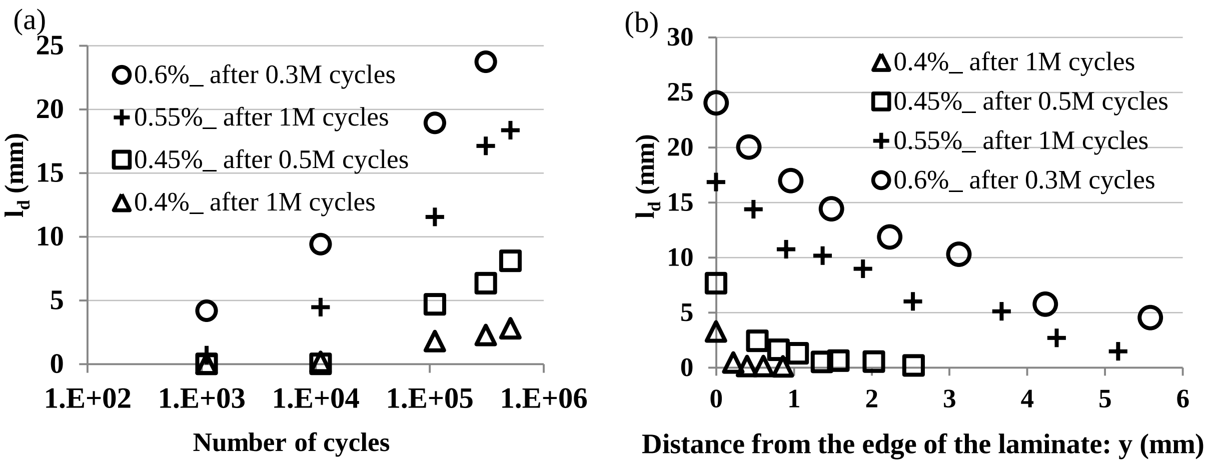

Figure 5. (a) Evolution of the average delamination length between the neighboring interfaces of the 90°-layer as a function of fatigue cycles. (b) Dependence of the average delamination length of both 90°/±45° interfaces on the number of cycles at different maximum strain level in fatigue.

3.5. Axial Modulus reduction

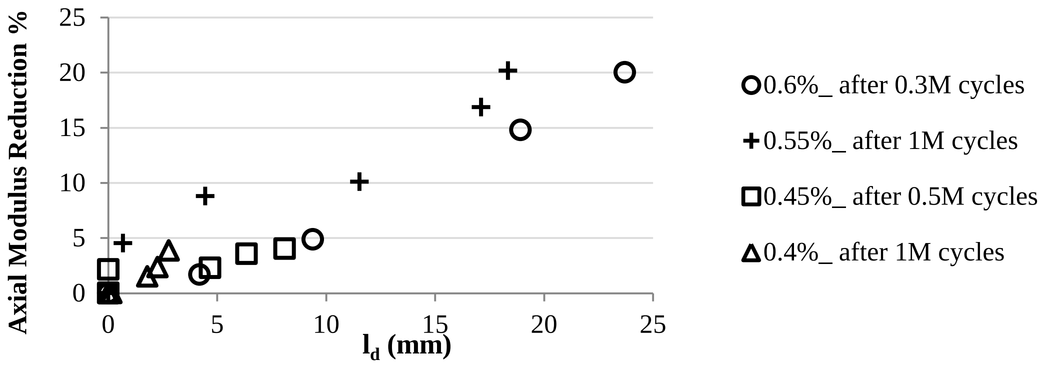

Figure 6. Axial modulus reduction dependence on average delamination length of the interfaces ±45/90 observed over a 50 mm of length.

The same value of the axial modulus reduction was observed for different delamination lengths corresponding to various maximum of strain applied at different cycling steps as shows Figure 6. For low strain levels in fatigue, the degradation of stiffness is not significant. That could be explained by slow propagation of the delamination inside of the composite. The edge delamination extent, as described below, could not alone explain the stiffness reduction; other parameters should be taken into account. A delamination extent of approximately 4.5 mm (over 50 mm length distance) is found for 0.45% of strain at 111 111 cycles and for 0.55 % of strain at 11 111 cycles. The axial modulus reduction of the latter is more than three times that of the former. The crack densities in the different layers don’t explain this significant difference on the stiffness reduction since they are around 50% less in the case of higher strain level applied. Figure 5 could explain the peculiarities in stiffness degradation. Higher loads and /or number of cycles promote more the delamination growth in both x- and y-directions. Delaminations are propagating more in the y-direction of the laminate in cyclic than in quasi-static loading. The delaminations increase the opening and sliding displacements of the cracks leading to much larger stiffness degradation than in the case when little surface delaminations are observed. The stiffness reduction for relatively low quasi-static and fatigue strain levels depends mainly on the crack density in the different layers and because the l_d measured on the surface is just an edge effect. For high fatigue strain levels, the y-direction delamination growth, influenced by the applied strain becomes the most important factor affecting the stiffness reduction.

4. Conclusions

Damage initiation and growth characterization in both quasi-static and fatigue loading is required to develop efficient testing methodology for statistical fatigue damage behaviour. The similarities and differences observed in the damage behavior of $[-45/90/45/0]_s$ NCF composites in quasi-static and tension-tension fatigue loading in this work helped to decrypt when quasi-static testing would be useful to predict the fatigue behavior in an efficient and less time-consuming way .
A test-validated approach using Weibull distribution for non interactive 90˚-layer crack regions allows efficient prediction of the crack density in fatigue: the shape parameter comes from quasi-static testing and only a small number of cyclic tests at one strain level are required. A triggering mechanism, when cracking which starts in 90°-layer leads to immediate cracking in the neighboring off-axis layers, even when the average stresses in the off-axis layer are low, is observed in both quasi-static and fatigue loading. Those cracks are not propagating as well defined tunnels but could interact with local delamination to reduce the mechanical properties of the laminate**.** Intralaminar crack induced delaminations, which are larger and growing deeper inside of the laminate in cyclic than in quasi-static loading, lead to much larger axial modulus reduction. Modeling the stiffness reduction in the fatigue loading, the quasi-static test results may be unreliable because of the differences in the delamination growth ($l_d(y)$). The model should also take into account the delamination growth rate which depends on the number of cycles and also on the maximum strain applied in fatigue.

References

[1] Mattsson, D., Joffe, R., & Varna, J. (2008). Damage in NCF composites under tension: effect of layer stacking sequence. *Engineering Fracture Mechanics*, *75*(9), 2666-2682.
[2] Mikhaluk, D. S., Truong, T. C., Borovkov, A. I., Lomov, S. V., & Verpoest, I. (2008). Experimental observations and finite element modelling of damage initiation and evolution in carbon/epoxy non-crimp fabric composites. *Engineering Fracture Mechanics*, *75*(9), 2751-2766.
[3] Vallons, K., Lomov, S. V., & Verpoest, I. (2009). Fatigue and post-fatigue behaviour of carbon/epoxy non-crimp fabric composites. *Composites Part A: Applied Science and Manufacturing*, *40*(3), 251-259.
[4] Charalambous, G., Allegri, G., & Hallett, S. R. (2015). Temperature effects on mixed mode I/II delamination under quasi-static and fatigue loading of a carbon/epoxy composite. *Composites Part A: Applied Science and Manufacturing*, *77*, 75-86.
[5] Ben Kahla, H., & Varna, J. (2015). Microcracking in layers of composite laminates in cyclic loading with tensile transverse and shear stress components, *Proceedings of 20th International Conference on Composite Materials, 2015.*
[6] Hosoi, A., Sato, N., Kusumoto, Y., Fujiwara, K., & Kawada, H. (2010). High-cycle fatigue characteristics of quasi-isotropic CFRP laminates over 108 cycles (initiation and propagation of delamination considering interaction with transverse cracks). *International Journal of Fatigu*e, 32(1), 29-36.
[7] Yu, B., Bradley, R. S., Soutis, C., Hogg, P. J., & Withers, P. J. (2015). 2D and 3D imaging of fatigue failure mechanisms of 3D woven composites. *Composites Part A: Applied Science and Manufacturing*, *77*, 37-49.
[8] O'Brien, T. K. (1982). Characterization of delamination onset and growth in a composite laminate. In *Damage in Composite Materials: Basic Mechanisms, Accumulation, Tolerance, and Characterization*. ASTM International.