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Stress-controlled Fatigue Testing of E-glass Epoxy Composite

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Abstract. The paper deals with progressive and fatigue damage of E-glass epoxy composites. The objective of the research is to experimentally investigate progressive failure modes, stiffness degradation and corresponding transverse matrix crack density of long fiber E-glass epoxy composite loaded in quasi-static tension and repeated one direction tension with constant load amplitude. Stress controlled fatigue tests of plain $[\pm 60]_S$; $[\pm 30]_S$; $[0]_8$ and $[0/90_2/\pm 45/90]_S$ samples were carried out in order to investigate residual stiffness degradation, corresponding fatigue progressive damage and failure modes of the material of different layups. Sudden onset of the transverse matrix cracks has been observed in off-axis plies. The crack density increases with increasing number of cycles as new transverse matrix cracks instantaneously form. Composite residual stiffness and corresponding transverse matrix crack density were correlated to the number of cycles and loading level.

Introduction

Even though composite material can sustain certain amount of fatigue damage - it is damage tolerant - its mechanical properties decline as a result of fatigue loading. The objective of this paper is to investigate stiffness degradation of long fiber E-glass/epoxy composite loaded in cyclic tension with constant load amplitude and to study progressive failure modes, transverse matrix crack density and consequent stiffness decline.

In contrast to conventional materials such as steel, more phenomena are involved in the process of composite fatigue. Fatigue of fiber, matrix and the interface takes place and interact with each other. This results in several interacting failure modes such as matrix micro-cracking, fiber-matrix debonding, fiber rupture, delamination, fiber kinking, fiber pullout, etc. There is usually no dominant fatigue crack as in case of metals.

Micro-damage of the constituents as well as changes in mechanical properties of a particular constituent affects global mechanical properties such as stiffness or strength. In order to predict residual mechanical properties in the most general case it is essential to analyze and understand the progressive damage failure modes.

It is relatively simple to predict the initial failure of the composite ply – first ply failure *(FPF)*. Existing failure criteria such as maximal strain or Tsai-Wu can be used. However, it is not an easy issue to detect *FPF* experimentally. Moreover, it is very complicated to study progressive and fatigue damage evolution after *FPF* and composite final failure. Stress redistribution due to existing damage takes place and must be taken into account in that case.

First attempts to study fatigue damage of composites were based on traditional approach of S-N curves. However, this method can hardly be used for general laminates because of great number of combinations of fiber and matrix materials, orientations of fibers, stacking sequences, etc. Montesano et. al. [1] distinguishes empirical or semi-empirical models based on extensive fatigue testing, models based on residual stiffness and strength and progressive failure models based on real failure modes. Mao and Mahadevan [2] use their method based on residual stiffness. Damage parameter is defined by initial, residual and fracture stiffness. Damage increment per cycle is given by function *f* dependent on stress range, stress ratio, damage, etc. Talreja [3] uses continuum damage mechanics to homogenize micro-damage. Muc [4] defines residual stiffness as a function of initial stiffness, fictive time, stress range, stress ratio and a measurable damage parameter such as matrix crack density. He proposes empirical relation between residual Young's modulus and number of loading cycles. The degradation factors in all previous approaches are estimated based on observation or calibrated with experiments. On the other hand, Tsai [5] uses mechanical and fatigue properties of composite constituents to determine state of stress at micro level (individual fibers and surrounding matrix) and to predict real failure modes and residual life. He suggests that the failure envelope of the constituents shrinks with increasing number of loading cycles and hence new micro damage develops. Liu et. al. [6] uses similar multi-scale analysis for progressive failure of composite pressure vessel.

The objective of this research is to experimentally investigate progressive failure modes, stiffness degradation and corresponding micro damage state of long fiber E-glass/epoxy composite loaded in quasi-static tension and cyclic load controlled tension. Once real progressive failure modes and mechanisms are understood, it can be computationally simulated. Acquired data will be used as the input data into the multi-scale numerical model capable of modeling real micro-damage, its evolution and its influence on the mechanical response of the material. Avoiding the homogenization of progressive damage usually done by employing complicated material models will allow general use of the model for an arbitrary layup and stacking sequence and should significantly reduce the scope of experimental testing needed to obtain input data. Matrix micro-cracking is of particular interest because it is believed to be the main cause of delamination that can lead to fatal failure of a structure. Delamination itself and the phase of composite final failure are outside the scope of this research.

Material and Experimental Setup

The aim of the experimental testing was to investigate stress-strain behavior, stiffness degradation and corresponding progressive damage failure modes of long fiber E-glass epoxy composite samples loaded in quasi-static tension and cyclic tension with constant load amplitude. The testing followed the principles of ASTM D3479 [7] and ASTM D3039 [8] standards.

Samples preparation. The material is E-glass/epoxy laminate certified for aeronautics (fiber Interglas 92145, epoxy MGS LR385, hardener MGS LH 385/386). Fiber volume fraction is 40-41 %. Thickness of one laminate ply is 0.25mm. The laminate was fabricated using standard vacuum surface infusion method. Laminate plates were hardened for 24 hours on air and finish hardened in the furnace. Aluminum pads with chamfer angle of 90° were attached and the laminate plate was cut using water jet cutter. Dimensions of rectangular samples were 140x20mm.Surfaces of the samples were smooth to facilitate in-situ optical monitoring of micro-damage. Four sets of laminate layup were used: $[\pm 60]_S$; $[\pm 30]_S$; $[0]_8$ and $[0/90_2/\pm 45/90]_S$. Layup of the sets was chosen to represent various combinations of normal and shear straining within individual plies when loaded by axial force.

Experimental setup. Universal testing machine MTS 810 equipped with hydraulic clamps was used for fatigue tension-tension loading. The testing machine is controlled by MTS

458.20 controller capable of processing load cell, extensometer and strain gauge data. The acquired data is stored in the memory of controlling PC. Progressive failure modes – especially transverse matrix cracks and its density – were recorded using in-situ micro-camera (200x magnification). Detailed snapshot of transverse micro-cracks in $[\pm 60]_S$ laminate is depicted in Fig. 1. Self-compensating foil strain gauges Omega SGD-7/350-LY43 were used to measure strain. Post-mortem investigation of the fracture surface was performed employing optical microscope Nikon Eclipse LV100.

Testing procedure. In case of quasi-static testing the samples were loaded in monotonous tension with constant displacement rate 0.5 mm/s. Stress-strain response and corresponding progressive failure modes were recorded using load cell, strain gauges and in-situ micro-camera. In fatigue, samples were loaded in repeated one direction tension with constant load amplitude. Stress ratio was close to 0.1. Frequency of the loading was 5 Hz. No autogenous heating was observed at this frequency. All samples were tested at room temperature. At least 6 samples of every layup were tested in fatigue. Initial and residual stiffness of the specimens was recorded. Corresponding progressive failure modes were recorded employing in-situ micro-camera and processed using direct optical observation. This method is analogical to X-ray NDT method. However, E-glass epoxy is transparent and transverse matrix cracks can be observed straight away. Therefore, radiation-resistant penetrant that can influence fatigue properties of the material does not need to be used. Moreover, the method of direct observation leads to significant time savings.

Whilst peak load remained constant throughout cyclic testing (load controlled loading), peak strain continuously increased due to softening of the samples. This softening is induced by progressive damage evolution. However, peak strain increases also due to permanent strain accumulation. Hence, minimal strain in the cycle increases with increasing number of cycles as well in this case. In contrary to the softening induced by progressive damage evolution, peak strain growth due to permanent strain accumulation is not the measure of material softening. For this reason, fatigue testing was repeatedly interrupted and the samples were statically loaded to the maximal load used during fatigue loading to measure strain induced by such loading. The relation between such load and corresponding strain was identified as residual stiffness. Afterwards, residual stiffness was normalized with respect to its initial value to form normalized residual stiffness.

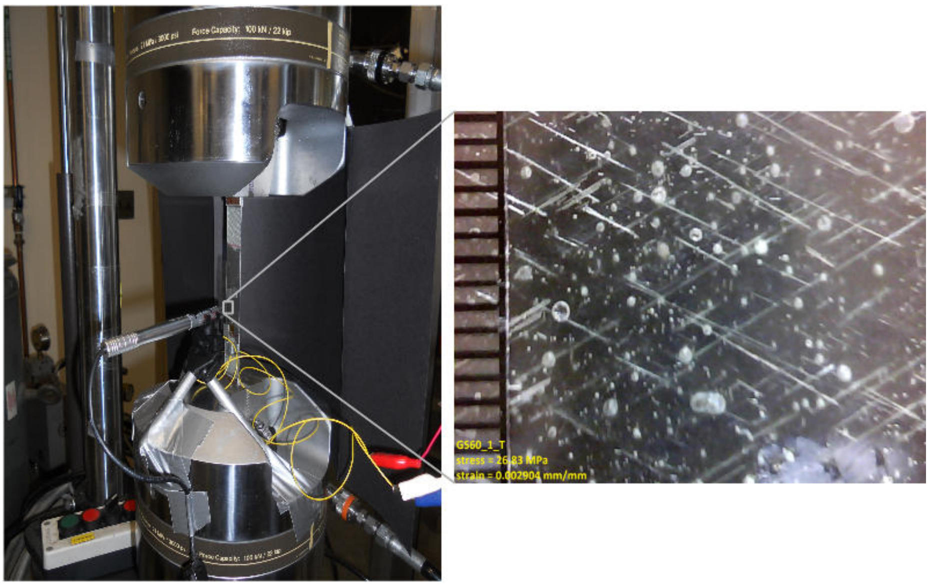
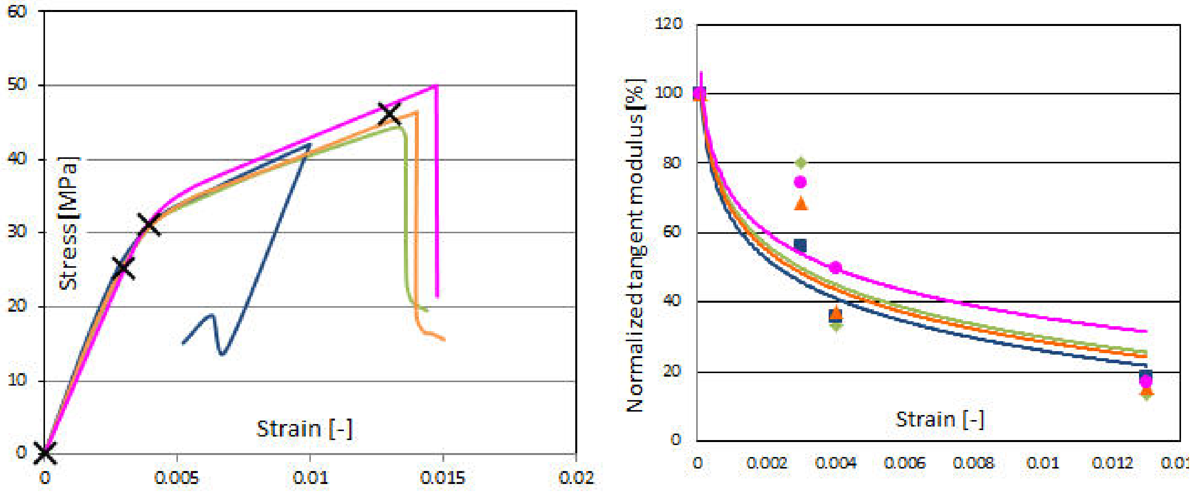


Fig. 1. Experimental Setup: E-glass/epoxy sample attached in hydraulic clamps with in-situ micro-camera to monitor micro-damage. Internal micro-cracks in $[\pm 60]_S$ sample in detail at right.

Results and Discussion

Static testing. Stress strain response of several samples of all layups is shown in Figs. 2a, 3, 5 and 6a. Tangent modulus was evaluated in highlighted points in Figs. 2b and 6b. Transverse matrix cracks and the development of its density are shown in Figs. 4 and 7 for $[\pm60]_S$ and $[0/90_2/\pm45/90]_S$ layups. No matrix cracking was observed in case of $[\pm30]_S$ and $[0]_8$ samples.



(a) (b)

Fig. 2. Stress strain response (a), relation between tangent modulus normalized to the initial modulus E_{init} and strain (b) for $[\pm60]_S$ layup.

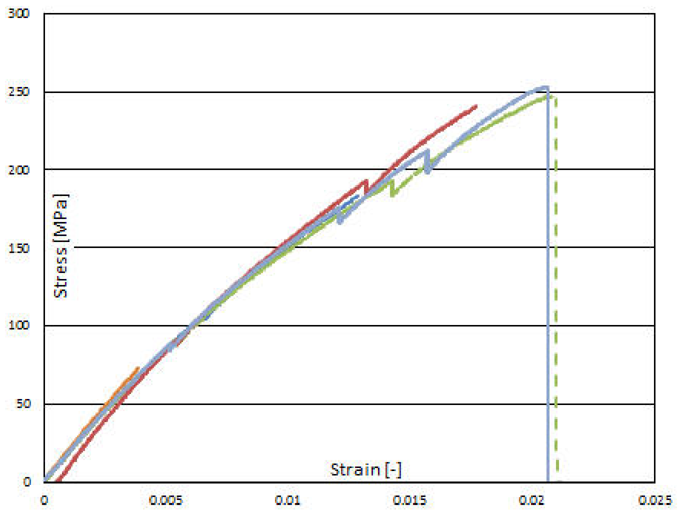
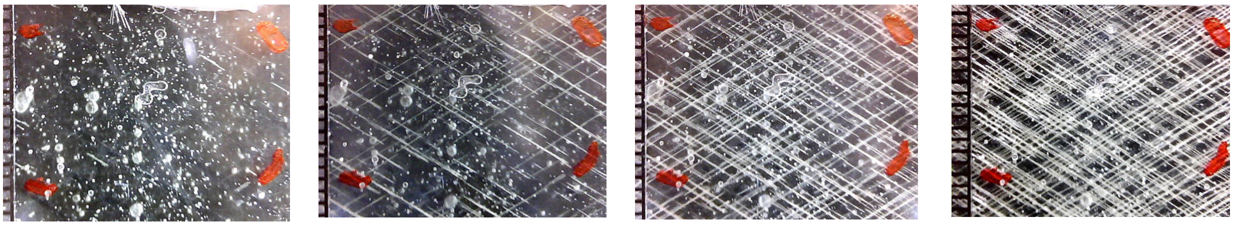


Fig. 3. Quasi-static stress strain response for $[\pm30]_S$ samples.

The main attention was paid to the mechanism of composite progressive damage and consequent tangent modulus decrease. It has been observed, especially for 90°, 60°and 45° plies, that the progressive damage is not a continuous gradual process. Contrariwise, it is a series of discrete events – formations of transverse matrix cracks (micro-cracks). Once critical strain for *FPF* of the weakest lamina is reached, first transverse matrix cracks form; e.g. Fig. 4b.



(a) (b) (c) (d)

Fig. 4. Snapshots of composite micro-damage (transverse matrix cracks) obtained using in-situ camera for $[\pm 60]_S$ sample for loading levels highlighted in figure 2. No load (a), shortly before final failure (d).

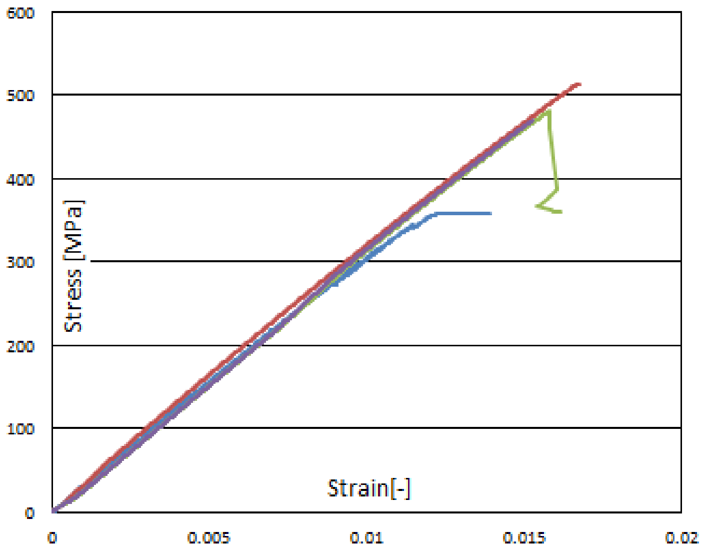
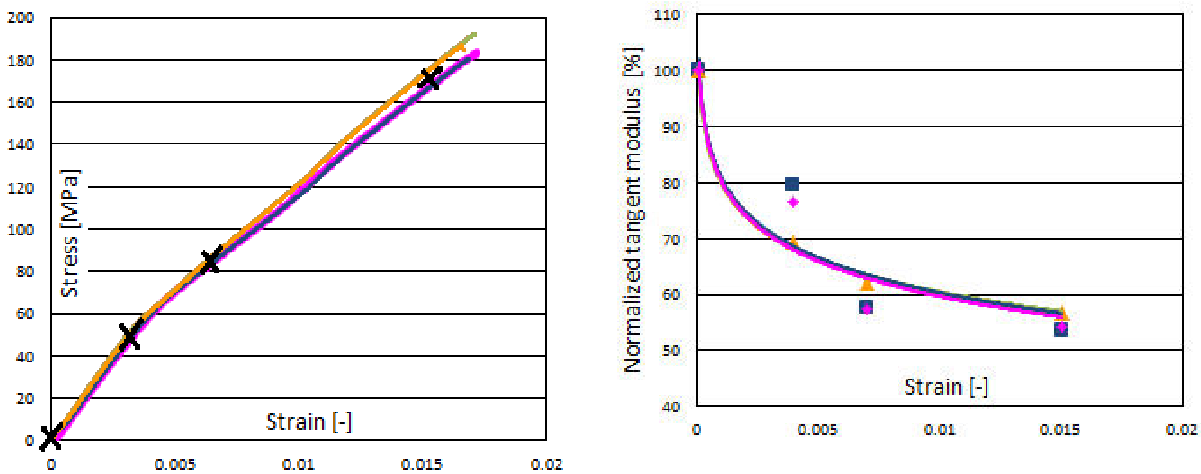
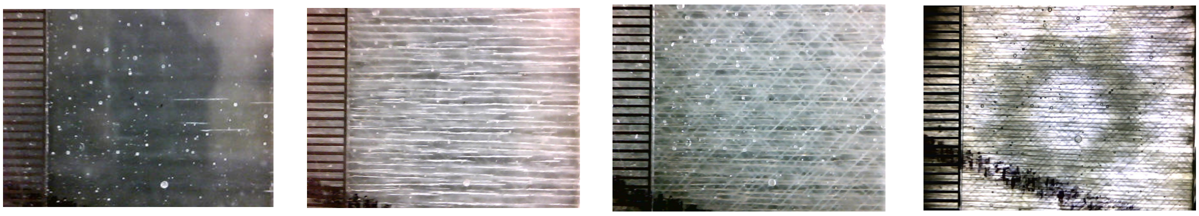


Fig. 5. Quasi-static stress strain response for $[0]_8$ samples.



(a) (b)

Fig. 6. Stress strain response (a), relation between tangent modulus normalized to the initial modulus E_{init} and strain (b) for $[0/90_2/\pm 45/90]$ layup.



(a) (b) (c) (d)

Fig. 7. Snapshots of composite micro-damage (transverse matrix cracks) obtained using in-situ camera for $[0/90_2/\pm45/90]_S$ sample for loading levels highlighted in figure 6a. Before loading (a), shortly before final failure (d).

Fatigue testing. Fatigue results are shown in Figs. 8-10 as the relationship between number of loading cycles and residual normalized stiffness as described in the experimental section for various loading levels. The loading level is described as the percentage of the peak load of the cycle normalized to static strength of the composite. Initial steep decrease followed by gradual decline of the residual stiffness was observed as expected. Extensive matrix cracking can be observed using in-situ micro-camera in case of $[\pm60]_S$ and $[0/90_2/\pm45/90]_S$ samples. The principles of progressive damage development are analogous to those described in the previous section. The matrix micro-cracks propagate instantaneously across the entire thickness of the ply and stop at the ply interface where it reaches equilibrium. Since the cracked ply is constrained at its boundaries by the neighboring plies the crack relieves the stress in the adjacent region. With increasing number of cycles fatigue properties of matrix degrade and new matrix cracks are formed. The phenomenon of residual stiffness saturation can be observed. The actual progressive damage state corresponding to the number of cycles is depicted in Fig. 8 for $[\pm60]_S$ layup.

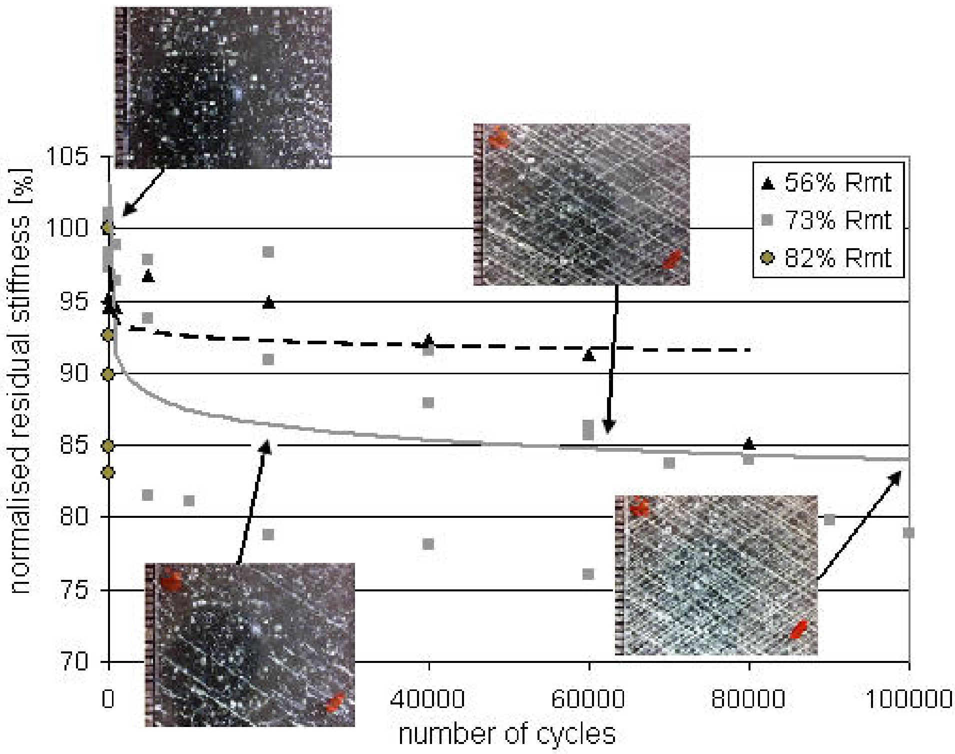


Fig. 8. Relationship between number of loading cycles and residual stiffness normalized to its initial value E_0 for $[\pm60]_S$ layup.

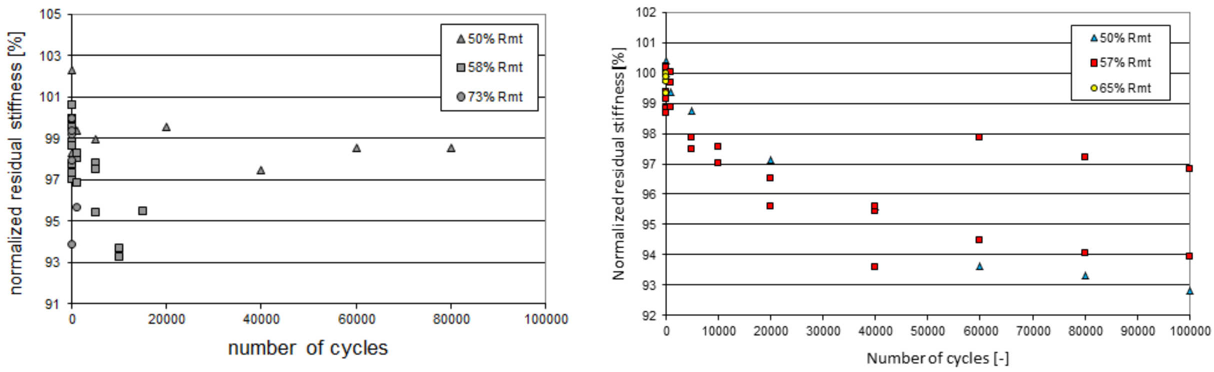


Fig. 9. Relationship between number of loading cycles and residual stiffness normalized to its initial value E_0 for $[\pm 30]_S$ and $[\pm 0]_8$ layups.

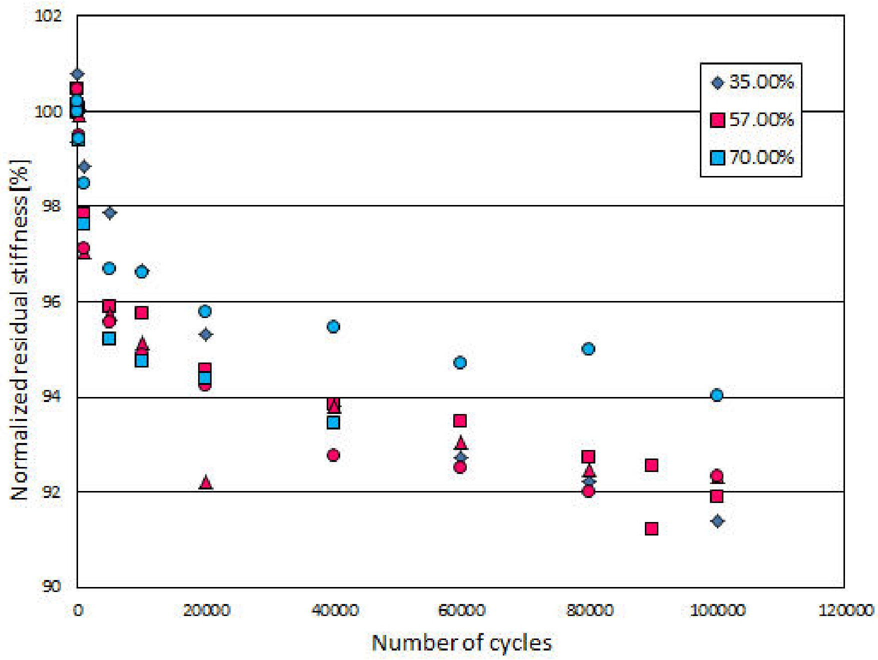


Fig. 10. Relationship between number of loading cycles and residual stiffness normalized to its initial value E_0 for $[0/90_2/\pm 45/90]_S$ layup.

Conclusion

Both quasi-static and load-controlled fatigue testing of E-glass epoxy samples of various layups have been performed. Obtained experimental data including progressive failure modes and the damage density are used as the input to a multi-scale numerical model capable of simulating both progressive quasi-static and fatigue damage.

Quasi-static progressive and fatigue damage was numerically simulated taking into account real progressive failure mode (transverse matrix cracks and its density) and its effect on the tangent modulus and residual stiffness. No homogenization of damage by introducing any complicated material model was needed. It has been found that the higher the crack density the higher global strain needed to form new matrix cracks. Hence, strain density and therefore tangent modulus and residual stiffness in case of fatigue loading saturates at high level of global strain or high number of cycles for fatigue loading. This observation is consistent with what can be observed in Figs. 8-10 and also with what Shahid [9] has concluded.

Delamination and the phase of composite final failure are outside the scope of this research. However, it has been concluded that strength of the laminate significantly decreases due to fatigue damage induced by the cyclic loading.

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