Technological approach to fatigue life prediction of CFRP

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Abstract
In this paper the issue of adequate stiffness measurement and use of fatigue stiffnesses for fatigue life prediction is investigated. Studies on the experimental measurement of stiffness properties of unidirectional carbon/epoxy laminates under tension-tension fatigue loads are presented. Moduli are calculated from stress-strain hysteresis. Results differ from quasi-static scales because of the different load speeds and strain rate dependent material behaviour. A new test procedure for measuring adequate stiffness properties in fatigue tests is presented. This method can be used to determine adequate cycle-dependent material properties for implementation in classical laminate theory or software based fatigue life prediction.

1. Introduction

Continuously fibre reinforced composites offer great possibilities for lightweight construction due to their outstanding mechanical properties in relation to weight. This material class has found an increasing number of applications in structural parts in the aircraft and in the automotive industry. To assure both weight reduction and safety material utilisation has to be optimized. As a result, composite parts are load-tailored and need to be designed individually. Stress analysis is therefore of tremendous importance. In contrast to most metal materials, highly anisotropic material behaviour has to be taken into account.

The most well-known approach to simple but effective stress analysis of composite materials under quasi-static loads is the classical laminate theory (CLT) [1]. CLT can be used to calculate stresses and strains in each layer of laminates or multiaxial lay-ups and provide information about resulting linkages which could lead to bending, shear or other deformations. Therefore, stresses in different multiaxial lay-ups can be compared and applications can be improved. Preconditions for accurate use of CLT are small deformations, ideal bonding between fibre and matrix material and linear elastic material behaviour. Voids, cracks or pores, which can cause complicated stress states, are not taken into account [1]. These simplifications make CLT an effective and fast tool for application-oriented estimation. Minimal required input parameters for CLT as well as for much more complex finite element based software tools are the anisotropic stiffness parameters of the material. These stiffnesses are usually determined in quasi-static tests with constant load speeds.

The issue of fatigue life estimation of continuously fibre reinforced materials is many times more sophisticated than the quasi-static load case. For fatigue loads as well, stiffnesses are very important information about material behaviour. Though, the common definition of stiffnesses in fatigue tests calculated from stress-strain hysteresis does not provide satisfying results for further. The test speed under fatigue tests with e.g. 10 Hz is higher than in quasi-static tests with 0.5 mm / min cross-head speed. Especially for polymeric materials, effects such as strain-rate dependence or cyclic creep have major influence on the slopes and on the shape of hysteresis. Usually dynamic moduli of polymeric materials are higher than respective quasi-static moduli during the entire fatigue test. Secant moduli decrease during fatigue tests because of creep effects in the materials [2]. As a consequence, the interpretation of dynamic and secant moduli calculated from stress-strain hysteresis in relation to quasi-static moduli is very difficult. It seems very unlikely that materials possess higher stiffnesses under fatigue than under quasi-static loads. Under quasi-static conditions Young's moduli measured in and transverse to fibre direction can be used in combination with Poison ratios for calculation of further material parameters such as shear modulus [3]. Under fatigue loads, secant and dynamic moduli cannot be used in theories developed for quasi-static parameters because they describe a different aspect of fatigue behaviour and are not measured under load conditions comparable to classical quasi-static material parameters.

In this work, experimental measurements of fatigue stiffnesses which can be used for known theories such as CLT are presented. Measuring under comparable load conditions is a necessary prerequisite for further use of cycle-dependent material properties in theories developed for quasi-static parameters. Therefore, a test procedure called "cyclic tensile tests" was implemented [4]. The Young's modulus of the material could be monitored with progressing number of cycles starting at the quasi-static value. This approach is considered "technological", because all effects occurring in the specimen under fatigue loading such as crack growth, delamination, fiber matrix debonding etc. are included in the measured material parameters and further calculation with these measured parameters. It is shown, that stiffnesses are material parameters but that they depend highly on the measurement and the strain range used for calculation. The parameters measured in cyclic tensile tests allow the extension of calculation tools such CLT for fatigue loads.

2. Experimental

In this work unidirectional laminates made of carbon fibres and epoxy resin and the stacking sequences $[0°]_4$, $[45°]_8$ and $[90°]_8$ were investigated. The fibre volume content was 55 % (measured by thermo gravimetric analysis). The specimens' geometry was 200x20x1 mm for $[0°]_4$ and 200x20x2 mm for $[45°]_8$ and $[90°]_8$ specimens. Aluminium-tabs with 1 mm thickness were glued on both sides of the specimens. Clamping length for all specimens was 100 mm. Quasistatic and cyclic tests were performed at room temperature on a servohydraulic testing machine equipped with a 100 kN load cell by MTS Systems Corporations. Quasi-static tests were evaluated according to ASTM E 739 [5]. All fatigue tests were performed with the R-value ($= F_{min}/F_{max}$) of 0.1. Specimens were tested on four different stress levels, at least three specimens were tested per stress level. Stress-strain hysteresis were recorded locally with a mechanical extensometer by MTS Systems Corporations with a fixing length of 50 mm. The test procedure of cyclic tensile tests is illustrated in figure 1. The servohydraulic test machine started the testing procedure with a defined number of sinusoidal cycles under load control. After that, the servohydraulic test machine unloaded the specimen to 0 N, switched to displacement control and performed a tensile test with a speed of 0.5 mm / min. The tensile tests were performed up to the mean displacement of the respective fatigue tests to avoid additional damaging [4].

Recorded stress-strain hysteresis were used for calculation of the secant and the dynamic modulus [2, 6]. The secant modulus is defined as maximum stress of hysteresis devided by maximum strain (1). The dynamic modulus is calculated from delta values of the stress and strain values of the hysteresis (2). The moduli from cyclic tensile tests were calculated between 0.1 % and 0.3 % strain according to ASTM E 739 [5] (3).

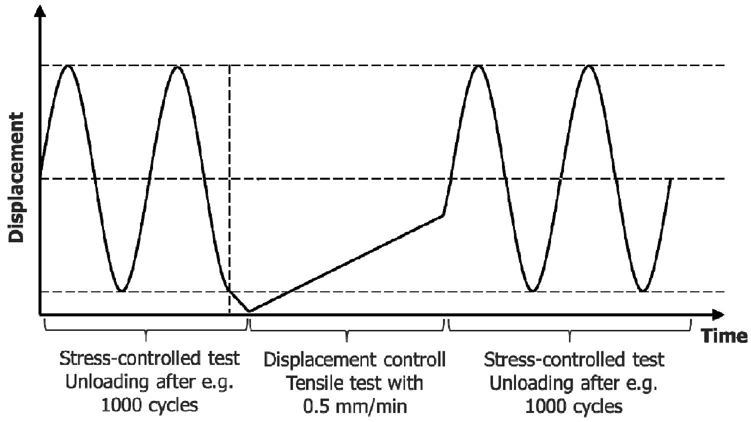

Figure 1: Test procedure for cyclic tensile tests [4].

$$E_s=\sigma_{max}/\varepsilon_{max} \tag{1}$$

$$E_{dyn}=(\sigma_{max}-\sigma_{min})/(\varepsilon_{max}-\varepsilon_{min}) \tag{2}$$

$$E_{cyclic\ tensile\ tests}=(\sigma_{0.003}-\sigma_{0.001})/(0.003-0.001) \tag{3}$$

3. Results and Discussion

For all results presented in this work it was assured in pre-tests that the inclusion of quasi-static tensile tests in the fatigue test did not influence the number of cycles to failure of the specimens. The stiffnesses measured in quasi-static tests according to ASTM E 739 [5] are presented in table 1.

	$[0°]_4$ [GPa]	$[45°]_8$ [GPa]	$[90°]_8$ [GPa]
Young's modulus	105 ± 3.7	7.8 ± 0.1	6.3 ± 0.1

Table 1: Stiffnesses measured in quasi-static tests.

Stress-strain hysteresis and cyclic tensile tests measured after 10.000, 100.000, 200.000 and 400.000 cycles with $[45]_8$ specimens are illustrated in figure 2. Stress-strain hysteresis were steeper than the respective tensile tests. The moduli calculated from both stress-strain hysteresis and tensile tests showed that dynamic moduli for strain-rate dependent polymeric materials were usually higher than the respective quasi-static moduli (figure 3). Moduli measured in cyclic tensile tests corresponded accurately to the Young's modulus of 7.8 GPa, whereas the absolute value for dynamic modulus was 9.6 GPa. Dynamic moduli and moduli from cyclic tensile tests stayed on a constant level during the entire test time. The secant modulus did not decrease, either, which indicated that the specimen did not tend to creep during the fatigue test. When having a closer look at the results of cyclic tensile tests, it could be found that moduli increased at the end of the fatigue tests. Because not only local measurement systems such extensometer recorded this effect but the piston displacement too, it seemed that this was not a measuring artefact but effects actually happening in the specimen. Fibres in 45° were probably aligning in load direction with increasing number of cycles. Though, fibre movement was too small to be monitored with cameras recording the surface during fatigue tests.

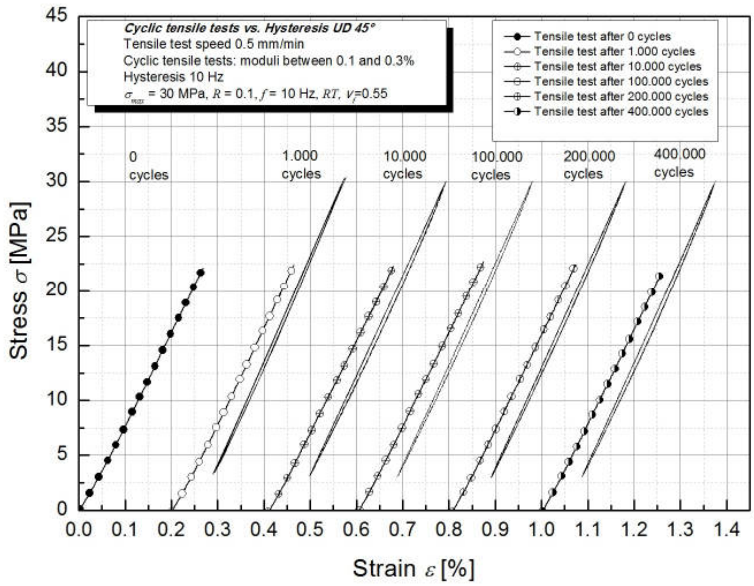

Figure 2: Cyclic tensile tests compared to stress strain hysteresis: $[45°]_8$ laminate, σ_{max}=30 MPa, R=0.1, 10 Hz, 0.5 mm/min in cyclic tensile tests.

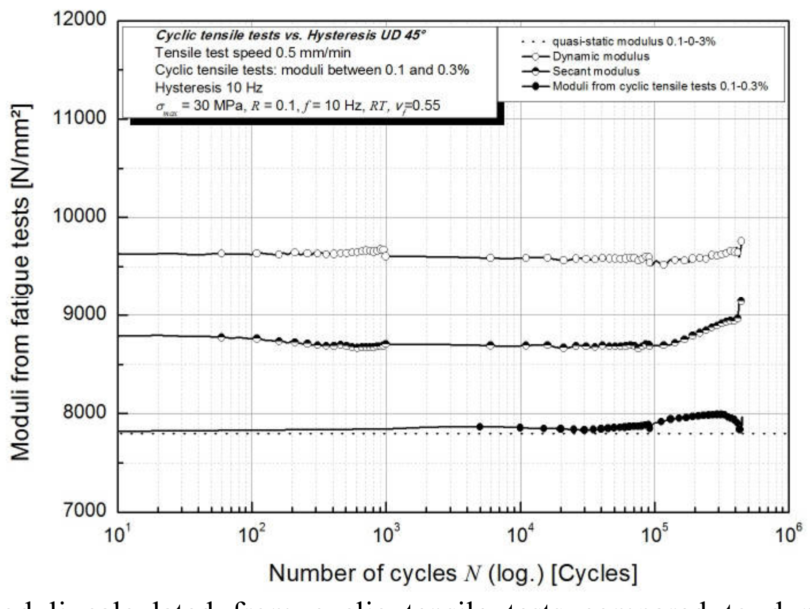

Figure 3: Moduli calculated from cyclic tensile tests compared to dynamic and secant modulus calculated from stress-strain hysteresis: $[45°]_8$ laminate, σ_{max}=30 MPa, R=0.1, 10 Hz, 0.5 mm/min in cyclic tensile tests.

Matrix dominated $[90°]_8$ specimens behaved non-linear in cyclic tests (figure 4). As a result of non-linear material behaviour, absolute stiffness values became somehow a matter of definition depending on the interpretation of stress-strain curves (figure 5). Again, moduli were calculated from the stress-strain hysteresis as well as from cyclic tensile tests. The dashed lines in figure 5 represent the Young's moduli evaluated from quasi-static tensile tests. The deviation between 6300 N/mm² and 6900 N/mm² depending on the strain range used for calculation of the Young's modulus emphasized the non-linear material behaviour.

Consequently, moduli from quasi-static tensile tests as well as cyclic tensile tests were calculated from linear part of measured stress-strain curves only, which equalled modulus calculation between 0.05 and 0.175 % strain. This observation showed clearly the strain-rate dependent material behaviour when testing unidirectional laminates transverse to fibre direction and the importance of measuring fatigue material parameters under load conditions comparable to quasi-static tests.

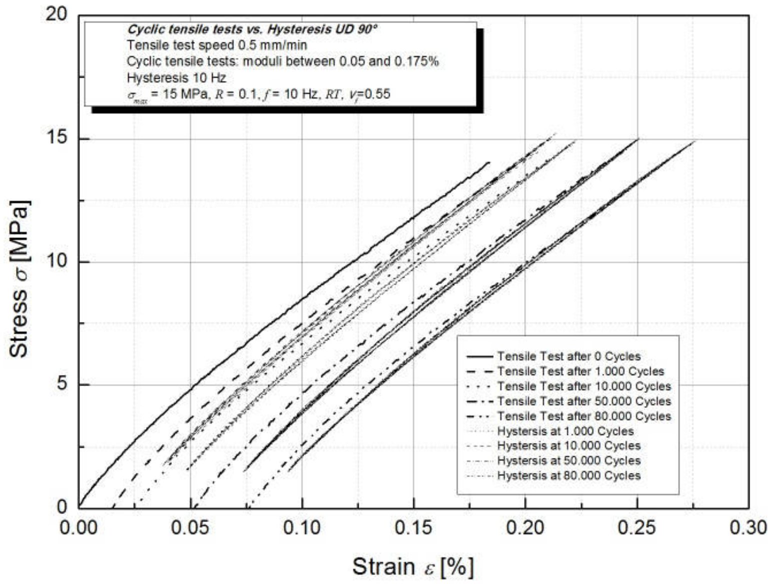

Figure 4: Cyclic tensile tests compared to stress strain hysteresis: $[90°]_8$ laminate, σ_{max}=15 MPa, R=0.1, 10 Hz, 0.5 mm/min in cyclic tensile tests.

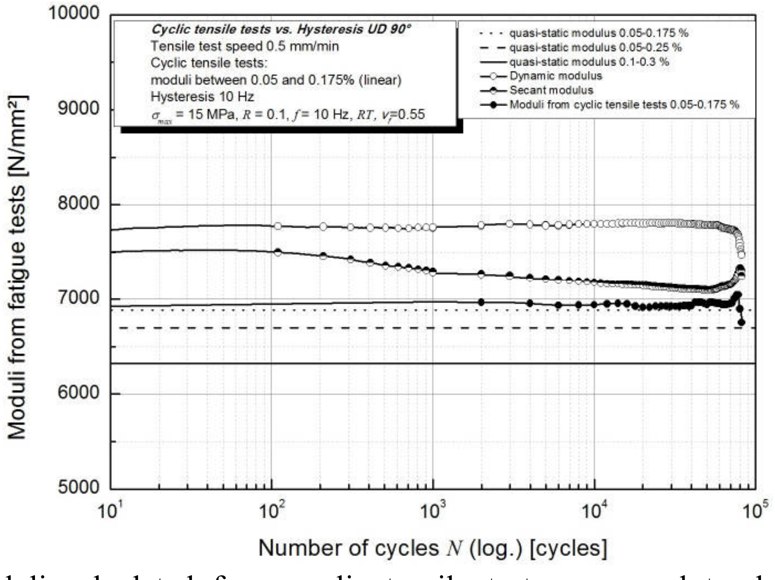

Figure 5: Moduli calculated from cyclic tensile tests compared to dynamic and secant modulus calculated from stress-strain hysteresis: $[90°]_8$ laminate, σ_{max}=15 MPa, R=0.1, 10 Hz, 0.5 mm/min in cyclic tensile tests.

$[0°]_4$ laminates did not show significant differences between dynamic modulus and moduli calculated from cyclic tensile tests. This resulted from the high fibre dominance in 0°-direction and non-speed dependent behaviour.

Results produced by using the cyclic tensile test procedure for unidirectional plies in 0°, 45° and 90° in fatigue tests are presented in Figure 6. The cycle-dependent moduli for $[0°]_4$, $[45°]_8$ and $[90°]_8$ are illustrated with their respective quasi-static values (dashed lines). Moduli measured with this method started at the respective value of the Young's moduli at 0 cycles. Moduli transverse to fibre direction $[90°]_8$ and $[45°]_8$ stayed on a constant level during the entire test time. This could be related to the damage mechanisms of sudden failure of these laminates. Beyond that, applied load level did not have influence on the progress of moduli. In contrast to that, $[0°]_4$ decreased as a consequence of delamination and damage progress in the specimens. Moduli processes of $[0°]_4$ were dependent on applied stress level (in Figure 6 one representative stress level is illustrated).

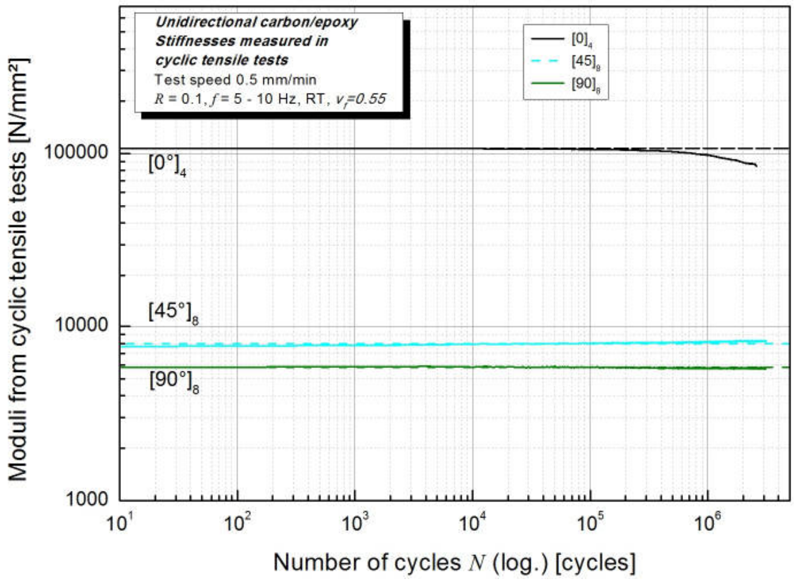

Figure 6: Moduli of $[0°]_4$, $[45°]_8$ and $[90°]_8$ laminates measured in cyclic tensile tests compared to the respective Young's moduli from quasi-static tests.

4. Conclusions and Outlook

In this work, a test procedure for determination of fatigue stiffnesses has been developed. The cyclic tensile tests procedure provides fatigue parameters measured under quasi-static conditions. It has been shown, that, in contrast to stress-strain analysis, strain-rate dependency of unidirectional plies measured under angles different from fibre direction can be excluded from fatigue results by using this new procedure. Cycle-dependent moduli measured in cyclic tensile tests can be correlated reasonably with the respective quasi-static Young's moduli which is often not the case when analysing stress-strain hysteresis. Besides, this test procedure can be easily implemented in conventional Wöhler tests because it does not influence number of cycles to failure in cyclic tests.

Furthermore, cyclic tensile tests can be used to measure cycle-dependent Poison's ratios and, in combination with cycle-dependent moduli in and transverse to fibre direction, to calculate cycle-dependent shear modulus of the UD layer in the same way as known for quasi-static parameters [3]. Furthermore, the cycle-dependent material parameters of the UD layer can be implemented in classical laminate theory to calculate $E_x(N)$, $E_y(N)$, $G_{xy}(N)$, $v_{xy}(N)$ and $v_{yx}(N)$ of any multiaxial stack. The results will be validated experimentally with a [0/45/-45/90/90/-45/45/90] CFRP multiaxial stack and published elsewhere.

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