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Fatigue life prediction of carbon fibre reinforced laminates by using cycle-dependent classical laminate theory

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ABSTRACT

In this work a study about the adaption of the classical laminate theory for fatigue loads is presented. Cycle dependent stiffnesses of single UD 0°, UD 45° and UD 90° plies are implemented in order to calculate the fatigue-induced stiffness decrease of a multidirectional lay-up with the stacking sequence [0°/+45°/−45°/90°/90°/−45°/+45°/0°]. As second input alternative, UD 0°, UD 90° and ±45° plies are used. The calculated cycle-dependent stiffness parameters are compared to experimentally measured fatigue data of the multidirectional lay-up. The experimental test procedure used for the measurement of cycle-dependent stiffness parameters has been published previously. Results show that the experimentally measured stiffness decreases of the multidirectional lay-up can be estimated accurately based on the cyclic unidirectional input parameters.

1. Introduction

Carbon/epoxy laminates are increasingly used because of their outstanding mechanical properties and light weight potential in the aircraft and automotive industry. Assuring the life-time of structural parts in such applications is a very important issue. Nowadays there are basically two approaches to technological life-time estimation of composites based on mechanical properties describing different aspects of fatigue life: fatigue strength represented by S–N curves as known from classical metal fatigue and fatigue stiffness. It is well known in literature that mechanical properties in composites decrease during fatigue life because of complex damage mechanisms. The progressing physical damage mechanisms can be reflected in the decreasing stiffness properties and depend on the height of the applied cyclic load [1,2]. Consequently, stiffness decreases can offer details about the physical behaviour of the material at each point of the fatigue test. Additionally, S–N curves contain information about the failure strength at the end of the stiffness decrease in dependency of the applied load level.

Unidirectional and multidirectional continuously fibre reinforced composites are among the easiest but most widely spread fibre architectures. Especially material tests of unidirectional laminates are important for the creation of basic material data, under quasi-static as well as fatigue loads. In many cases, multidirectional lay-ups made of the same material have to be characterised as well. Even if the fatigue properties of the unidirectional plies used in the multidirectional lay-up are known, the time consuming fatigue tests usually have to be started again. Consequently, a way to reduce testing time would be beneficial. One established possibility for calculating multidirectional properties based on unidirectional input parameters under quasi-static loads is the classical laminate theory (CLT). CLT is a powerful tool for the design and dimensioning of composite parts. By using stiffnesses and Poisson's ratios of single plies, the properties of multidirectional lay-ups can be estimated very accurately under quasi-static loads [3–5]. Necessary input parameters are the Young's modulus in fibre direction E_{11}, the Young's modulus transverse to fibre direction E_{22}, the shear modulus G_{12} and the major and minor Poisson's ratios υ_{12} and υ_{21}. An important prerequisite for the use of CLT is linear elastic material behaviour [4]. Beyond that it has to be considered that all effects such as fibre–matrix adhesion, interfaces and delaminations are already included in the parameters on ply level and taken on the next, multidirectional level by the classical laminate theory. CLT has been used and adapted for a variety of materials and applications e.g. [6–8]. However, the CLT is not applicable to fatigue so far.

In this paper, the classical laminate theory has been adapted in order to calculate the stiffness properties of a multidirectional lay-up under fatigue loads $E_x(N)$, $E_y(N)$, $G_{xy}(N)$ and $\upsilon_{xy}(N)$ based on the cycle-dependent properties of the unidirectional ply $E_{11}(N)$, $E_{22}(N)$,

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$G_{12}(N)$ and $\upsilon_{12}(N)$. To measure these input parameters, an experimental procedure had to be developed which could ensure measuring cycle-dependent linear elastic material properties under conditions comparable to the quasi-static Young's and shear moduli already published in [9]. This new cyclic test procedure was mainly necessary because the commonly used method for calculating fatigue moduli from stress–strain hystereses was not useful for further life-time estimation. Because of the strain rate dependent behaviour of the epoxy matrix absolute values of moduli calculated from stress–strain hystereses were not in the same scales as quasi-static moduli usually used in CLT [9,10]. Consequently, the 'cyclic tensile test' procedure was used for the experimental tests in this work which includes displacement controlled quasi-static tensile tests within force controlled tension–tension fatigue tests [9]. By evaluating the included quasi-static tensile tests, cycle-dependent Young's and shear moduli could be calculated. These cycle-dependent input parameters of the unidirectional ply were implemented in a programmed software routine which repeated the CLT for a defined number of cycles. Shear moduli were implemented in two different ways. Fatigue stiffness properties of a quasi-isotropic multidirectional lay-up [0°/+45°/−45°/90°/symm.] were calculated. Results were compared to the experimentally measured stiffness progresses at three different load levels. Additionally, multidirectional specimens were stopped after certain numbers of cycles and investigated by light microscopy to get qualitative insight in the damage mechanisms responsible for the stiffness degradation.

2. Experimental work

Unidirectional (UD) lamina made of carbon fibres and epoxy resin were tested at angles of 0°, 45° and 90°. Multidirectional specimens consisting of ±45° and [0°/+45°/−45°/90°/symm.] layers build in a symmetric way referring to the middle plane were investigated as well. The fibre volume content of all specimens was 55% (measured by thermo gravimetric analysis). UD 0° plies consisted of 4 layers, all other specimens were made of 8 layers. The specimens' geometry was 200 × 10 × 1 mm (length × width × thickness) for UD specimens in fibre direction and 200 × 20 × 2 mm for all other specimens. Aluminium tabs of 1 mm thickness were glued on both sides of the specimens.

Quasi-static tensile as well as tension–tension fatigue tests were performed on a servo-hydraulic test machine equipped with a load frame and load cell for 100 kN by MTS Systems Corporations (Minnesota, USA). Gauge length for all performed tests was 100 mm. Hydraulic wedge pressure of 5 MPa was chosen in order to prevent slipping without damaging the specimens. Good adhesion between aluminium tabs and CFRP specimen was assured in preliminary tests. Quasi-static tensile tests were performed with a test speed of 0.5 mm/min until failure. A digital image correlation (DIC) system by GOM (Braunschweig, Deutschland) was used for strain measurement in and transverse to fibre direction. Tensile moduli were calculated between 0.001 and 0.003 absolute strain according to [11]. Fatigue tests were performed at four different stress levels. A minimum of three specimens was tested on each stress level. Test frequency was chosen between 2 and 10 Hz depending on the test load and the hysteretic heating. Specimens' temperatures were controlled by infrared (IR) sensors in all tests. All fatigue tests were performed with the R-value (=minimum force/maximum force) 0.1.

Conventional sinusoidal tests with constant load amplitude as well as cyclic tensile tests were performed on different stress levels for comparison of numbers of cycles to failure. In tests according to cyclic tensile test procedure presented in [9], the servo-hydraulic test machine started the test procedure by performing a displacement controlled tensile test with a test speed of 0.5 mm/min. Displacements in these quasi-static tensile tests were always smaller than the respective, locally measured sinusoidal displacement of the specimens to avoid additional damaging as illustrated in Fig. 1. After a tensile test, the test machine switched to load control and performed 1000 sinusoidal cycles with $R = 0.1$. Subsequently, the servo-hydraulic test machine unloaded the specimen to 0 N, switched to displacement control and performed another quasi-static tensile test (Fig. 1). The tensile tests measured between the cyclic loads were used to calculate moduli and Poisson's ratios in exactly the same way as known for quasi-static tensile tests by means of the computer language matlab by MathWorks (Ismaning, Germany). Fatigue results were analysed statistically according to [12] in addition.

2.1. Shear moduli in quasi-static and fatigue tests

Different possibilities for the measurement of the shear stress–strain behaviour of composite materials are known. For woven or multidirectional materials, the rail shear test is a popular method [13,14]. However, the rail shear test cannot be recommended for unidirectional laminates because the measured properties do not correspond to reality [14]. There are basically two methods if the shear behaviour of unidirectional plies has to be characterised with rectangular specimens: First, the shear modulus G'_{12} can be calculated if the moduli in fibre direction E_{11}, transverse to fibre direction E_{22}, the modulus of a UD 45° ply E_{45} and the Poisson's ratio υ_{12} are known (1) [15]. Second, the in-plane shear behaviour can be evaluated in tensile tests with ±45° specimens. Tensile stresses are used to calculate shear stresses τ_{12}. The shear strain γ_{12} is evaluated as difference between the longitudinal and the transversal strain of the ±45° specimen. Finally, the shear modulus G^*_{12} is calculated between 0.002 and 0.006 absolute strain according to (2) [16]. Both methods were used for evaluation of shear moduli in quasi-static as well as fatigue tests and for further implementation in cycle-dependent CLT.

$$G'_{12} = \frac{E_{45} * E_{11} * E_{22}}{4 * E_{11} * E_{22} - E_{45} * (E_{22} - 2 * \upsilon_{12} * E_{22} + E_{11})} \tag{1}$$

$$G^*_{12} = \frac{\Delta\tau_{12}}{\Delta\gamma_{12}} \tag{2}$$

2.2. Poisson's ratios measured in quasi-static and fatigue tests

The two Poisson's ratios provide useful information about the anisotropic strain response of a material under load and are necessary input parameters for the CLT. The major Poisson's ratio υ_{12} can be evaluated from quasi-static tensile or cyclic tensile tests with UD 0° specimens by measuring strains transverse to (22-direction) and in fibre direction (11-direction) (3). The minor Poisson's ratio υ_{21} can either be measured in the same way with UD 90° specimens or it can be calculated according to (4). Both formula were used for the calculation and validation of υ_{12} and υ_{21} as well as $\upsilon_{12}(N)$ and $\upsilon_{21}(N)$.

$$\upsilon_{12} = \frac{\varepsilon_{22,2} - \varepsilon_{22,1}}{\varepsilon_{11,2} - \varepsilon_{11,1}} \tag{3}$$

$$\upsilon_{21} = \frac{E_{22}}{E_{11}} * \upsilon_{12} \tag{4}$$

2.3. Fatigue life prediction with CLT

The known procedure of the CLT [3–5] and its extension for fatigue loads were implemented in the computer language matlab. The schematic progress of the programmed procedure is illustrated in Fig. 2. Because the laminate which should be calculated was