# FATIGUE BEHAVIOR OF MULTIFUNCTIONAL CFRP LAMINATES AND INTRINSIC CAPABILITIES FOR DAMAGE MONITORING

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## ABSTRACT

Due to their outstanding mechanical performance Carbon Fibre Reinforced Polymers (CFRP) are today´s primary chosen material for load carrying structures in aircraft applications. Compared to the excellent strength to density ratio some disadvantages like the electrical properties, the poor damage tolerance and a brittle failure behaviour limits the lightweight potential of the composite. Modern airliners such as Airbus´ A350 or Boeing´s 787 consist of more than 50 vol-% composite materials [1]. The increasing use of composite materials causes new challenges for engineers. Especially for electrical installation like lightning strike protection or grounding, additional metallic masses are used which deteriorate the weight balance of the structure. Former researches were concentrated on modifying the matrix system to improve the electrical properties [2-4]. However a significant breakthrough could not be reached so far. The idea of combining the advantages of metal foils and fibre reinforced polymers was firstly realized in fibre-metal laminate such as GLARE® or ARALL®. The idea of combining thin metal fibres with conventional fibre reinforced polymers (MCFRP) seems to be a promising new approach for a multifunctional composite. Stress tailored design as well as increased electrical conductivity can be mentioned as significant progress. Because of the manifold cyclic loadings during their lifetime of structural components the present study focuses on the fatigue behaviour of MCFRP. Especially the influence of the chosen metastable austenitic stainless steel fibres is discussed. In addition to the standard measurement equipment a new possibility of monitoring ongoing damage progress by magnetic inductive measurements is shown. Differences in failure mechanisms of CFRP and MCFRP are discussed based on interrupted fatigue tests combined with scanning electron microscopy.

## 1 INTRODUCTION

Driven by society and politics the requirements for modern aircrafts considering fuel consumption and pollution are highly ambitious. Reducing structural mass by smart material solutions is a necessary goal to fulfil next generation´s demands. The use of fibre reinforced polymers increased over the last decades up to a value of over 50 wt.-%. For further mass reduction improvements in design principles and application of smart multifunctional materials are indispensable. The brittle failure behaviour and the comparable poor electrical conductivity limit the lightweight potential of conventional carbon fibre reinforced polymers. Lightning strike protection, electrical shielding and signal transfer are still requirements which have to be fulfilled by additional metallic masses added to the load carrying structure. The combination of single benefits of metallic materials and fibre reinforced polymers in one smart hybrid composite could be an expediently approach to substitute the additional mass and reducing weight, see Figure 1. Researches on modifying the resin system have been carried out without fundamental improvements [2-4]. In monotonic tensile tests the combination of thin austenitic stainless steel fibres with conventional CFRP laminates showed improved failure behaviour as well as increased values of energy absorption and electrical conductivity [5-7].

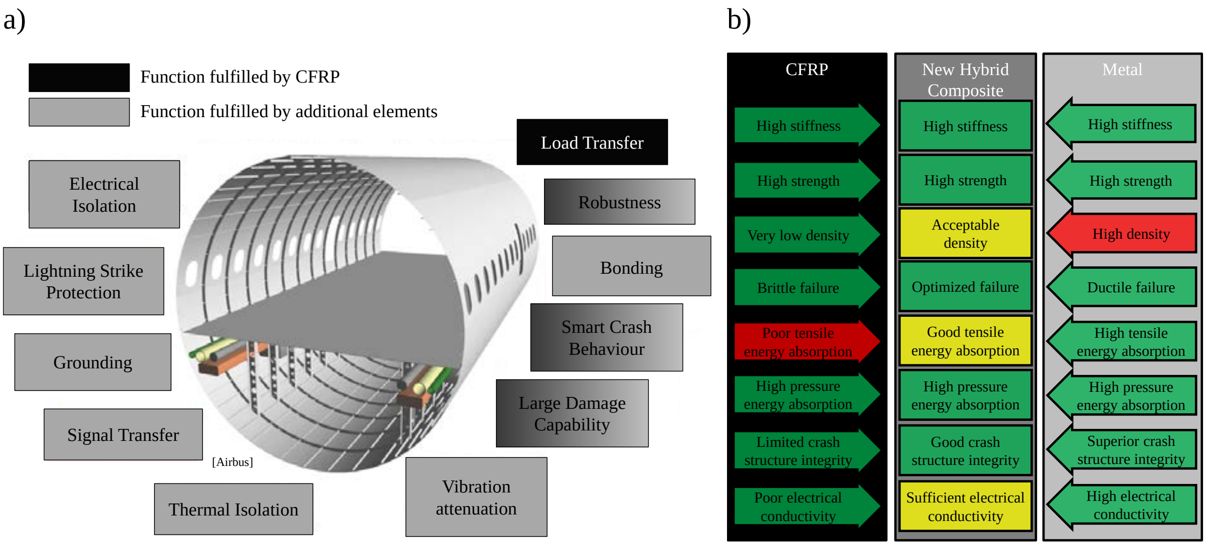


Figure 1: a) Functions of fuselage structures, acc. to [1], b) Benefits of MCFRP

Beside electrical and monotonic mechanical properties the fatigue behaviour of structural components in aircraft manufacturing is a decisive element. Maintenance of load carrying components is a very cost effective part for airlines. Therefore the design principle of "no-crack-growth" for the entire service time should reduce the effort [1]. Conventional CFRP structures were intensively investigated in the past by e.g. Talreja et al [8]. To investigate the influence of steel fibre reinforcement on the fatigue behaviour of CFRP laminates the present study focuses on the fatigue properties in the low cycle fatigue (LCF) as well as high cycle fatigue (HCF) regime. The multiaxial CFRP laminate is compared to a new hybrid composite (MCFRP) including specific damage mechanisms during the lifetime. In addition a new possibility of structural health monitoring by magnetic inductive measuring methods is presented and discussed, as a further concept to reduce the effort of maintenance. This possibility is given by monitoring the change of magnetic volume fraction, caused by the plasticity induced phase transformation from paramagnetic austenite to ferromagnetic martensite of the metastable austenitic steel fibres, by the application of magnetic inductive measuring devices.

## 2 MATERIALS – METAL AND CARBON FIBER REINFORCED POLYMER (MCFRP)

The present study discusses the fatigue properties of two different composites: The reference-laminate is a 13-layered conventional CFRP laminate produced in a tape laying process. The new developed MCFRP laminate consists of a 13-layered CFRP core with similar stacking sequence to the reference laminate. 4 layers of dry austenitic stainless steel fibres (AISI 304) are added in the top layers by a filament winding process. The steel fibres occur in bundels of 7 single fibres. Lightoptical micrographs of both laminates are given in Figure 2. The polymer matrix of the composites is an epoxy based resin and commercially available from Cytec (Cycom 977-2). For reinforcement HTS40 carbon fibres by Toho Tenax are used. Outstanding mechanical performance as well as excellent impact resistance and high service temperature are leading to the common use in aircraft applications especially in primary and secondary load carrying structures [1].

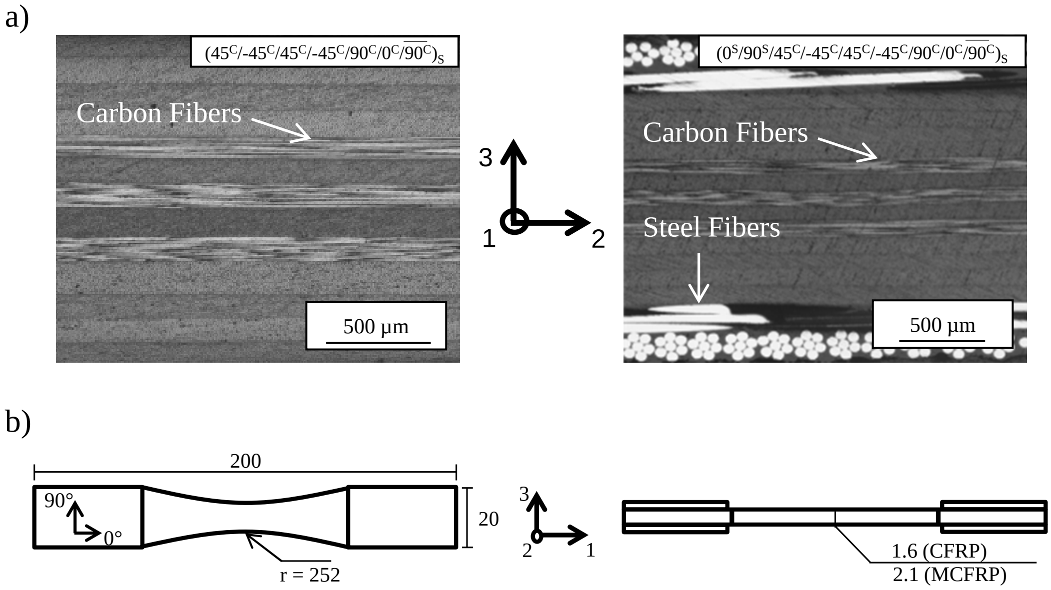


Figure 2: a) Microstructure of CFRP- (left) and MCFRP-Laminates (right),
b) Specimen geometry for tensile and fatigue testing (all dimensions in mm)

Selected physical and mechanical properties are listed in table 1 below.

| Laminate | | CFRP | MCFRP |
|---|---|---|---|
| *Thickness* | [mm] | 1.6 | 2.14 |
| *Density* | [g/cm³] | 1.59 | 2.82 |
| *Carbon Fibre* | [Vol-%] | 61.6 | 46 |
| *Metal Fibre* | [Vol-%] | 0 | 19.5 |
| *Young´s Modulus in 1-dir* | [GPa] | 40.3±0.5 | 33.2±0.8 |
| *Ultimate tensile strength in 1-dir.* | [MPa] | 497±22 | 482±14 |

Table 1: Selected properties of multiaxial CFRP and MCFRP laminates

The evaluation of the mechanical properties in tensile tests was based on DIN EN ISO 527-4. The specimen design was slightly different to the standards. The specimen design is shown in Figure 2 b). The sample geometry with a constant radius was chosen to realize a defined location with highest stress amplitudes.

## 3 EXPERIMENTAL SETUP FOR FATIGUE TESTING

The presented fatigue tests were performed in sinusoidal shape. Beside stress controlled constant amplitude tests, load increase tests were realized to identify the critical load level for the constant amplitude tests. The experiments for the Low Cycle Fatigue Regime (LCF) were realized with a stress ratio of R = 0.1 and a frequency of 0.2 Hz up to $10^4$ cycles. For the High Cycle Fatigue (HCF) tests up to $2x10^6$ cycles a testing frequency of 5 Hz was used with the identical stress ratio. The experimental setup is schematically shown in Figure 3 a).

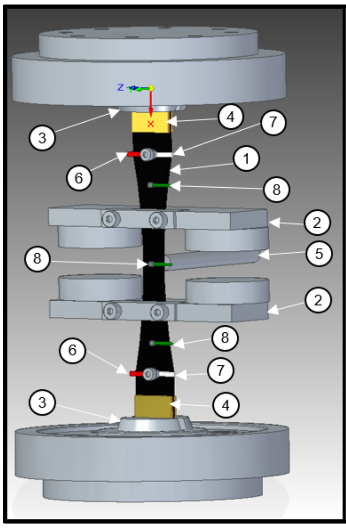


Figure 3: Fatigue testing setup for polymer laminates

A capacitive displacement sensor with a gauge length of 30mm determined the total strain amplitude. The LabView based data acquisition provides the plastic strain amplitude by calculating half of the total strain amplitude at mean stress level in each cycle from the logged stress-strain hysteresis. Beside the observation of the sample temperature by thermocouples (TC) the determination of dynamic stiffness based on the measured gradient of each cycles´ stress-strain hysteresis is implemented. The change of sample temperature is calculated by the following equation 1.

$$\Delta T = T_2 - \frac{T_1 + T_3}{2} \tag{1}$$

To measure the fatigue induced thermal increase, TC 2 is positioned at the surface of highest cyclic stresses in the middle of the specimen. TC1 and TC3 are used to include environmental influences in the calculation. They are located near to the caps where no fatigue induced damage is expected. A further indication for the damage progression is the increasing electrical resistance of the specimen. To evaluate the change of electrical resistance a constant current of 100 mA is introduced through metallic bolts ($\Delta R_c$) and the changing voltage ($\Delta R_v$) is metered. Due to the low current a thermal induced increase electrical resistance is excluded [6]. For the MCFRP laminate additionally a magnetic inductive measuring dev ice (Feritscope® FMP30, Helmut Fischer GmbH, Sindelfingen – Germany) is applied at the surface of the MCFRP laminate for measuring the magnetic phase fraction in the metastable steel fiber layers. Further technical functionality is given in [9].

## 4 RESULTS AND DISCUSSION

### 4.1 Fatigue Properties

The fatigue behavior of CFRP and MCFRP was evaluated by constant amplitude tests with a frequency of 0.2 Hz for the LCF regime up to $10^4$ cycles and 5 Hz for the HCF regime up to $2x10^6$ cycles. The stress amplitudes for the single step tests varied between 112.5 and 235 MPa based on the results of previous performed load increase tests. Figure 4 a) shows selected results of the global stress amplitude (in 1-direction) in a double-log scale over the number of cycles to failure $N_f$. The stress ratio for all constant amplitude tests in the LCF and HCF regime was kept constant at R = 0.1. With a rising number of cycles to failure both laminates show a nearly similar decrease of tolerated stress amplitudes in the LCF regime. In general both laminates show a comparable fatigue behavior with only small deviation. For the HCF regime between $10^4$ and $2x10^6$ cycles the MCFRP laminate shows a lower decrease of tolerable stress amplitudes with rising number of cycles.

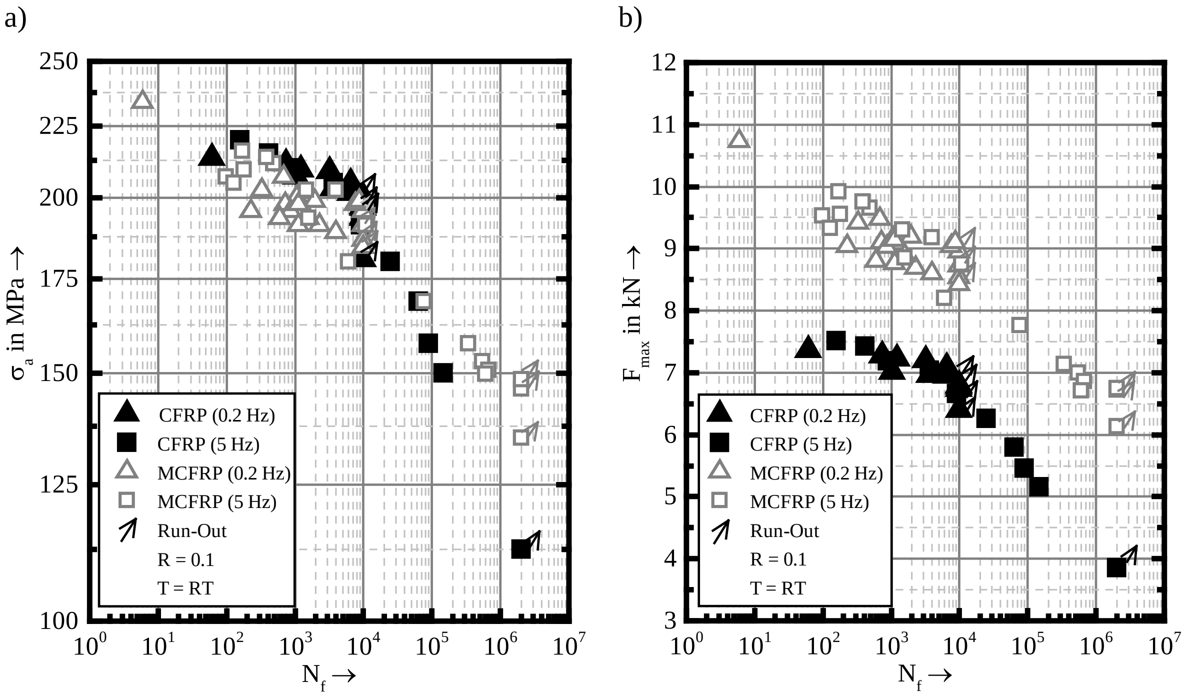


Figure 4: a) S-N curves for CFRP and MCFRP b) F-N curves for CFRP and MCFRP in case of weight-neutral approach

In aeronautical application purposes, especially in primary load carrying structures like the fuselage, metallic masses are added to fulfill the electrical requirements. The simultaneous utilization of these masses for electrical purposes and increasing load carrying capability of the structure is completely new. Therefore the consideration of maximum tolerated force over the entire lifetime highlights the benefit of MCFRP compared to conventional CFRP laminates.

To understand the fatigue behavior of both composites the stiffness degradation over lifetime is considered and supplemented by different damage mechanisms investigated in interrupted fatigue tests combined with scanning electron microscopy. The specimen stiffness in 1-direction ($E_1$) is kept at different stages and the correlating mean value and standard deviation based on 5 different constant amplitude tests is plotted over lifetime in Figure 5. Up to 500 cycles both laminates show comparable progress of stiffness degradation. The stiffness degradation is defined by the ratio between the current specimen stiffness in 1-direction ($E_{1,1}$) and the specimen stiffness in 1-direction in the initial state ($E_{1,0}$). After 500 cycles the rate of decreasing stiffness is lower for the metal fiber reinforced laminate architecture. With continuous lifetime the gap of remaining stiffness between the conventional CFRP and MCFRP is getting higher.

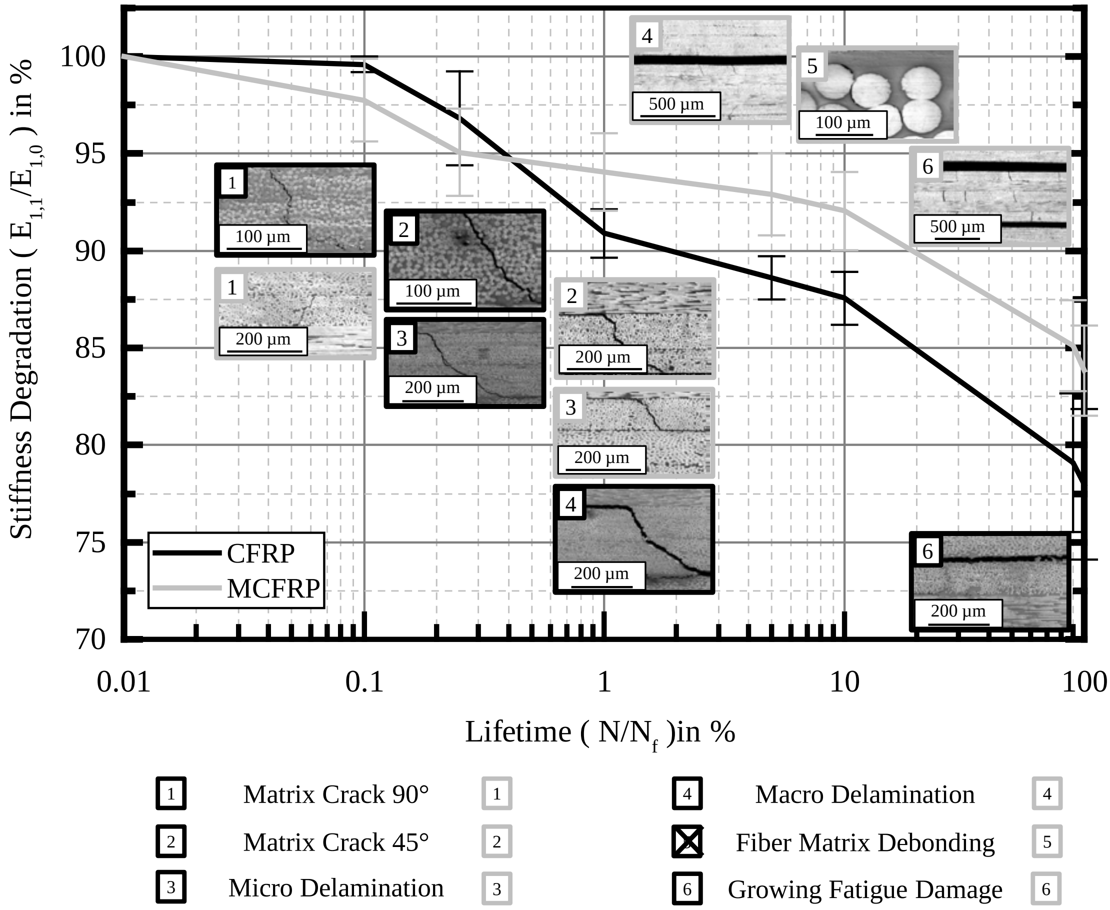


Figure 5: Stiffness Degradation for LCF regime

To investigate the different fatigue induced damage stages the specimen was removed from the servohydraulic testing device after a defined number of cycles (0.1 % to 100 % fatigue life). Using a scanning electron microscope both lateral edges were mapped. The different damage mechanisms are also illustrated in figure 5 with their corresponding occurrence in lifetime of the sample. The first damage is detected early after only 10 cycles. Matrix cracks in the 90° layers (1) appear in both laminate architectures. The first relevant stiffness degradation of the CFRP laminate results from Matrix Cracks in the 45° layers (2) and first micro delaminations (3) occurring after 0.25% of lifetime. The MCFRP laminate shows comparable damage mechanisms but the occurrence is postponed to a later stage of lifetime. The first macro delaminations (4) appear after 1 % of lifetime in case of the CFRP laminate, for the metal fiber reinforced composite after 5 % of lifetime. The steel fiber layer shows no visible damage at the same state. First fiber matrix debondings in the steel layers occur after 10 % of lifetime. The further damage progress in the LCF regime is characterized by growing fatigue damage until the final failure of the specimen is caused by the failure of 0° carbon plies.

### 4.2 Structural Health Monitoring by magnetic measurements

The standard fatigue testing equipment is supplemented by a magnetic inductive measuring device (Feritscope ®) in case of the MCFRP laminate. The simultaneous use of the metastable austenitic steel fibers for reinforcement and intrinsic damage sensor is aspired. In Figure 6 the plastic strain amplitude $\varepsilon_{a,p}$, stiffness degradation and the change of magnetic volume fraction $\xi$ is illustrated over the number of cycles for a characterisitc constant amplitude test. The cyclic hardening of the austenitic steel fibers causes a low decrease of plastic strain in the early state of the test, proofed by the simultaneous increase of magnetic volume fraction. The highlighted point of a significant new damage state causes a stronger rate of stiffness degradation. The parallel strong increase of the magnetic volume fraction in the steel layers, resulting from progressing defects in carbon layers leading to higher stresses in steel layers, proofs the possibility to view growing damage by monitor the change of magnetic volume fraction with magnetic inductive measuring devices like the used Feritscope ®. The observed increase of magnetic volume fraction is caused by plasticity induced phase transformation from paramagnetic austenite to ferromagnetic martensite, like Smaga et al [9] observed for austenitic stainless steel AISI 304.

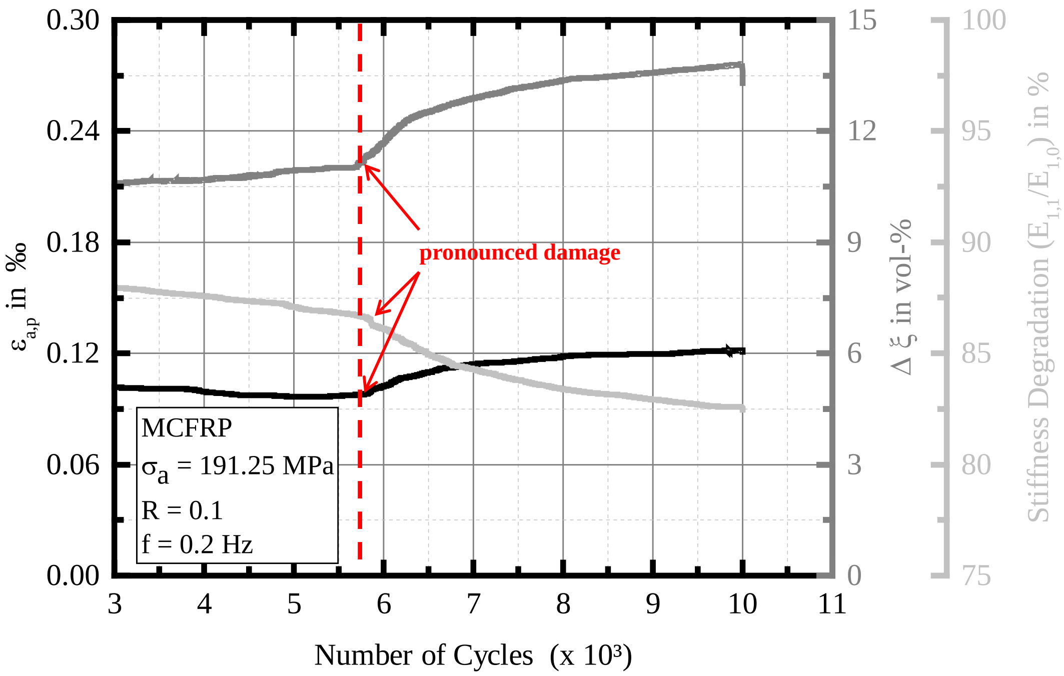


Figure 6: Magnetic phase fraction for a constant amplitude test of MCFRP-laminate in the LCF regime

## 5 CONCLUSIONS AND OUTLOOK

The realized advanced fatigue experiments in the LCF- and HCF regime with a stress ratio of R 0.1 show a comparable behaviour of both laminate architectures. A slight advantage of tolerable stress amplitudes for MCFRP laminates with growing number of cycles is visible. In case of a weight neutral approach, considering a possible use in fuselage structures, the advantage of MCFRP is even higher over the entire lifetime. The damage mechanisms of both composites are comparable. However the metallic reinforcement causes a longer lasting stiffness, proofed by a delayed start of delaminations, and brings up a further advantage of the metal fibre reinforced concept. Interrupted fatigue tests in the HCF regime will show if the advantage of MCFRP is getting higher with rising number of cycles. The possibility of monitoring ongoing damage progress by considering the magnetic volume fraction in the steel layers is discussed. The clear correlation between stiffness degradation and magnetic volume content proofs the principal of this method. However a different laminate architecture causing reduced stresses in the steel layers, even before a significant state of damage is reached, would be preferable.

## ACKNOWLEDGEMENTS

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