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COMPRESSION FATIGUE OF WIND TURBINE BLADE COMPOSITE MATERIALS AND DAMAGE MECHANISM

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ABSTRACT

According to the new IEC 61400-5-rev0 recommendation, which is under preparation it will be required to qualify wind turbine blade (WTB) composite materials in fatigue at $R=0.1$, $R=-1$, and $R=10$. As a minimum fatigue at $R=-1$ is required. This is a consequence of the ever-growing blades, where gravity driven edgewise bending introduces significant fully reversed cycling at the leading and trailing edges. Therefore, material manufacturer and WTB manufacturer demand test results of highest reliability and reproducibility. However, these requirements for compression-compression and tension-compression fatigue properties are a big challenge for the test institutes to meet. Tests are very difficult to perform, as it is nearly impossible to design an optimal test setup.

This study shows a newly developed sample geometry and test method in order to obtain representative and reliable results. Two different laminate architectures have been tested in order to validate the test method. Damage mechanisms and damage progression in compression fatigue have been investigated using 3D X-Ray Tomography and a qualitative explanation of the damage mechanisms is presented.

1. INTRODUCTION

With the constant growing blades, improved materials and processes, and the new qualification demands [1;2], it is constantly required to qualify the composite materials used in wind turbine blades. Measuring both their static properties in tension, compression and shear, and their fatigue properties at different load patterns defined by the R (min stress/max stress) ratios. E.g. tension-tension $R=0.1$, tension compression $R=-1$, and compression-compression $R=10$.

Because of the new high quality materials, i.e. high performance glass fibres with improved sizing, interacting with resins specifically formulated, much better performing laminates are seen in the market today than 10 years ago. In order to reflect this performance correctly, improved test procedures and test specimens need to be developed.

Test methods development has not followed the constant material improvement. Standardised and recommended mechanical test procedures do not reflect the true performance of the materials, resulting in design properties much lower than the actual values. Due to a non-optimised design test specimens fail in the load introduction sections leading to low values, low reproducibility, and high scatter in the test.

Characteristic design values, which are based on the variance of the test results [1] are therefore not reflecting the correct high performance of the materials.

In the years, 2000 to 2006 the integrated European Optimat Blade project was focused on fatigue issues in WTBs material's [3]. Test methods for tension-tension, tension-compression, and compression-compression were suggested and ran. However, a unique specification and standardisation never became the outcome of the project due to its complexities and individual interest from the different partners. The results from the enormous amounts of tests are reported in the OPTIDAT database [3]. As an example of the large diversity in results Figure 1 shows the unsorted results from compression-compression fatigue test performed by the participating partners. Although one manufacturer provided the materials tested, reproducible and acceptable results were not obtained. This demonstrated the still existing need for a better understanding of the test methods and basic damage mechanisms.

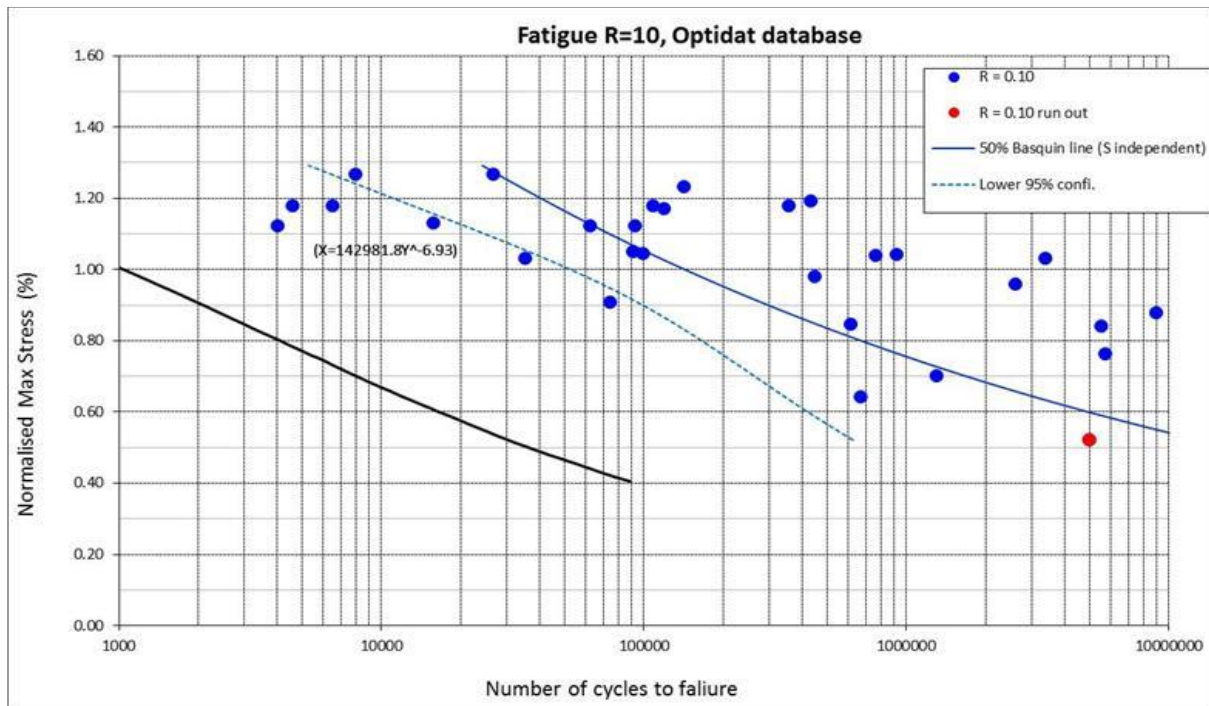


Figure 1: All results from R=10 fatigue test in OPTIDAT database (unfiltered).

In this paper focus is put on the fatigue performance of the WTB materials. In order to fully optimise the experimental methods, it is essential to identify and understand the basic mechanisms degrading the materials when exposed to fatigue loadings, called the fatigue damage mechanisms. For the unidirectional fabrics normally used in WTBs the fatigue damage mechanisms have been postulated and validated by Zangenberg et al (2012) [4] and Zangenberg et al (2013) [5]. These results permitted a better understanding and hereby optimising tension fatigue. Following this, several investigations, e.g. using advanced CT scanning techniques have confirmed these mechanisms, Jespersen and Mikkelsen [6] Beck and Brøndsted [7] and Mishnaevsky et al [8]. This realisation not only lead to improved test procedures [9] results, but also to understanding the curing processing and the influence of the material architecture Hüther [10], and Pereira et al.[11].

However, knowing and understanding the damage mechanisms in tension fatigue is not sufficient for establishing the all-over design values. Before being able to establish a relevant method for tension-compression and compression-compression the compression fatigue damage mechanisms need to be as well understood as they are for tension fatigue. For this reason today's focus has been given to compression fatigue testing and optimization. Using newly developed test specimen geometries, reproducible fatigue test and damage can be obtained. In the test section, results with a minimized variance are presented. This permits to follow the correct damage progress during fatigue and to give higher design limits to the manufacturers. As described in this paper, compression damage modes in the materials are potentially identified and mapped, but still need to be fully characterized.

Hopefully, suggestions for standardisation can be made thanks to these results, and hopefully they can be approved by all interested parties in this field. The test procedures are optimised by using a special designed compression test fixture where the load introduction is partly shear loading and partly axial loading [12]. The fixture is optimally aligned in order to reduce bending and off axes loading to a minimum. Specimens' geometry has been designed to reduce the stress concentrations at the load introduction also by using special materials for tabs and high performance adhesives to reduce debonding between tabs and test specimen. Compression damage progression, characterized by 3D X-Ray Tomography, in unidirectional glass fibre reinforced composites manufactured of a non-crimp fabric is studied and a qualitative explanation of the damage mechanism is suggested.

2. MATERIALS & METHODS

2.1. Materials

The materials presented in this paper are glass fiber reinforced polymer composites. A 6 layer UD 650 laminate with biax on top for the first test series and a 4 layer Triax 1800 laminate for the second test series. In both of the laminates, the resin used is a standard infusion resin from Huntsman.

2.2. Test fixture

A new type of mechanical combined loading fixture especially designed for compression fatigue was previously developed at DTU Wind Energy [12]. This fixture has been used in the current investigation to test the samples in compression. The main advantage of this fixture is to combine end load and shear load. This ratio is kept constant during all the test series. Moreover, thanks to the stiffening column, it is possible to conserve an optimal alignment during the fatigue test. The fixture is shown in Figure 2.

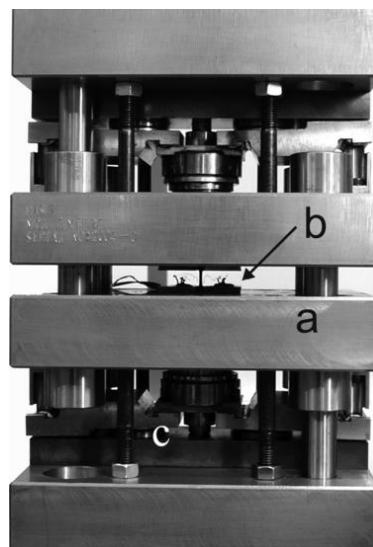


Figure 2: Mechanical combined loading fixture. a) steel block with machined cavities; b) specimen wedge assembly; c) load introduction mechanism [11]

2.3. Specimen specifications

The specimen geometry and specifications were developed using both Finite Element Model analysis and experimental results. The first parameter to avoid while developing a compression sample geometry is the buckling. The test results will be dramatically influenced if the samples buckle. This bending will affect the load introduction components and therefore affect the test results. Special care is therefore taken for the tabs manufacturing. The tabs material was manufactured by Vacuum Assisted Resin

Transfer Moulding with a 7 layer OC W2000 400g fabrics, $\pm 45^\circ$ layup. Infused with epoxy Huntsman LY 1568/3489.

The next aspect to take into account is maintaining a uniform load introduction during the fatigue test. In some cases the tabs will delaminate, due to glue failure, which will influence the load introduction and the stress state in the gauge length. In order to avoid this problem, the tab material was glued on the panels with a controlled bond line of 0.2mm using PU adhesive from BASF (Elastan 6581/131) and 0.2mm diameter glass balls. This glue has a high fracture toughness, especially in Mode II, which resist during fatigue. The glue properties have been measured in a joined project between DTU and BASF.

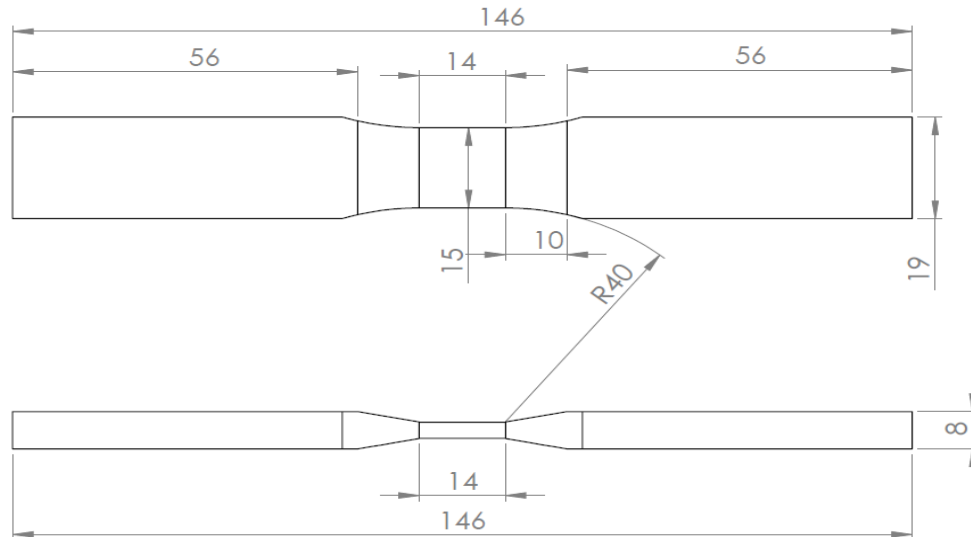


Figure 3: Test specimen geometry

2.4. Compression fatigue

Compression fatigue is a complex test as explained above, different parameters need to be taken into account while setting up the tests. The first issue to be faced is the E-modulus measurement prior to test. As the gauge length of the specimen is short, to avoid buckling, the constant stress state is only achieved in the middle of it. Measuring the Young's modulus with 10mm gauge length extensometers isn't satisfying enough, therefore, 1.5mm strain gauges are mounted on both sides of each specimen. Using these strain gauges permits to measure an accurate Young's modulus for each sample and therefore target the right levels. As shown on Figure 5, the SN curves in compression fatigue are really flat. All fatigue tests are run in load controlled mode (constant load amplitudes) at $R=10$, and the results are presented as normalised stress (stress/initial modulus of the test samples) versus number of cycles.

2.5. 3D X-Ray Tomography

3D X-Ray tomography scans were performed using a Zeiss Xradia 520 Versa, which allow scanning of samples up to 10cm with a resolution 100 μ m, and smaller samples with a resolution down to less than 1 μ m. For this investigation, the sample size was defined by the test geometry. Having samples 15mm wide permit to ensure good scan quality.

The main purpose of performing a 3D ex-situ tomography study is to identify and follow the compression damage mechanism occurring during fatigue testing. Fatigue tests are performed sequential in the fatigue test fixture. After each fatigue sequence the test specimen are removed from the test machine and mounted in the scanning fixture and scanning are performed to follow the damage progression. In order to be able to scan the same volume special attention needs to be put to the mounting of the sample in the scanning fixture. As shown in Figure 4, the fixture was designed in order to place the specimen in the same position for each scan.

The parameters used to obtain the scans presented in the following parts are collected in Table 1.

Objective	Binning	Exposure time (s)	Filtre	Voltage (kV)	Field of View (mm)	Distance to detector (mm)	Distance to source (mm)
4	2	16	LE3	60	18.3	60	22

Table 1. Scan parameters used during experiments

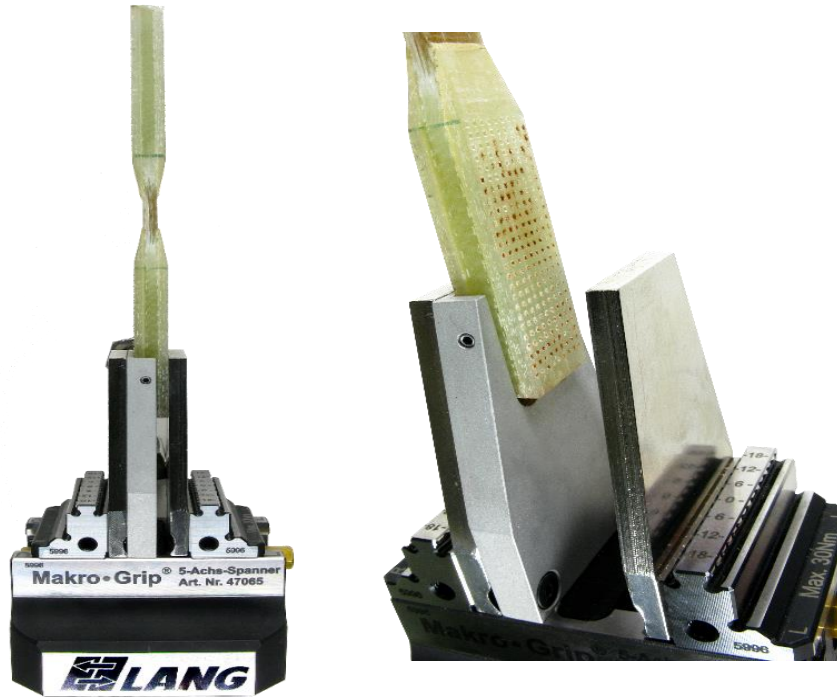


Figure 4. Specimen holder for 3D X-Ray ex-situ study.

3. RESULTS AND DISCUSSION

3.1. SN diagrams

Compression fatigue, $R=10$, is a complex test to perform. Only using the developed specimen geometry, it is possible to obtain representative and repeatable results. As shown in Figure 5, the variance between the different test levels is low and the data points are lying on the 50% Basquin line. Having a low variance in the test series allows a reasonable design curve. In total, 13 samples were tested in fatigue for the UD laminate and 8 for the Triax laminate. The run out of the test was defined equal to 2 million cycles.

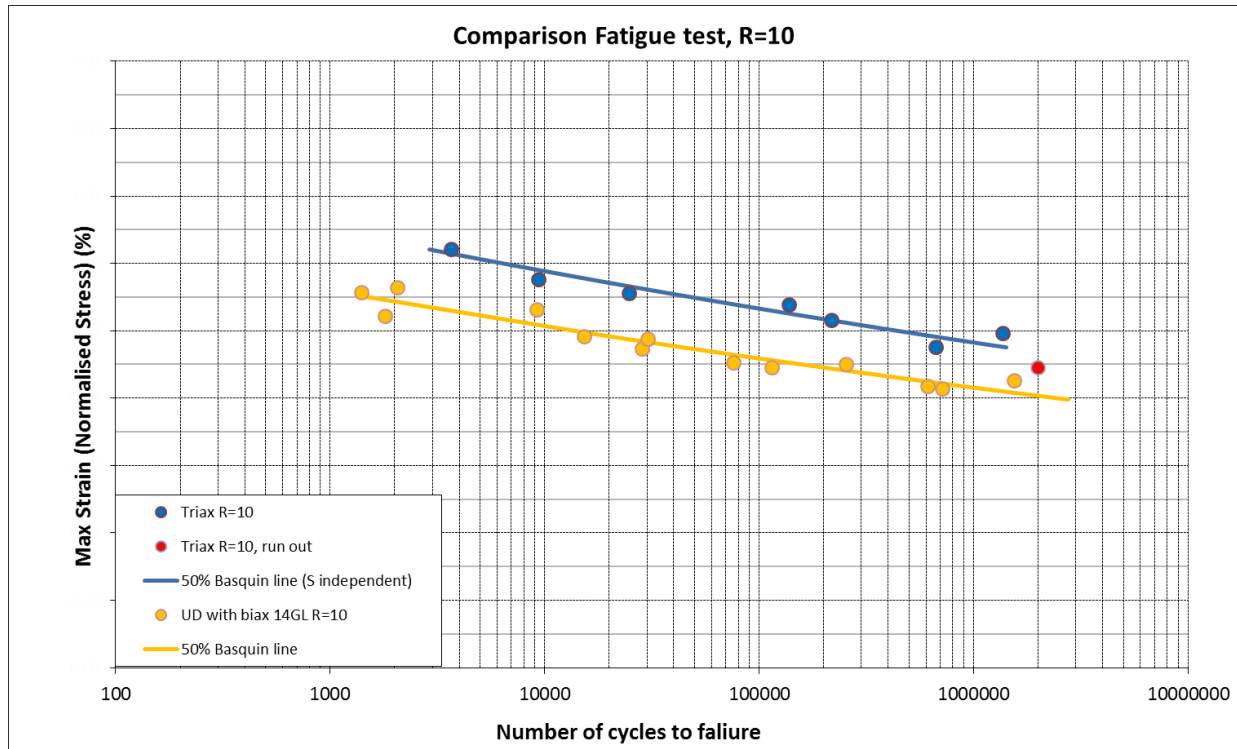


Figure 5. SN diagrams for the UD with biax and the Triax laminates

3.2. Damage mechanisms

To explore the damage mechanisms (initiation and growth) under compression fatigue a 3D X-Ray ex-situ study is started. By now a single UD specimen has been scanned four times along its lifetime. In order to determine the number of cycles when to perform the scans, the stiffness degradation curve from another sample ran at the same stress level (300MPa) was used (Figure 6). The compression fatigue test was stopped at 70 000 cycles, 150 000 cycles, 300 000 cycles and 500 000 cycles. As explained earlier, the biggest challenge faced when performing an ex-situ tomography study is the perfect alignment of the specimens in order to scan the same position. The last scan, realized at 500 000 cycles, was misaligned and therefore it could not present the damage progression; that's why only three scans cut view are shown in Figure 6.

The ex-situ study shows a clear damage development over the specimen lifetime, the cracks are located in the resin rich areas inside the fibre bundles. The crack orientation, which is close to 45 degrees, indicates that the damages are induced by a shear component. With time, during the fatigue test, the resin starts cracking due to the shear stresses. Crack in one resin rich area will release the stress in that part but increase the stress in the neighbouring resin areas, which will start cracking one after another as shown in Figure 6.

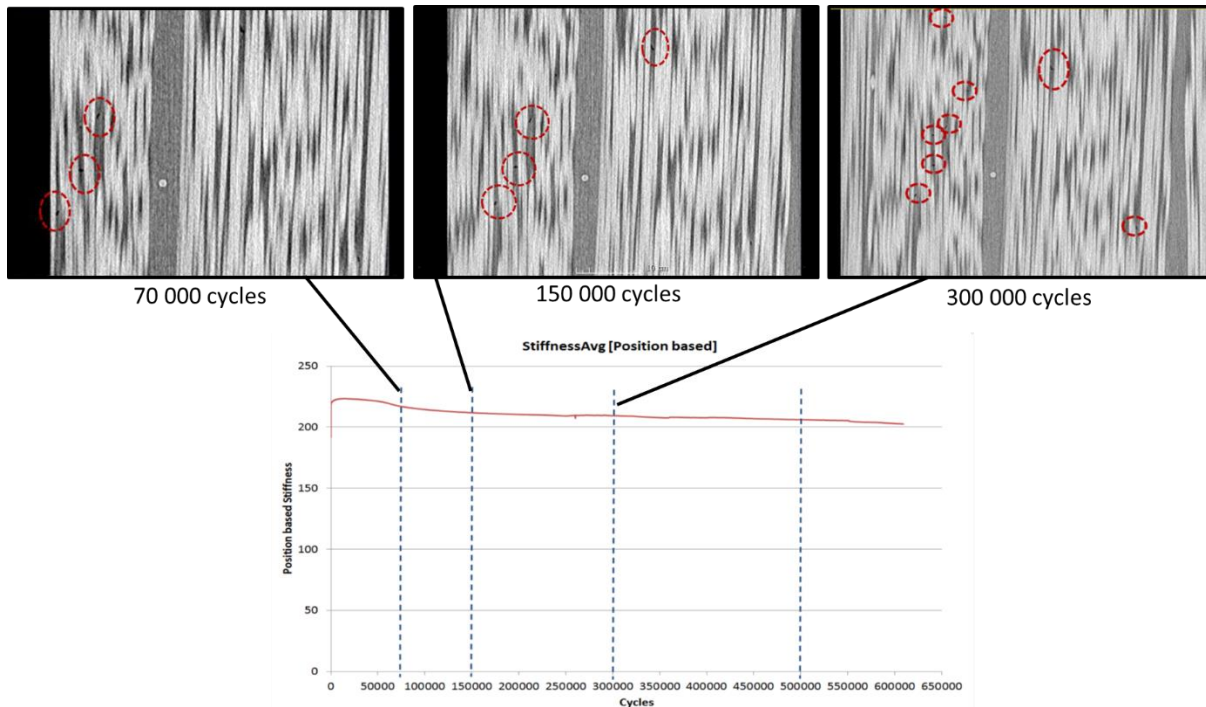


Figure 6. Ex-situ study on compression damage progression

4. CONCLUSION

Considering the results presented in this paper, it is possible to perform compression fatigue on reinforced polymer composites and obtain representative and reproducible results. Two different architectures have been investigated in this study, a UD laminate and a Triax laminate. Both of these lay ups show results that can be used to get representative design values especially thanks to the low variance between the tests. The acquisition of such results is an important improvement compares to previous reports results and database.

Until now only limited work on detecting damage mechanisms has been done. A qualitative explanation of the damage mechanism observed by 3D X-Ray Tomography was suggested. The crack development in compression fatigue appears to be linked to the resin rich region in the bundles. Due to their orientation, it is possible to define the damages as shear cracks.

In further work, the presented geometry could be used to perform fatigue on other fibre architectures and also on carbon reinforced polymers. The observation of the damage mechanisms shown in the paper is only at its start and much more focus are set on this in the ongoing work. Damage mechanisms need to be confirmed and fully understood.

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