NOVEL TEST METHOD FOR CHARACTERIZATION OF UNIDIRECTIONAL COMPOSITE FATIGUE PROPERTIES

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Abstract
The experimental fatigue characterization of unidirectional fiber reinforced plastics (FRP, UD) is highly influenced by the high anisotropic behavior of the material leading to non-valid specimen failure in the area of load introduction. The present test standards and test methods only give limited access to cover this UD specific issue. Thus, the determined fatigue properties cannot represent the full material strength leading to underestimated design values. Based on the IMA Dresden UniDirectional FAtigue (UDFA), a test method for specimen thickness up to 2 mm, an extended test method for thicker laminates should be developed. Therefore a finite element analysis was carried out in order to investigate an optimized specimen design. Further on an anti-buckling device was designed to support test specimens during all tests containing compression loads. Performed fatigue validations tests on unidirectional non-crimped fabrics with epoxy resin systems show a good correlation between standard UDFA and the extended up-scaled UDFA (Up-UDFA) method. Investigations including further design optimization and increasing of the experimental database are in progress.

1. Introduction

Fiber reinforced plastics (FRP) became one of the major materials for lightweight structural components in various applications due to their high strength and stiffness to weight ratio. In order to use the full potential of lightweight design, the characterization and determination of the static and fatigue material properties are of essential relevance. Especially for the investigation of the longitudinal fatigue strength of unidirectional composites only limited test methods and standards are available at present. I.e. ASTM D3479 [1] only give specifications for tension-tension tests with specimen geometry originally designed for static tests according to ASTM D3039 [2]. ISO 13003 [3] propose to use the standard specimen design of tensile and compression tests for fatigue (ISO 527-5A [4] and ISO 14126 [5]) for fatigue tests.

The key issue for the lack of suitable test methods is defined by the high longitudinal strength of UD composites in comparison to their low transverse strength. During fatigue tests this fact often leads to non-valid specimen failures within the tabbing area caused by the necessary high clamping loads, as

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shown in Figure 1. Thus, the determined fatigue properties cannot represent the full material strength leading to underestimated design values.

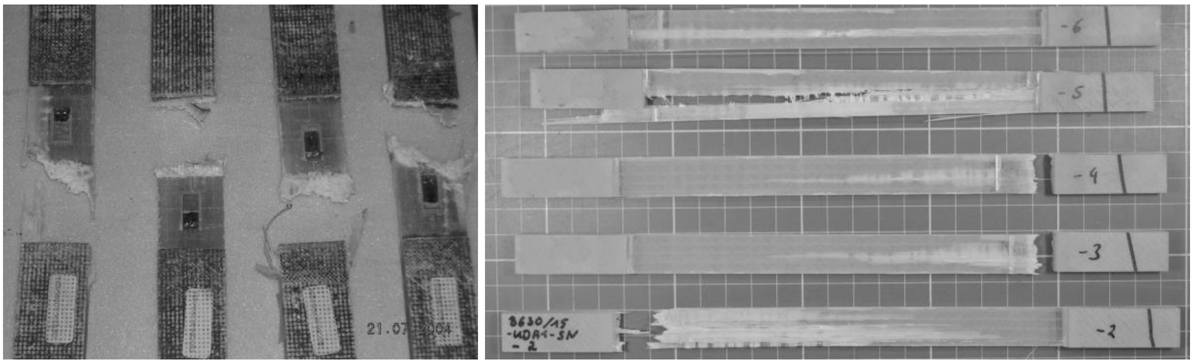

Figure 1. Invalid Fatigue Failure R = -1 (left) [6] and R = 0,1 (right)

In 2009 IMA Materialforschung und Anwendungstechnik GmbH developed the test method UniDirectional Fatigue (UDFA) which is able to test UD laminates at all load ratios for laminate thicknesses up to 2 mm. The general principle of the method is based on a tailored geometry using thickness and width reduction from the clamping area to the gage section (see Figure 3 for a detailed drawing of the specimen).

Within the recent years new non-crimped fabrics (NCF) with fiber area weight higher than 1.600 g/m^2 were put on the market for wind energy applications. Due to the high area weight a typical UDFA specimen with two remaining layers would exceed the maximum allowable thickness of 2 mm. In order to cover the ongoing demand for fatigue tests of thick laminate structures, the objective of the present study is focused on the development of a novel test method for the characterization of UD composites fatigue properties for material thicknesses up to 5 mm. The test method should also be suitable for testing all relevant load ratios, including tension-tension (TT), compression-compression (CC) and tension-compression (TC). Further requirements are listed in Table 1.

Table 1. General Definitions for Novel Test Method

Parameter	Value	Reason for Restrictions
Material	GFRP	Definition
Max. Load	100 kN	Machine Parameter
Thickness at Gage Section	5 mm	Definition
Width at Gage Section	15 mm	Definition
Thickness at Clamping Area	Max. 30 mm	Manufacturing Costs
Specimen Length	Max. 500 mm	Manufacturing Costs
Clamping Length	Max. 63 mm	Machine Parameter
Clamping Width	Max. 45 mm	Machine Parameter & Manufacturing Costs

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2. Design Optimization with Finite Element Analysis

Based on the given design restrictions of Table 1 and the characteristic stress state of the UDFA specimen geometry for comparative means, an extensive parameter study was performed in ANSYS to identify an optimal up-scaled specimen design for the increased cross-section of 5 x 15 [mm] for the gage area. The FE model included the steel loading wedge and the GFRP fatigue specimen. Both were meshed with Solid 186 elements for the simulation. The relevant regions of interest with their corresponding stress component and the stress distribution for the UDFA design are illustrated in Figure 2.

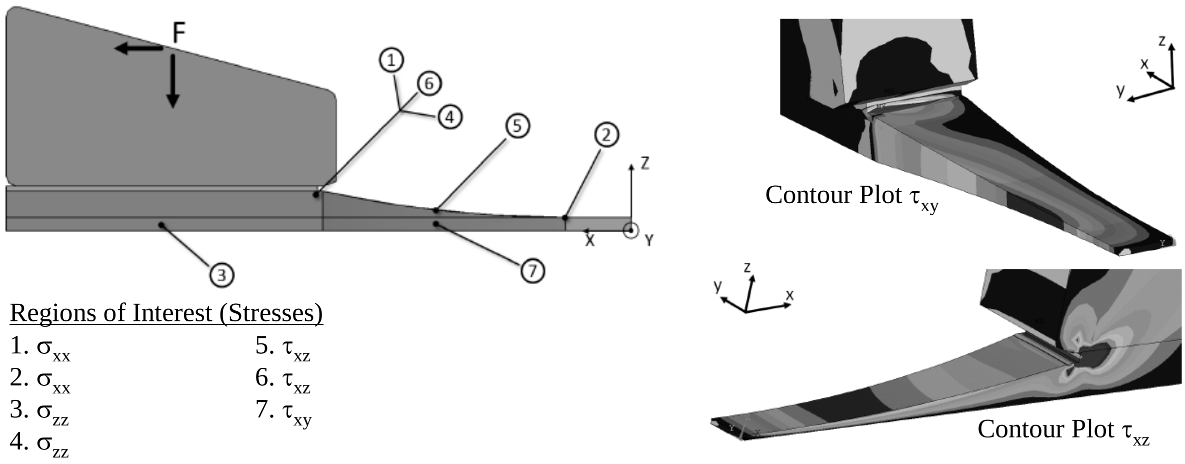

Figure 2. Region of Interest for FEA (left) and Stress Distribution of UDFA Specimen (right)

Beside the region at the clamping, the shear stresses at position 5 and 7 were of exceeding interest. These regions are responsible for a proper load transfer from the larger cross-section at the clamping to the reduced one of the gage section. Otherwise shear stresses would lead to inter fiber fracture (IFF) originating from the fiber ends in the tailored area into the specimen. The final specimen design fulfilled all geometric requirements and the resulting stresses were within the permitted limits. The geometry of the so called up-scaled UDFA (Up-UDFA) is displayed in Figure 3.

3. Materials and Processing

In order to reference the investigation to typical wind energy applications the chosen materials were standard systems used by rotor blade manufactures. A material overview is given in Table 2.

Table 2. Material Overview

Load Ratio	Fabric	Resin System	Fiber Volume Fraction	Curing Post-Curing
0,1	Glass Fiber UD (Saertex U-E-1200)	Epoxy (Resin: Araldite LY 1572 CI, Hardener: Aradur 3486 CI Blue)	54	3,5 h at 68 °C 5,0 h at 78 °C
-1	Glass Fiber UD (CPIC UD E-L1200-7-TM)	Epoxy (Resin: Swancor 2511-1A, Hardener: Swancor 2511-1BS)	56	24 h at 23 °C 15 h at 80 °C

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Following the selected materials and required number of layers for UDFA and Up-UDFA method four laminates were manufactured in total (two per material system). For the infusion process, the vaccum assisted resin infusion technique was used with an additional press support after the infusion process in order to achieve the target fiber volume fraction by adjusting the laminate thickness. After the resin infusion, curing and post-curing was carried out according to Table 2. The final specimen geometry, as shown in Figure 3, resulted from milling. During the machining special care was taken to not damage the remaining layers in the gage section.

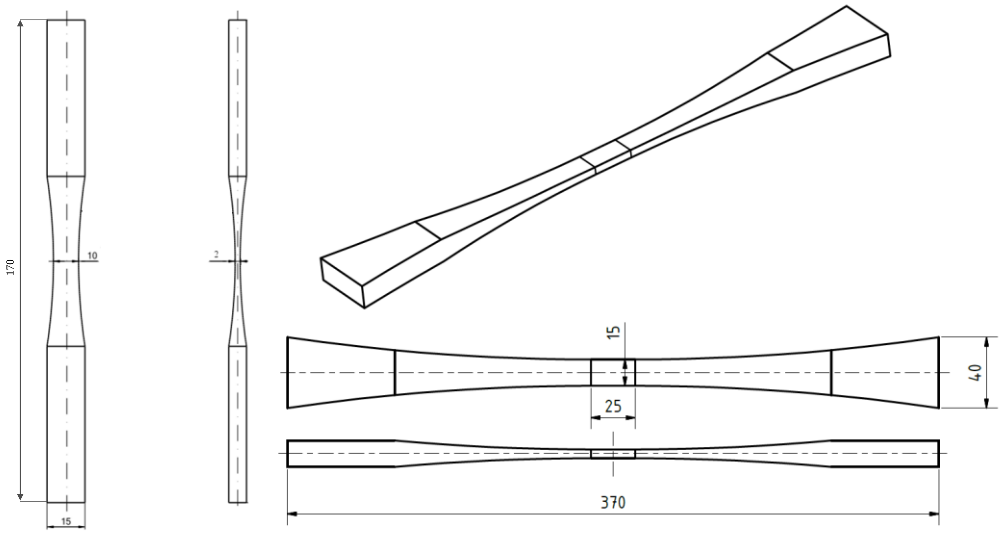

Figure 3. Specimen Geometry UDFA (left) and Up-UDFA (right)

4. Experimental Investigations

All fatigue tests were performed on a 100 kN MTS Landmark testing machine equipped with a MTS side-loading 100 kN hydraulic wedge grip. For the experimental comparison of fatigue properties of standard UDFA and Up-UDFA, S-N curves with a load ratio of R = 0,1 and R = -1 were derived for each test method at versatile load levels. An overview of the general test parameters is displayed in Table 3. The tests were carried out load controlled with a sinusoidal wave form.

Table 3. Fatigue Test Parameters

Test Series Nomenclature	Test Method	Load Ratio	No. of Specimens	Test Frequency (Hz)
UDFA_R0,1	UDFA	0,1	8	3 - 5
Up-UDFA_R0,1	Up-UDFA		7	3
UDFA_R-1	UDFA	-1	19	2 - 4
Up-UDFA_R-1	Up-UDFA		5	1 - 2

For tests at R = -1 anti-buckling devices (ABD) were necessary to prevent buckling of both specimen types during compression loading. The different devices consisted of outer steel plates combined with flexible polyurethane (PU) pads joint together by for screws. Due to the low stiffness of PU these pads enabled the specimens to freely move along loading direction. Simultaneously it supported the specimens against lateral buckling. The ABD of Up-UDFA used the PU pads only at the tailored area of the specimens. At the gage section a PTFE foil was applied. A schematic illustration of the ABD is shown in Figure 4.

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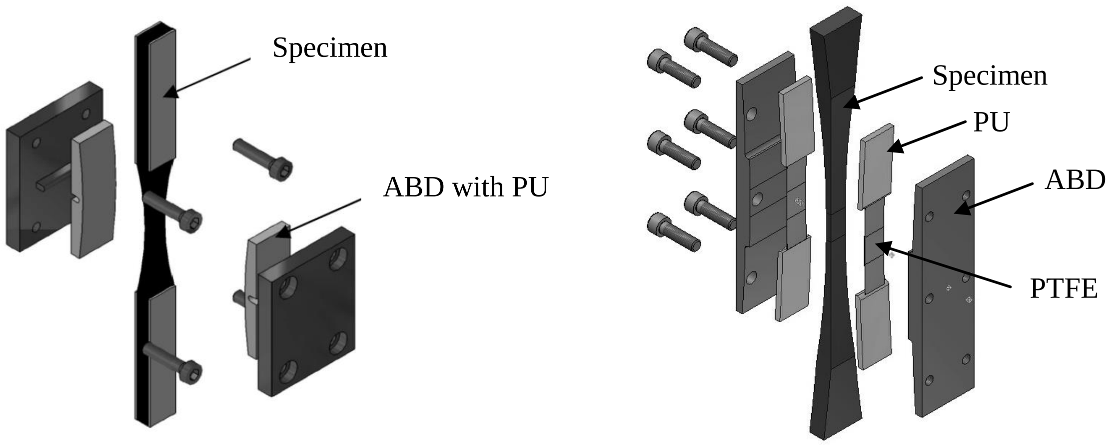
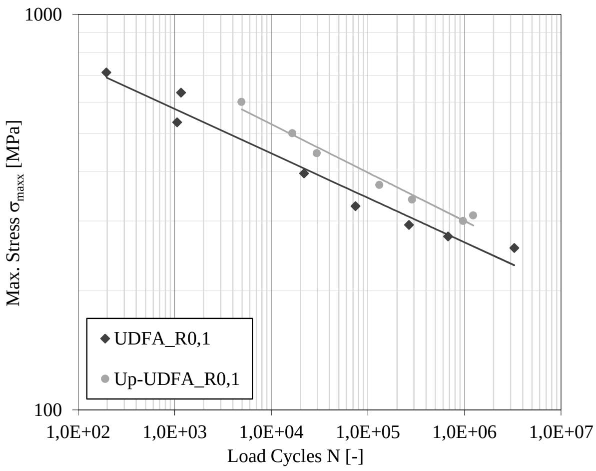


Figure 4. ABD for UDFA (left) and Up-UDFA (right)

5. Test Results and Discussion

The test results of the different test methods and tested load ratio are shown in Figure 5. The derived S-N curves for UDFA and Up-UDFA at R = 0,1 showed a good correlation with slightly higher stress level for the larger specimens. The slope values of $m_{UDFA\_R0,1} = 9{,}1$ and $m_{Up\text{-}UDFA\_R0,1} = 8{,}2$ are the result of the corresponding S-N curves. The difference in lower stress level of UDFA_R0,1 may be explained by possible material inhomogeneity, i.e. fiber waviness or local resin rich areas, which can have a larger impact on the smaller representative volume of the gage section in comparison to Up-UDFA_R0,1. The database for Up-UDFA_R-1 only consisted 5 specimens yet and further tests are currently still in progress. Nevertheless, the available fatigue results within the load cycle range of 10^4 to 4 x 10^5 are in a good accordance with the more extensive data of UDFA_R-1 so far. Thus, although the specimen thickness increased significantly from UDFA to Up-UDFA, still comparable fatigue results can be received for tension-tension and tension-compression tests.



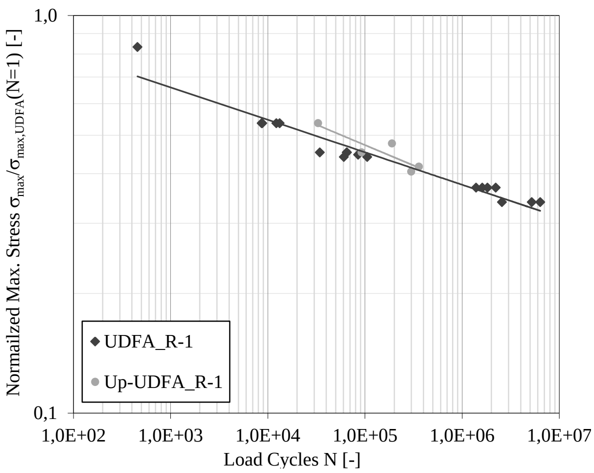


Figure 5. S-N Curve for UDFA and Up-UDFA at R = 0,1 (left) and R = -1 (right), (Data of R = -1 are displayed normalized to $\sigma_{max}(N=1)$ of UDFA Test Series due to Customer Data Property)

All test series are characterized by specimen failure in the gage section or closed by in the area of the beginning tailoring. Figure 6 illustrates an overview of the test series failure modes and some detailed

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damage characteristics. Invalid specimen failure at the load introduction, leading to low fatigue design values, caused by high stress concentrations could be prevented. The existing shear stress, as a result of the load transfer from the clamping area to the gage section, created IFF in thickness and width direction of the tailoring beginning at the end of the UD layer. These IFFs could growth during the tests into the tailoring splitting the inner UD strand from the tailoring. But as total failure still occurred predominantly in the gage section, this failure mechanism is assessed as a secondary damage process with low influence of UD fiber fatigue strength.

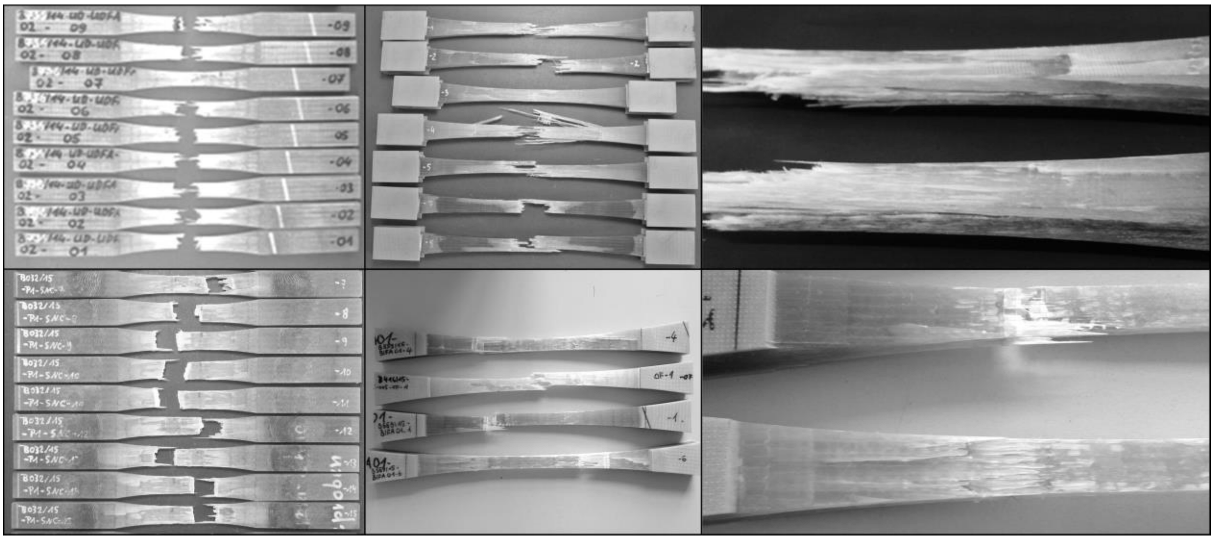

Figure 6. Failure Figures of UDFA and Up-UDFA Specimens at R = 0,1 (top) and R = -1 (bottom)

The validation of non-interaction of the ABD during compression loads was investigated experimentally using hysteresis data of stress-deflection relationship. Therefore the stress-deflection slope for tension and compression (m_{te}, m_{co}) was analyzed separately using the mid deflection d_{mid} at a stress level of 0 MPa combined with the maximum/minimum deflection d_{max}/d_{min} at maximum/minimum stress $\sigma_{max}/\sigma_{min}$. The derived values for m_{te} and m_{co} only showed a slight difference < 1%, thus proving that there was no parallel load transfer via the PU pads (see Figure 7).

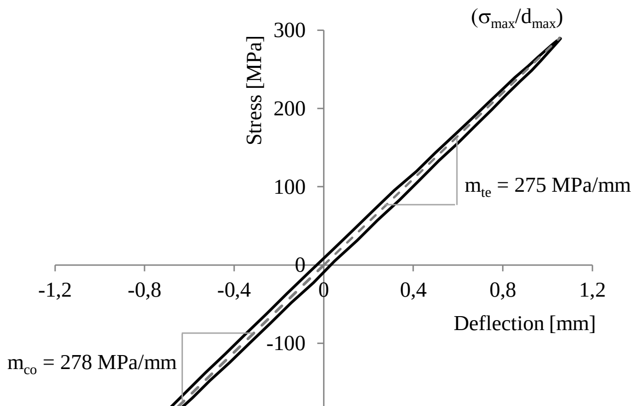

Figure 7. Stress-Deflection Hysteresis and Slope of Up-UDFA Specimen at R = -1

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6. Conclusion and Outlook

UD composites proved themselves to be very difficult for a proper fatigue characterization. The ongoing demand for representative design values combined with an increase of the fiber areal weight of NCF for wind energy applications sets the requirement for new fatigue testing techniques. Consequently the general goal of this research was the development of an appropriate test method covering the mentioned challenges.

Based on a FEA study an optimized geometry for thick UD specimens was developed called Up-UDFA. The experimental validation took placed by comparative fatigue tests deriving S-N curves for UDFA and Up-UDFA specimens at two different load ratios. The determined fatigue data of both methods were in good agreement to each other. Thus it appears that the novel method Up-UDFA is suitable for the characterization of UD composites.

Beside the current work of extending the fatigue database for Up-UDFA at versatile load ratios, further investigation are planned to exchange the thickness milling process by an near neat shape manufacturing. The aim of this research shall be to enable tailored specimens with continuous layers on the outside. Thereby the risk of IFF at the tailoring shall be reduced.

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