Influence of Loads and Environmental Conditions on Material Properties over the Service Life of Rotor Blades

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Summary
This paper presents investigations on the DEBRA-25 wind turbine blades from 1984. The weather condition and the loading of the blade are discussed and compared to modern wind turbine blades. The results of a detailed visual inspection of the blades are described. Furthermore the results of experimental investigations on the moisture content of the load carrying material, the relaxation behaviour of the coupling joints, the natural frequencies of the blade and a full scale static blade test are presented. It is shown that the loading of the DEBRA-25 service blades are comparable to modern wind turbine blades. Although some damage was found by visual inspection, the service blade of the DEBRA-25 showed excellent mechanical behaviour in the full scale blade test.

1. Introduction
The 100 kW wind turbine DEBRA-25 with 25 m rotor diameter was developed in the beginning of the eighties of the 20th century in an R&D project by the Brazilian “Centro Tecnico Aeroespacial” (CTA) and the German Aerospace Research Establishment (DFVLR), Germany. One of the main objectives in the design phase was the transport concept: The turbine including the three blades, the nacelle, and the tower had to fit in a standard 20ft container which required a separation in the middle of the blades.

The DEBRA-25 prototype turbine was erected 1984 in Schnittlingen (Germany) next to a weather station. It has been operated by DFVLR until 1991 and 4 additional years in service under the local utility company. In total the DEBRA 25 has been in operation for 18 years. Today the blades are again subject of a research project.

The DEBRA-25 blades are a unique opportunity to investigate the effects of service life on wind turbine blades. The outcome of the project poses a reality check for many of the design assumptions and guidelines within the industry. In the future, a follow-up project could focus on some of the structural details of the blade.

2. The DEBRA-25 Rotor Blade
The DEBRA-25 blades were developed by the DFVLR and built under the supervision of Walter Keller by AeroConstruct GmbH, Bundenthal (Germany).

In spite of their age the DEBRA-25 blades have an innovative and modern design. Although the load carrying “C-beam-
structure” is not directly comparable to modern wind turbine blades, the strains in the material are comparable. Furthermore the nowadays widely used concept of IKEA-bolt connections was implemented for the first time in glass fibre reinforced plastic (GFRP) in the DEBRA-25 blades.

The length of the DEBRA-25 blade is 11.6 m. Its structural layout provides a monolithic GFRP C-beam and a foam-core GFRP sandwich shear-web as main load carrying parts. The same sandwich structure has been used for the trailing edge shells to avoid buckling (see Fig. 1). The monolithic C-Beam has a thickness varying from 9.5 mm to 3.5 mm towards the tip and reinforcements leading to 45 mm at the root and 35 mm at the coupling joint, respectively.

A coupling joint based on the IKEA-bolt principle was implemented at both sides of the separation in the middle of the blade (see Fig. 2). Additionally, the single shear web of the blade was divided into two parts in this area of the connection in order to provide a smoother load transition across the blade’s section in the vicinity of the coupling.

2.1 The First DEBRA Project 1981-88

In the years 1981 to 1983 the DEBRA 25 was designed, constructed and erected at the “Ulrich Hütter” test station of DFVLR in Southern Germany. The objective of the research project was to develop a suitable wind turbine that could easily be shipped and erected at remote sites world-wide. Additionally, the turbine had to be capable of performing in low wind areas and the entire turbine had to be manufacturable with present technologies in both participating countries.

In addition to the design, which was based on the further developed load assumptions of Hütter, specimens of the material used for the rotor blades were tested, creeping tests, a static and a fatigue test of the IKEA-connection were carried out, a static and a fatigue test of a test rotor blade was performed and the first natural frequencies were determined [1]. After the erection the prototype machine was commissioned, extensively optimised and tested until 1990, including power curve and mechanical load measurements [2].

The test station and the prototype turbine were transferred to the local utility which operated the DEBRA 25 until 2002. In this year a 1 MW turbine was erected very close to the DEBRA 25 and the building authority stopped the grid operation. The rotor was idling until 2006 when the turbine was dismantled and the rotor blades transported to Bremerhaven.
The main advantage of using the rotor blades of the DEBRA 25 is that similar materials and strains have been used compared to today’s designs, intensive tests in laboratory and free field have been carried out and all load assumptions, data and results are still available today.

2.2 The New DEBRA Project 2007-08

After almost 20 years of operation the DEBRA 25 wind turbine blades are investigated by the University of Applied Science Bremerhaven and the Fraunhofer CWMT. The objective was a detailed evaluation of a set of blades after a real time of 20 years of applied operation loads. Meteorological data are available covering the entire life span of the DEBRA turbine. These data, along with status data of operating conditions as well as representative load data collected over the years are now used to check the predicted design loads against the actual loads during operation.

These real load spectra, in combination with several structural test programs, are then used to assess the impact of the 20 years of operation on materials, especially on the fatigue behaviour of the used GFRP structures.
3. DEBRA 25 Blade Investigations

3.1 Environmental Conditions

The Ulrich Hütter test station of the DLVLR was situated close to a weather station of the German meteorological service. Thus, standard meteorological long term data before and during the operation of the DEBRA 25 are available. Additionally, wind speed up to hub height, wind direction as well as operational data and load data have been acquired in 10-minute averages and as time series in up to 200 Hz sampling rate in special measurement campaigns [2].

Fig. 3 shows the wind speed distribution as a function of height. Fig. 4 shows the corresponding wind speeds from 1985 to 2004.

The year 1987 in Fig. 4 has been used as a reference year and a basis for the following evaluation. During the operation by DFVLR [3] the different operation modes such as standstill, waiting position, load operation 1 and 2, pitch operation in load 2 have been recorded and documented well. Also the transients between the modes of operation and emergency stops have been counted. For the whole wind speed range and all operation conditions and transients representative load measurement campaigns have been measured and documented. These measurements are the basis for the load spectra evaluated for the entire life time for the blade structure presented here.

The average wind speed over the years observed at 10 m height is 4.6 m/s with a turbulence intensity of up to 14.3 % (see Fig. 4). For the fatigue loads the number of rotor revolutions, the turbulence and the wind profile are the main responsible factors during the life of a turbine. The maximum gust recorded during the tests performed by DFVLR was an increase of wind speed from 28 m/s up to 40 m/s within 1 s. During this gust the turbine operated and, due to temporary overpower, the supervisory system started an emergency stop, causing 80 % of the maximum design load at the blade root.

In total the turbine delivered 1.57 million kWh to the utility during 52,271 grid connection hours. Together with revolutions due to idling and waiting for wind the rotor added up about $1.3 \times 10^8$ revolutions. Assuming the same load level used today this can be compared with the number of revolutions expected for a typical 1.5 MW turbine of today [4]. This can be seen in Fig. 5. Normalising the range of the bending moment at the blade root caused by the movement of the blade through the field of gravity to unity, the damage of the material can be compared by means of the one Hz equivalent load. For the GFRP material the slope of the S-N-curve has therefore been chosen as $m=10$. For the DEBRA 25 blade root section the overall spectra in edgewise direction the equivalent load is 16 % higher, for the flapwise direction 60 % higher. Comparing the equivalent load of the fatigue test performed in the DFVLR laboratory in 1994, the value is remarkably close to the one of the overall spectrum.
3.2 Blade Inspection

A first inspection of the blade root and separation joint was carried out in the year 1988 by DFVLR. The pre-stressing of the bolts was checked with a torque wrench at the site where the blades could be reached by a lift. Naturally, the method delivered a wide scatter of values, however, close around the expected ones. The visual inspection gave some corrosion at the nuts of the joints in the middle of the blades.

The final inspection in the laboratory of CWMT showed a lot of cracks in the coating and filler under the cover of the separation position. After removing the coating down to the load carrying glass fibre material, no more cracks could be found. The same has been observed at the trailing edge close to the root, where large strains are usually expected. The material will be further investigated under the microscope to be sure that no micro cracks are found.

Fig. 6 shows a view of the IKEA bolt at the blade separation joint taken at the first inspection 1988, in 2008 (right side).

In Fig. 7 the gelcoat at the trailing edge can be seen. The cracks in the gelcoat are showing the softening of the laminate underneath. This phenomenon occurred at every blade likewise.

Except for visual changes of the surface a degradation of the ± 45°-laminate was not found by the visual inspection.

3.3 Moisture in the Material

For the investigation of moisture absorption of the DEBRA-25 GFRP laminates, a specimen was taken from the root section of the service blade. The thickness of the specimen was 42 mm. Several specimens were taken over the blade thickness, so that changes in the moisture content over the specimen thickness would be detected. In addition to this, a specimen was stored in water at room temperature to find out about the maximum water absorption of the material. The weight of the samples was determined and the amount of water was analysed with a TGA in combination with a water sensor.

The Materials used in the DEBRA-25 were Interglas glass wovens and a Rütapox L20 /SL resin.

Fig. 8 shows the moisture content in the thick region of the service blade of the DEBRA-25. From the single measurements for the moisture content over the blade thickness no significant gradient could be found. It can be assumed that the laminate achieved stable moisture constant after 22 years outside, being exposed to the weather conditions near Stuttgart, Germany.

3.4 Natural Frequencies

After the turbine was installed in 1984 the natural frequencies of the blades were measured with acceleration sensors. For one blade the natural frequencies have been measured within this project again. Therefore, the blade was fixed to the test rig with the original test pitch bearing. With a shaker the blade was forced into its natural frequencies with a load of ± 50 N. The results of the measurement and the difference to the data from 1984, is shown in Tab. 1. The natural frequencies on the service blade measured from the DFVLR were determined on the wind turbine.

For the first two natural frequencies in flap wise direction the difference is about 0.21 % to 0.22 %. If the values from
1984 are rounded to 0.05 the difference might be slightly higher. But the low value of the difference leads to the conclusion that the stiffness in flap wise direction has not changed due to the fatigue or static loading of the blade.

With 3.31% the difference in edge wise direction is cognisably higher compared to the flap wise direction. The lower value of the natural frequency in edge wise direction was measured after the lifetime of the blades. It can be explained due to two changes in the structure of the blade. Therefore either the mass of the blade has increased or the stiffness of the material has decreased or both. Because the natural frequency in flap wise direction has not changed and the laminate was not saturated with water (see Fig. 8), the mass has not changed. The measurement of the blade weight in 1984 and 2008 supports this assumption.

So the lower frequency is caused by a decrease of the stiffness in edge wise direction. This can be explained by the build up of the blade structure (as seen in Fig. 1). Compared to present blade designs the DEBRA-25 blade was build up with a C shaped spar. The important difference is the non-existence of UD-laminate at the trailing edge of the cross section. This leads to a relatively flexible structure in edge wise direction, because at the trailing edge only 45° laminates have been used. The laminate may have stiffened the blade for the first month in use, but after 18 years this part of the blade was softened due to the fatigue loading. With a smaller stiffness in edge wise direction this could result in a lower natural frequency in this direction.

### 3.5 Coupling Joint

For the connection between both parts of the DEBRA-25 rotor blades a bolted connection as depicted in [1] was designed. The design features 14 high quality steel bolts connecting the covers of the blades as well as two thicker bolts situated in the middle of the profile to carry the shear loads. The bolts connecting the covers had been pre-stressed with 28 kN tension load in order to never reach a tensionless situation throughout operation. It was especially interesting to examine how this pre-stress in the bolts changed through the 20 years of operation, as this type of interface design can be seen in current rotor blade designs and little long term experience exists.

To determine the state of stress in the bolts, which could not be accessed directly, strain gauges were applied on the covers close to the connection bolts. The change of the strain values was measured while the bolts were released and the blade was separated. Then a steel plate (see Fig. 9), penetrated by the bolts, was attached to the one blade part, and the bolts were again pulled and fixed to reach the same level of pre-stress as imposed during original assembly. As this loading was done in the laboratories of Fraunhofer CWMT with high accuracy, the change of strain measured can be regarded as realistic values which can be compared to the changes of strain measured while separating the blade after operation.

Keeping in mind that the actual state of pre-stress imposed on the bolts during original assembly may have varied due to the limited accessibility of the bolts, the results show a clear tendency. With a variance of less than 20% the bolts have kept up their state of stress.

10 of the 14 bolts even show a higher level of pre-stress than planned in the original design and only 4 of them show a
lower level today (see Fig. 10). The results suggest that these 4 bolts might not have been pre-stressed accurately, but future investigation must validate this assumption.

3.6 Full Scale Blade Test
At the Fraunhofer CWMT a full scale blade test was performed. The test set up is an as-close-as-possible reproduction of the set up used in March 1984 in the laboratories of DFVLR to do a static and cyclic full scale blade test (see Fig. 11). Additionally the positions of all measurement devices were reproduced as accurate as possible to ensure a good comparability between the new and the original data. A static full scale blade test was performed to 100% of the limit load and compared to the data recorded in 1984. Quiet a good correlation was found. The results of the blade tests at the DFVLR (test blade) and at the FhG CWMT (service blade) are shown in Tab. 2. The given load in the table refers to the load on the ruffle tree.

These results imply that the blade properties in flap wise direction have not changed due to the service life of the blade.

In a final static blade test the service blade withstood a loading of over 300 % of the limit load of the blade. A final brake test of the DEBRA-25 service blade was not possible with the current test set up.

4. Conclusions
From the investigation of the environmental condition the loading of the DEBRA-25 blades was calculated and compared to 1.5 and 3 MW scale blades. It was shown that the loading of the DEBRA-25 blades were comparable to these modern wind turbine blades. However even after 18 years in service (as shown corresponding to 20 years for a modern wind turbine) no significant damage was found by visual inspection as well as no significant loss in blade stiffness was found. This might be seen as hint for the good design methodology of the DFVLR more than 25 years ago as well
as the consideration of the relaxation processes in the design of the T-bolt connection.

Although the DEBRA-25 service blades still shows good mechanical behaviour further research has to be addressed to the mechanical behaviour of the sandwich and adhesive material in the trailing edge (change of the 2nd natural frequency), the strong rain erosion at the blade tip and the GFRP laminate has to be checked for micro cracking.

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References:


