

# Lifetime Prediction for GFRP Fabrics Comparing the WISPERX Standard and a Measured Spectrum<sup>1</sup>

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## Background

More than 10 years ago, the WISPER/WISPERX standard was introduced specifically for wind energy application by an IEA study group. It represents a world-wide available, non-changeable load sequence composed by measurements on various Horizontal Axis Wind Turbines (HAWT) of sizes between 10 kW and 3 MW. It was intended to use it for purpose like e.g. material comparison and methodology of lifetime prediction. Today, the development of wind turbines is focussed more on large machines, beyond about 0.3 MW. Therefore, the question may be raised whether the WISPER-standard as a mixture of fatigue loads of all possible rotor sizes reflects the damage on rotor blades of modern machines in the right way and/or whether it could be used even for HAWT certification.

Moreover, WISPER is a result from short-term measurements which were extrapolated to a fictive 2-months operational time. In the last years, DEWI Wilhelmshaven performed long-term online measurements on large machines which allow a comparative fatigue life assessment of a wind turbine now on the basis of two different load spectra.

DLR Stuttgart has developed a code to calculate the lifetime by means of a constant amplitude life diagram, the application of the linear Palmgren-Miner rule and rainflow-counted load spectra like WISPER and the DEWI measurements.

## The WISPER/WISPERX standard

The load sequence WISPER (WInd SPEctrum Reference) is described in [1]. A short review is given here. It is based on flap load measurements of 9 different HAWT's rotor blades made of different materials like steel, GFRP, wood epoxy with diameters between 11.7 m and 100 m, situated at different locations. It is the only loading standard for HAWT blades. It consists of 265.423 loading reversals, i.e. 132.711 load cycles. The WISPER sequence is a row of integers ranging from 1 to 64, with zero level at 25 and maximum load at 64. WISPERX is the short term variant with 12.831 load cycles in which the ranges below level 17 have been omitted so that the time for one lifecycle is only about the tenth part of WISPER. One cycle represents a 2-months operation of a fictive turbine.

WISPER/WISPERX are standards which are intended for comparative purposes only, like evaluating materials and structural details, dimensions, design alternatives, and lifetime prediction methods.

A lifetime prediction can be based on a rainflow-counted WISPER/WISPERX 64x64 from-to markov-matrix. A damage can be obtained by dividing the number of cycles in each matrix element by the number of cycles to failure calculated with the relevant constant life diagram. Figure 1 shows the three dimensional matrix of WISPERX.

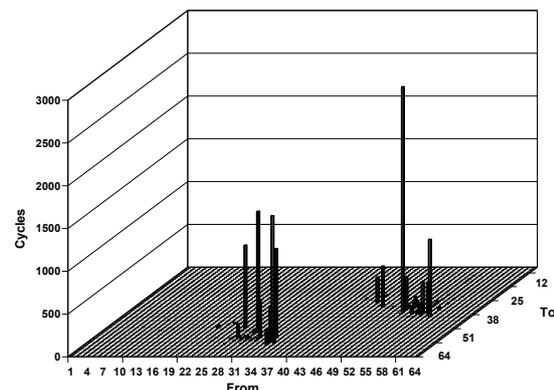


Fig. 1: Rainflow counted Markov-Matrix of WISPERX

## DEWI-load measurement

The data used in this investigation have been measured in the research project "Monitoring Fatigue Loads on Wind Turbines Using Cycle Counting Data Acquisition Systems". The project has been sponsored in the framework of the EU's JOULE II Non Nuclear Energy Programme. The measurements were carried out by DEWI in the wind farm Hamswehrum [2]. One of the main objective of the project was to prove on-line cycle counting techniques to be valuable tools in the assessment of wind turbine fatigue loads.

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The data presented below represent the flapwise and edgewise fatigue loading on the blade root of a 300kW wind turbine during a 37 days period. The data have been scaled to account for 2 months (corresponding to 2.876.458 load cycles) and have then been used for comparison with the WISPER/WISPERX standard. Although 37 days of continuous measurements may appear a long time it should be noted that within the project valid fatigue load data have been assessed for no less than 9 months on two machines.

Figure 2 depicts the meteorological conditions present during acquisition of the fatigue load data in Figures 3 and 4. As the wind turbine is situated in a wind farm it should be pointed out that the data used for comparison in this investigation have been chosen to eliminate wake inflow to the observed machine. The wind distribution shown below may be regarded as a necessary condition for a judgement on validity of the corresponding fatigue data. It shows a clear Rayleigh character with a mean wind speed of 7.5 m/s throughout the measurement period.

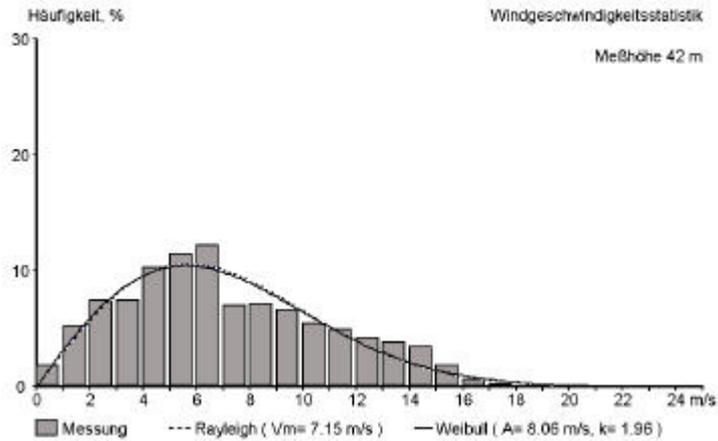


Fig. 2: The wind conditions present during acquisition of the fatigue load data reflect the Rayleigh distribution

The matrices shown in Figures 3 and 4 contain on-line rainflow counted load cycles. As the from-to matrix representation has been chosen each column of the matrix stands for a respective number of full load cycles from class x to class y and back to class x. Therefore the matrices are in fact not symmetric.

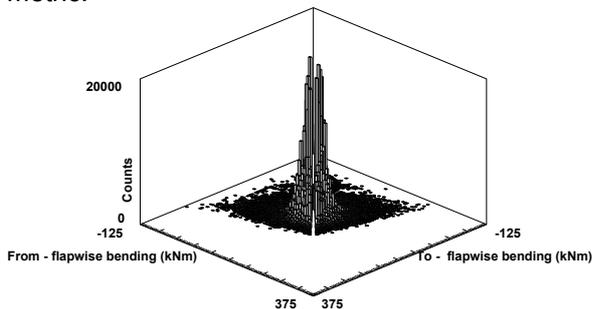


Fig. 3: Rainflow-counted matrix for flapwise bending

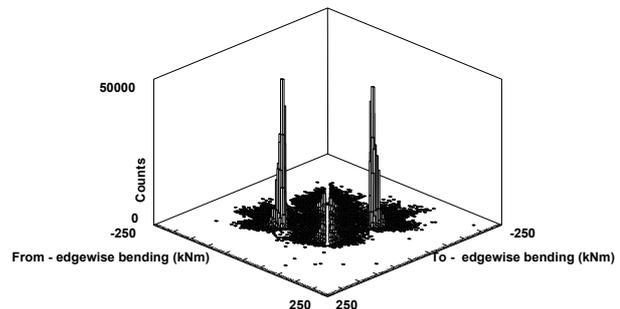


Fig. 4: Rainflow-counted matrix for edgewise bending

**Method of lifetime prediction**

In principle, the method is described in various reports, see e.g. [3, 4]. For completeness, a short review is given in the following. The basis for a good lifetime prediction are the s-n or Wöhler-curves of the materials the concerned structure is made from. By convention, they are presented in stress ( $\sigma$ ) or strain ( $\epsilon$ ) versus number of cycles n either in a lin-log or a log-log plot for constant ratios of stress R which are defined as

$$R = \frac{S_u}{S_o}$$

For fibre composites, the  $\epsilon$ -n presentation is recommended, since optimally the main fibre direction is orientated in the designed load direction. The failure strain of the whole compound is dominated by that of the fibres. Thus, via strain presentation, an objective comparison of fatigue curves of different composites is possible.

There are various methods for the statistical evaluation of the fatigue data. The linear regression in a log-log scale is very simple and achieves good results especially in the high-cycle range. This advantage is used by a method proposed by Sendeckyj [5] which additionally considers also the static test

data and the behaviour in the low-cycle range. It is based on a 2-parametric Weibull distribution including Halpin's "wearout"-model [6]. It is widely used in airspace technology and chosen also for our application. The curve is described according to the equation:

$$e_a = b \cdot \frac{(-\ln P(N))^{\frac{1}{\alpha}}}{((N - A) \cdot C)^S} \cdot e^{-\frac{U_g(P(N))}{\sqrt{n} \cdot a}}$$

It includes the consideration of survivability and the confidence limits where  $\epsilon_a$  is the maximum applied strain,  $\beta$  the scale and  $\alpha$  the shape parameter of the Weibull distribution. N is the number of cycles to failure and P(N) the probability of survival. A stands for  $-(1-C)/C$ . S defines the slope in the high cycle range. The other parameter, C, allows for flattening or steepening the curve at low cycles.

The second part of the equation considers the confidence bounds. Here is  $U_g(P(N))$  the percentage point of the survivability (Bain [7]).

The damage propagation in a composite structure is strongly depending on the amplitudes and load cycles which stochastically occur during the service life. For a fair judgement about the influence on the lifetime, a constant amplitude life (Haigh-) diagram can give information. The usual procedure is the construction of this diagram with e.g. three fatigue curves achieved at stress ratios of  $R = 0.1, -1$  and  $10$ . In our case, Wöhler curves for the shear loaded web material of a spar are taken into consideration since this seems to be more fatigue sensitive than the girder [8]. Figure 5 contains the fatigue curves for GI-Ep fabric at  $R = 0.1$  and  $R = -1$ . The tests were carried out on torsionally loaded tubes, see Figure 6. The fabrics were plain (92115 from CS Interglas), for the matrix an epoxy resin from Shell (GE162/C260) was used. The results are presented as mean values. The statistical parameters are presented as table in Figure 5.

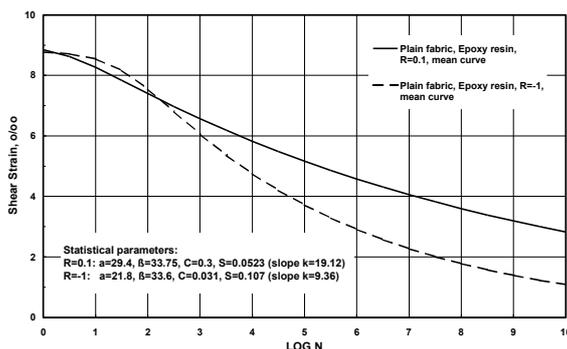


Fig. 5: Fatigue curves for torsionally loaded  $\pm 45^\circ$  GI-Ep tubes at  $R = 0.1$  and  $R = -1$  (mean values of diagonal strain)

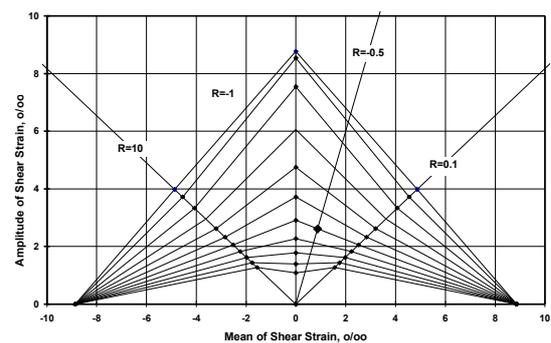


Fig. 6: Constant amplitude life diagram (Haigh-) for the GI-Ep tubes (mean values)

It is anticipated that the  $R = 10$  curve is identical to  $R = 0.1$ . Thus, for the design of the symmetric Haigh-diagram only the static strength data (identical with the scale parameters of the relevant curves) and the two established Wöhler curves are necessary, see Fig. 6.

The analytical tool used at DLR for the lifetime prediction has the following options:

- Calculation of a 2-parametric Weibull distribution,
- taking into account confidence limits of 90, 95, 98 and 100%,
- choice for different survivabilities (here: 50% survivability (mean values), 100% confidence limit),
- construction of constant amplitude life diagram,
- construction of a rainflow-counted matrix from a load sequence,
- calculation of the lifetime according to the linear Palmgren-Miner rule.

The rainflow-counted load spectra like WISPERX and that measured by DEWI are superposed with the Haigh-diagram. The damage accumulation is done by interpolation between the R-radials and the splines of constant lifetime.

## Results

The results of the lifetime predictions (mean values) are shown in Figure 7. Some test results on torsional tubes by WISPERX are also presented. They demonstrate that the prediction with the

WISPERX sequence is slightly optimistic. On the other hand, the prediction for the lifetime with the DEWI-measured load spectra is very close to the prediction with WISPERX and, thus, also optimistic. However, they are within the range of life-factor of 10 what is quite normal for the application of Miners rule.

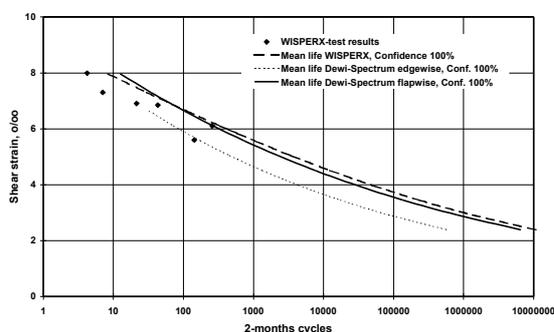


Fig. 7: Lifetime prediction for a GI-Ep fabric representing a shear web of a rotor blade spar on the basis of WISPERX and flapwise and edgewise online measurements of DEWI on a 300 kW wind turbine

Also the damage due to edgewise bending was evaluated. The resulting curve shows clearly that the damaging nature of these deterministic loads is more severe than the flapwise fatigue loads. This does not concern the shear web because that is not stressed by the edgewise loads in such a manner. But it is of importance for other structural parts of a rotor blade like the root, the leading and the trailing edge and the respective material lay-up.

## Conclusions and Outlook

WISPERX and another 2-months load spectra of a wind turbine with a well distributed wind regime were presented. Lifetime predictions were performed on the basis of

- these load spectra
- a Haigh diagram for shear loaded GI-Ep fabrics
- and the linear Palmgren-Miner rule.

The lifetimes due to WISPERX and to the flapwise load spectrum are relatively close together. This could suggest that WISPER would possibly be a tool to be used also for certification purposes. However, WISPER/WISPERX are more artificial standards with additionally one positive and one negative gust per cycle whereas the DEWI-measured spectrum reflects better realistic long time loading without "century-gust" influence, and beyond that without omission.

Therefore a need is stated for more information by long term measurements on large wind turbines which should also contain different intensities of turbulence and especially also loads by heavy gusts. This must be accompanied by lifetime calculations to compare the damage accumulation by the different load sequences. Additionally the fatigue damage due to edgewise loading should be implicated.

In the case that as a result a new standard would be the aim which eventually could be used also for certification purposes of a wind turbine, also the fatigue influence of the waves for off-shore wind turbines should be taken into account.

## References

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