NEW WISPER
Creating a New Load Sequence From Modern Wind Turbine Data

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Abstract

Sixteen years back a load sequence for variable amplitude testing of materials in wind energy applications has been defined. The sequence has been synthesized from the measured flatwise blade root bending loads of 9 wind turbines varying from18 kW to 3 MW in power and from 12 m to 100 m in diameter. Very different operating philosophies have been covered. This load sequence called WISPER has found international acceptance and is widely used in variable amplitude testing of wind turbine rotor blade materials. In the context of the EU-co-funded OPTIMAT BLADES project that aims at optimizing materials and design recommendations for wind turbine rotor blade it has been proposed to set up a NEW WISPER standard load sequence that reflects today's state-of-the-art in wind energy conversion technology. The idea is that material characteristics like fatigue life limits can be provided with better confidence for use in modern wind turbine rotor blade design when a test sequence reflecting today's turbine technology is used to establish such characteristics.

Following this line of thinking a work group within the OPTIMAT BLADES project has been formed to work out a NEW WISPER standard load sequence. The work group consisting of CRES, ECN, DEWI, DLR and WMC represents considerable experience in the field of wind turbine load determination and material testing. The paper presents the major issues that have been discussed when creating NEW WISPER. The final resulting NEW WISPER sequence is presented and compared to the old WISPER standard sequence. The comparison is carried out on the basis of the rainflow range pair load spectra, 1-Hz equivalent load calculations and even more complex damage calculations using GFRP-material Goodman-diagrams and advanced damage accumulation models.

1. Optimat Blades Project

The described work is being carried out in the frame work of the EU-co-financed research project OPTIMAT BLADES [1] . The acronym stands for *Reliable Optimal Use of Materials for Wind Turbine Rotor Blades* and the project aims to provide accurate design recommendations for the optimized use of materials within wind turbine rotor blades to achieve improved reliability. In the framework of the project structural behavior of the composite materials exposed to complex variable amplitude loading, multi-axial stress state, extreme environmental conditions is investigated. More than that structural behavior of thick laminates is examined and residual strength prediction is being investigated by developing techniques for condition assessment and repair.

1.1 Variable Amplitude Loading

With respect to variable amplitude loading the project task group has benchmarked the individual lifetime prediction methods used by the project partners for composite materials. In a second step a reference material for the actual testing work has been selected and characterized on basis of S-N curves. The next step that is at present still being carried out is to test the reference material with the known WISPER (**WI**nd **SPE**ctrum **R**eference) sequence. In parallel a new NEW WISPER is being developed and will be tested in a further experimental sequence. Finally the results from the experiments (WISPER and NEW WISPER) will be compared to the life time predictions based on damage calculations (as explained later in this paper). This analysis is deemed to give valuable input to the process of

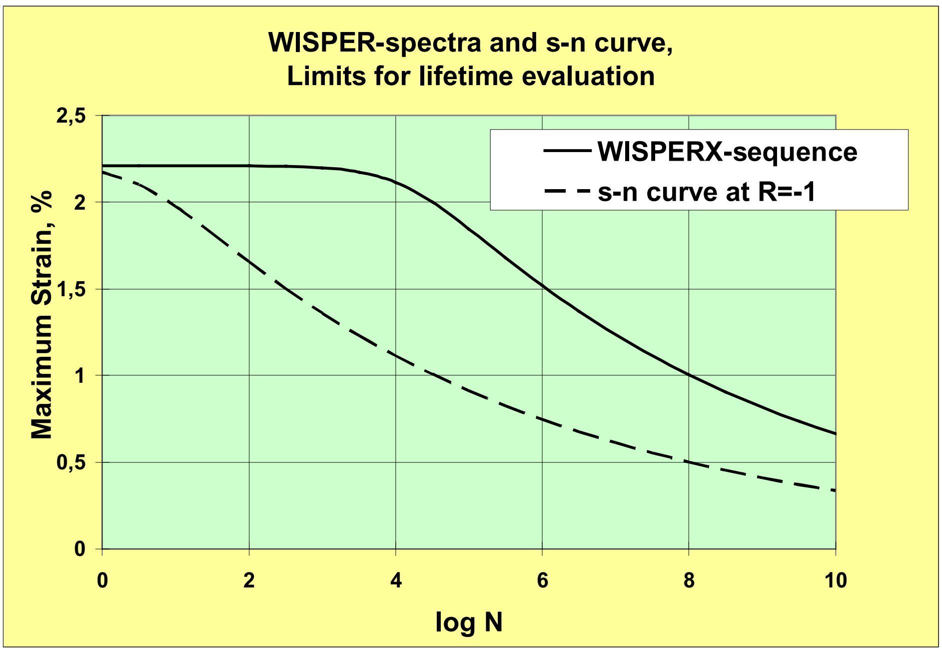

Fig.1: Number of Cycles to Failure for Variable Amplitude (WISPERX) and Constant Amplitude and R-Ratio Testing

design guideline formulation.

Variable amplitude testing is considered to be absolutely necessary as simple S-N curves (based on constant amplitude and R-ratio) insufficiently represent the interactions of large and small cycles in a realistic type of loading: when testing a specimen using the WISPER load sequence the number of load cycles (of varying amplitude) to failure for a given maximum strain level are considerably larger than for constant amplitude and R-ratio tests (see Fig. 1).

Test sequences like WISPER have been developed in other industries as well. Especially in aircraft industries the idea of standard load sequences is widely accepted as can be taken from the following examples:

HELIX/FELIX:	*Helicopters*
TWIST:	*Transport Aircraft*
FALSTAF:	*Military Aircraft*
KoSMOS:	*Light Aircraft/Sailplanes*
WISPER	*Wind energy*

2 WISPER vs NEW WISPER

The **WI**nd **SPE**ctrum **R**eference has been established by an IEA work group some 15 years ago [2]. It was based on measurements on 9 wind turbines of sizes between 11.7 m and 100 m, with blades of steel, GFRP, wood. The "dead" sequence holds 132.711 cycles in 64 load levels and is applied as a standard for comparison of materials and lifetime estimations in wind energy context. It has been derived from the flatwise rotor blade bending moments measured on several wind turbines. The WISPER sequence is largely accepted and is used by material testing laboratories, industry and the research community for comparisons of experimental and life time prediction results.

As WISPER comes of age and has been based on wind turbine technology of the early days the OPTIMAT BLADES consortium felt it was time for a NEW WISPER standard sequence that shall refer to the actual loads on today's large rotor blades that are designed with composite material blades and that are operated with modern control mechanisms. The vast majority of today's MW and Multi-MW scale turbines use full span pitch control and variable speed operating schemes. Also load measurements are more easily available and the data volumes being at hand are a multiple of those available in the days of creating WISPER.

The characteristics of the NEW WISPER sequence are:

- **8 turbines out which 6 are of MW or MMW - scale**
- **rotor diameters between 37m and > 100m**
- **rotor blades made of composites**
- 6 turbines pitch controlled / 2 turbines stall controlled
- 5 turbines with variable speed / 3 with two fixed speeds
- all turbines 3-bladed

3 The Making of NEW WISPER

In fact to describe the complete process of making NEW WISPER would be beyond the scope of this paper and hence the authors refrain to just outline the process in its major essentials. The process has been developed by the OPTIMAT BLADES work group consisting of CRES (Center of Renewable Energy Sources in Greece), DEWI, DLR, ECN (Netherlands Energy Research Foundation) and WMC (Knowledge Centre Wind Turbine Materials and Constructions) within the scope of the OTPIMAT BLADES project [3]. Generally standard techniques according to IEC 61400-13 are applied in order to achieve simplicity and transparency and to maintain confidentiality of data. The data were taken from commercial blade load measurements after permission had been acquired from the industrial parties owning them. In 7 easy steps the NEW WISPER standard load sequence for flatwise blade bending has been formed:

3.1 Step 1 (Per Turbine)

Turbine and site have to be described according to an agreed anonymous format. The data available had to be reported in capture matrices according to IEC 61400-13. For each individual capture matrix the data of the turbulence bin with widest coverage of wind speed bins had to be chosen together with those in the turbulence bin above and below. This ensures a sufficiently large data base. Lacking data at the high wind speed end had to be substituted either with data sets of the required wind speed but with turbulence out of the selected range or the data set with the largest available wind speed had to be used in the lacking bins up to cut out wind speed.

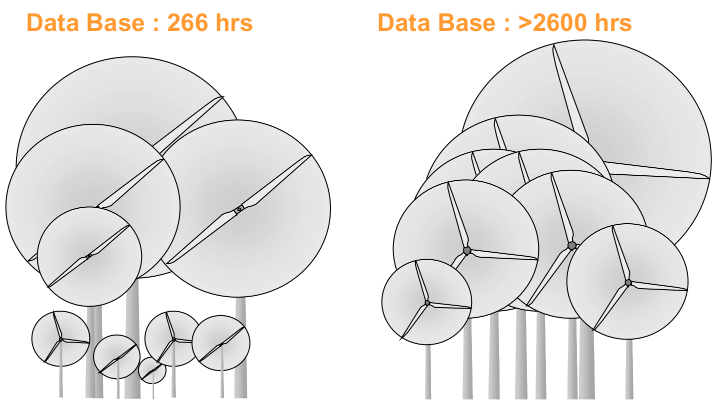

Fig. 2 : WISPER and NEW WISPER Turbines – Visual Comparison

3.2 Step 2 (Per Turbine)

The blade load data had to be normalized by dividing the actual measured value by the difference in loading between 80% and 20% electrical power output operation. This criterion proved to be working quite well for all selected data bases.

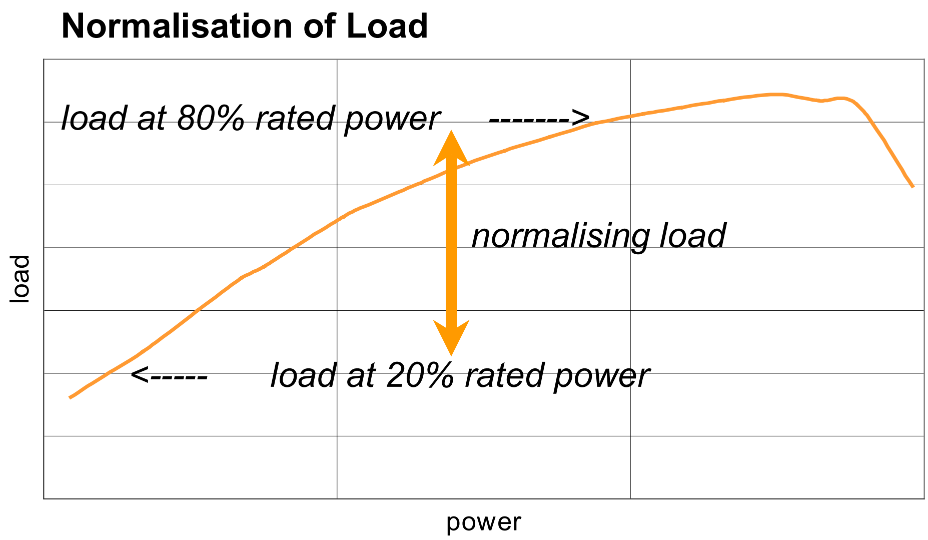

Fig. 3: Normalization of Load level

3.3 Step 3 (Per Turbine)

Using the selected data an annual cumulated Rainflow load spectrum had to be created for flatwise and edgewise blade bending. This load spectrum had to be derived for IEC wind turbine class II conditions i. e. Weibull- wind speed distribution with A= 9.59 C=2.0. In this context operation in each wind speed bin is regarded as an individual load case just as transient maneuvers.

3.4 Step 4 (Per Turbine)

As all machines have different rotor speeds and the occurrence of some loading phenomena are known to be dependent on the rotational frequency a normalisation of the cyclic content of the Rainflow load spectra was considered necessary. To do so the counts in the Rainflow matrix were to be scaled by a factor: reference number of revolutions for one year constant operation at 16 rpm / actual annual number of revolutions. It must be noted here that the old WISPER standard employed a reference rotor speed of 45 rpm!

3.5 Step 5 (Per Turbine)

Additional to step 3 an annual time series of 10-min-average wind speeds corresponding to the wind speed distribution of step 3 had to be applied for determination of the frequencies of transients and the load cycles arising from transitions from one load case to another. The annual 10-min-average wind speed sequence was taken from DEWI's wind speed measurements on a 130m-meteorological tower near the coast of Lower Saxony. The Low Cycle Fatigue loading was modelled according to the RISØ-method discussed in detail in [4].

3.6 Step 6

In this step the flatwise blade bending Rainflow Load Matrices have been merged to blend into an

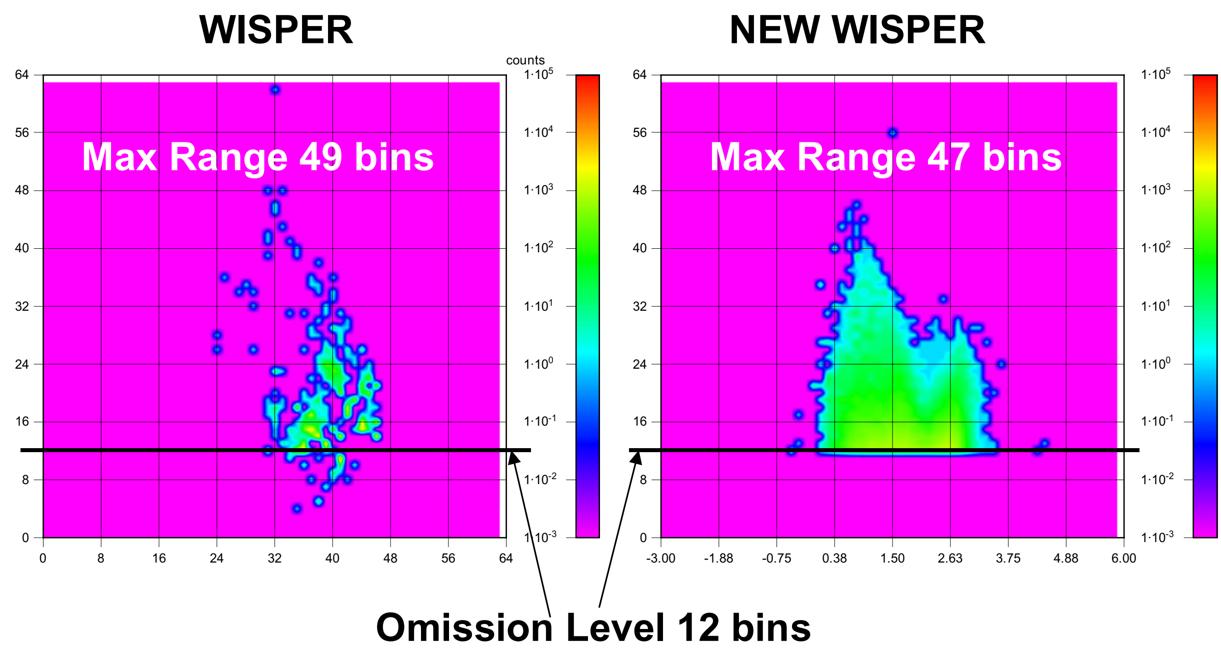

Fig.4 WISPER and NEW WISPER Range Mean Matrices

averaged NEW WISPER load matrix. This step is performed rather straight forward through summation of the individual RFL matrices and subsequent division of the matrix elements (counts) by the number of turbines.

Rainflow count on the NEW WISPER sequence will result in the identical Rainflow matrix from which it was generated.

Due to omission of small load cycles and due to reduction of the number of cycles by a factor of 6

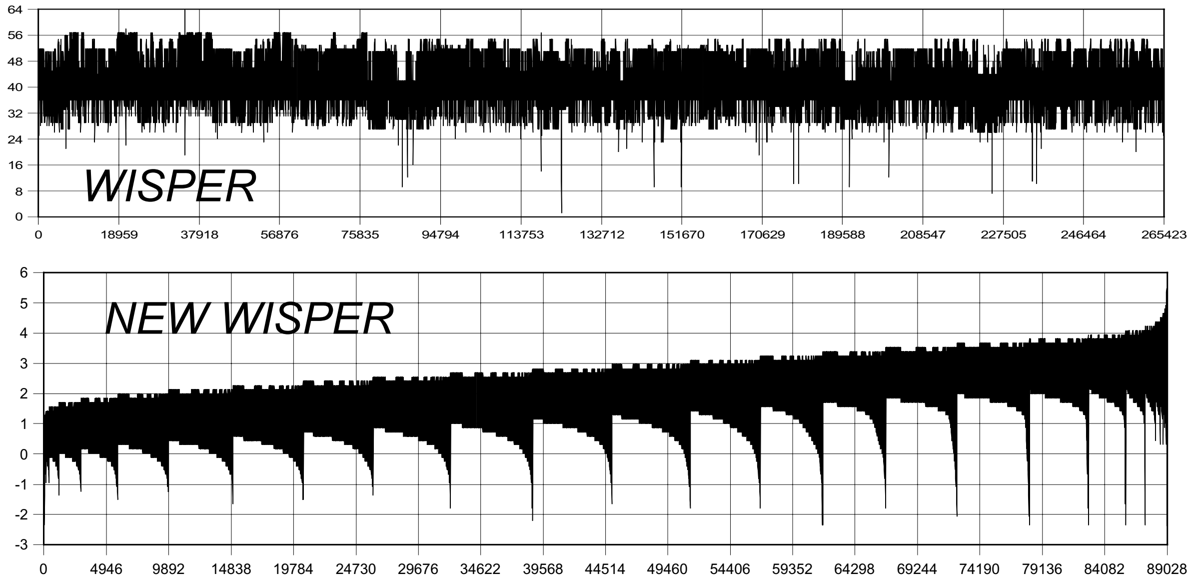

Fig.5 WISPER and NEW WISPER Sequences

3.7 Step 7

For better comparison a further step has to be taken: Omission (= leaving out the smallest load cycles with load ranges below a defined threshold) was applied to the NEW WISPER spectrum at 1.6 x normalising load level which corresponds to 0.6 x normalising load for WISPER. Also following the role model the number of cycles within the NEW WIPSER sequence was reduced by a factor of 6.

3.8 Step 8

Applying a standard rainflow equivalent routine the load cycle content of the NEW WISPER matrix was cast into a NEW WISPER sequence that looks quite different from its predecessor. As becomes clear the routine used on NEW WISPER does not involve a random scheme. Nevertheless, performing a (see step 7) the NEW WISPER spectrum holds a considerably smaller number of cycles than WISPER: 44247 vs. 132710. This difference is mainly due to the large difference in the reference rotor speed 16 rpm for NEW WISPER and 45 rpm for WISPER.

4 Comparing WISPER vs. NEW WISPER

For a simple comparison of WISPER and NEW WISPER the 1-Hz equivalent load (L_{eq} , formula given in Fig.6) has been applied on the range pair spectra depicted in Fig.6. It must be noted that both load spectra have been scaled to an equal absolute strain level at the absolute maximum load level. Table 1 gives the results obtained for characteristic materials such as glass fiber (m=10 – 12, m = S-N curve slope in log-log diagram):

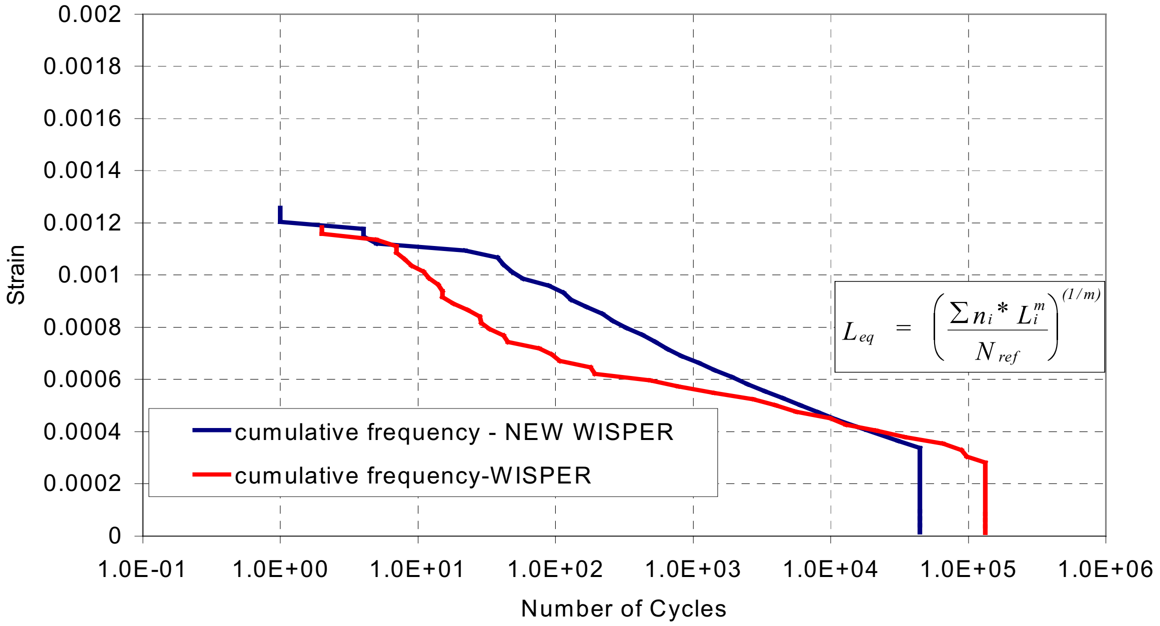

Fig.6: WISPER and NEW WISPER Cumulative Range Pair Spectra – Calibrated for Equal Strain at Max Load Level

material exponent	3	4	6	8	10	12
equiv. No. of cycles	5256000	5256000	5256000	5256000	5256000	5256000
EQL NEW WISPER	0.000087058	0.000134267	0.000218737	0.000296137	0.000367907	0.000432431
EQL WISPER	0.000104147	0.000144157	0.000205511	0.000258818	0.000318461	0.000382702
Ratio	1.196298157	1.073660754	0.939532961	0.873979992	0.865601787	0.88500231

Table 1: Equivalent Load Comparison of WISPER vs. NEW WISPER

As can be seen from Table 1 NEW WISPER has a 12- 15% higher equivalent load compared to WIPSER for material exponents >10. Cross referencing to the range pair spectra in Fig. 6 this result appears plausible as there is a larger cumulative number of load cycles for strain levels above 0.0004 for NEW WISPER. When evaluating the equivalent load for S-N curve slopes the picture is reversed: for m=3 (characteristic for welded steel) NEW WISPER equivalent load reduces to 84% of that of WISPER.

5 Rating WISPER / NEW WISPER Based on DLR Damage Calculations

To investigate further damage calculations DLR has carried out damage calculations employing experimental material data determined with a material that is typically applied wind turbine in rotor blades. The fatigue behavior of this material is characterized by means of several S-N curves at different R-ratios i.e. the ratio of the minimum applied strain to the maximum applied strain and static material parameters s. a. UTS (= ultimate tensile strength) and UCS (= ultimate compressive strength). Using these material data Goodman Diagrams or Constant Life Diagrams of specific materials are derived. From these material data for a given load cycle range the allowable number of load cycles is found through spatial interpolation and compared to the number of load cycles found in the fatigue load spectrum using linear Palmgren-Miner's Rule.

Table 3 presents the results of these computations in terms of the WISPER/NEW WIPER ratio of the Miner sum.

The computations have been performed for several stress levels and employing experimental data for a typical wind turbine in rotor blade material. The

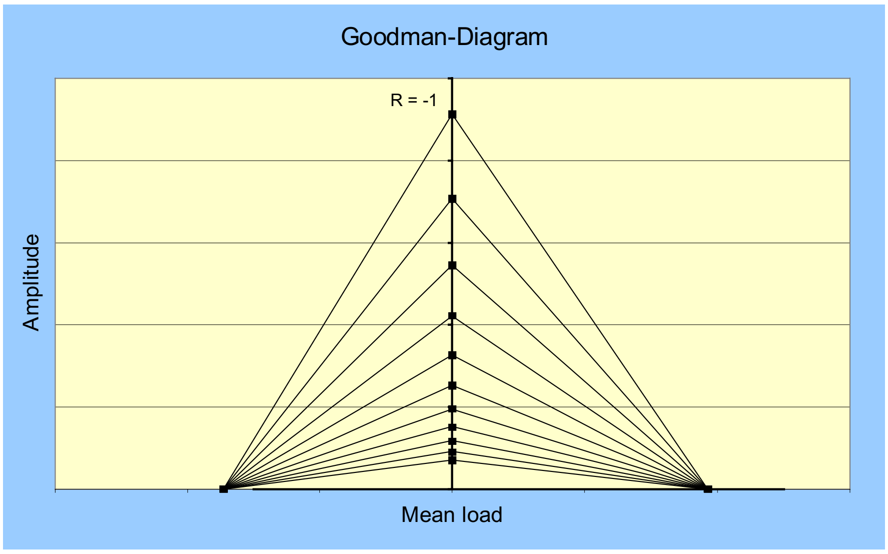

Fig. 4: Linear Goodman Diagram (Material data: S-N-Curves for R=-1, UTS,UCS - Linear interpolation between UCS/UTS and R= -1 for the individual load bins)

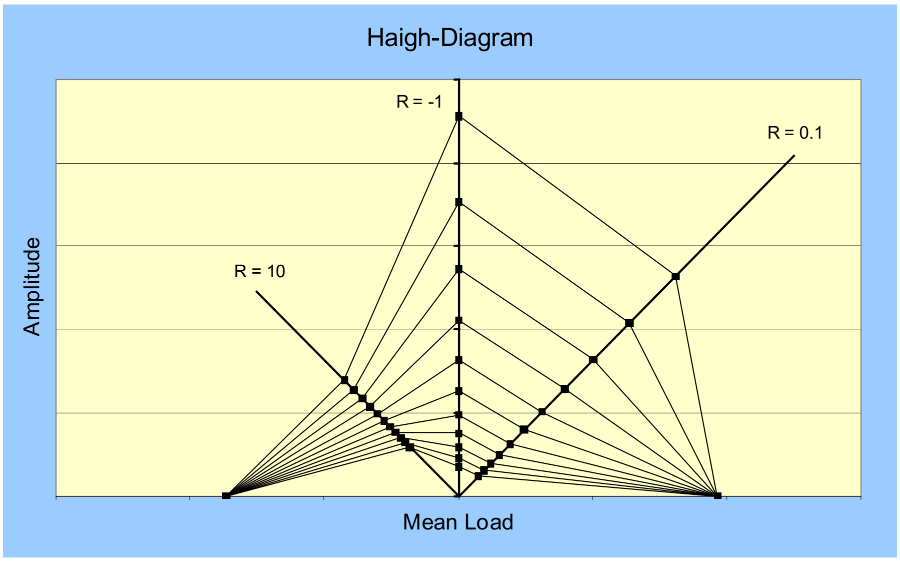

Fig. 5: Constant Life Diagram (Material data: S-N-Curves for R=-1, R=0.1, R=10, UTS,UCS - Linear interpolation between UCS/UTS and S-N-Curves for the individual load bins)

determined ratios surprisingly contradict the assessment by the 1-Hz- L_{eq} –criterion: in any case the WISPER spectrum is creating a considerably larger damage sum! Using the Goodman diagram WISPER's miner sum is some 50% to 100% larger depending on the stress level considered. The effect becomes even more pronounced when looking at the damage ratios for CLD calculations: here the old WISPER creates 4 times as much damage as the NEW WISPER spectrum.

Stress Level	Ratio Damage Sum	
Mpa	Goodman	CLD
100	153.04%	361.53%
200	184.32%	409.14%
300	228.37%	441.21%

Table 3 : WISPER / NEW WISPER Damage Sums Rated by DLR Damage Calculations

6 Conclusions

In general the authors conclude that the major goals in establishing a NEW WISPER standard sequence have been achieved i.e. NEW WISPER reflects today's wind turbine technology and at the same time is based on a very broad data base covering more than 2600 hours of measurements. Hence NEW WISPER can be considered statistically approved. Evaluating the shapes of the spectra and the sequence distinctly different characteristics s. a. smaller cyclic content, broader spread of load cycles, more damage accumulation for large material exponents are found.

Unfortunately not all damage qualifiers applied deliver consistent results: damage calculations by DLR using more complex material descriptions and considering also the mean load level at which the individual load cycle occur deliver less conservative results for the NEW WISPER sequence. This point certainly needs further attention and clarification.

Finally, the NEW WISPER sequence is Rainflow consistent but looks somewhat unnatural. The sequence is still to be approved by the OPTIMAT BLADES project partners and in the approval process the question whether or not to use random walk techniques will be discussed.

It is expected by the authors that a discussion in the OPTIMAT BLADES consortium will be led to settle the questions that have been raised.

7 Acknowledgement

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8 References

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