

The use of long term monitoring data for the extension of the service duration of existing wind turbine support structures

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Abstract. Actual wind energy converter (WEC) are designed for a relatively short service life of 20 years and the limiting criterion is the fatigue safety. However, effective fatigue loading endured by the structural components of the wind turbines (WT) is likely to be much below design assumptions provided by current codes. This paper describes a simple but efficient long term monitoring system that allows owners to verify the fatigue safety of their existing WT. The monitored data will also help to drastically extend the service life of existing wind turbine support structure and will thus reduce the global environmental footprint of WTs.

1. Introduction

Despite extensive measurements performed on WT prototypes [1], an increasing number of WEC will reach the limit of 20 years of operation provided by actual codes [2] without getting close to the limit of fatigue safety mainly because wind conditions are below the design assumptions [4]. In order to safely exceed the 20 year-service life, site-related wind conditions and their actions on structural components should be measured on existing WTs.

The monitoring system presented in this paper is installed since December 2014 on a 2.0MW Vestas V90 wind turbine [5], situated in the biggest wind farm of Switzerland (Mont-Crosin, BE). The measurement system is adapted from long term monitoring systems developed for structural and fatigue verification of existing concrete highway and railway bridges [6] [7]. Effective measurement of wind induced actions on a WT tower and wind fatigue loading is performed using conventional electric strain gauges. Environmental and operational data are also collected from the owner.

The final objective of this monitoring is to provide a model for the safe estimation of the remaining service duration of the wind turbine support structure by coupling direct strain measurement and the environmental and operational data of the wind turbine. The scheme of the proposed method is showed in Figure 1. This approach can also include a repowering of the WT with the replacement of the mechanical parts (including larger rotor, gearbox and generator).

2. Monitoring system

Various monitoring systems have already been installed on WT and focussing mainly on the vibration and the dynamic behaviour of the tower [4], [9] through the use of accelerometers. Long term monitoring was also performed in [10] and a short term method for wind force spectrum reconstruction is introduced in [4]. The monitoring presented in this paper shows a direct approach for strain measurement and



fatigue damage calculation, and provides optimal solutions in terms of sensors for evaluation of the future service duration of WT.

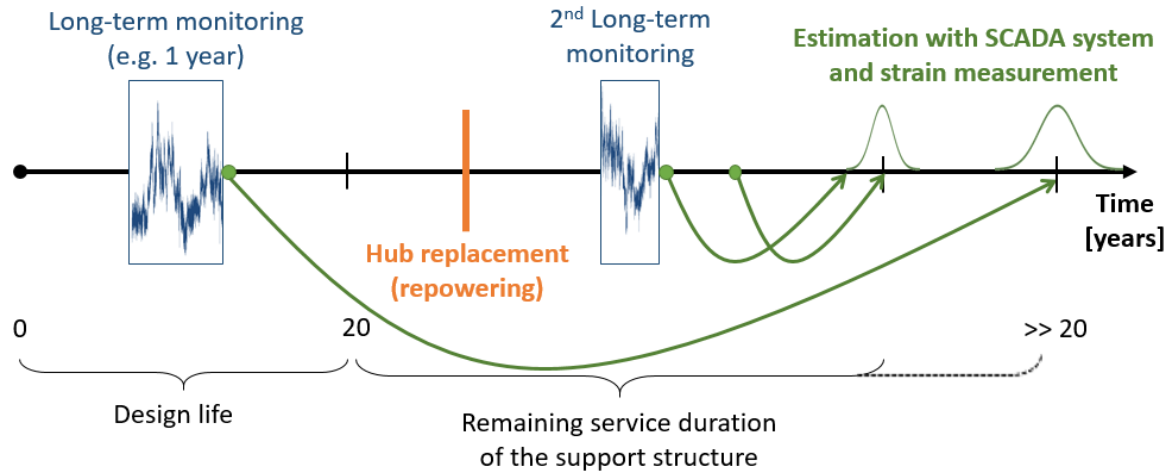


Figure 1. Proposed method for extension of service duration of the wind turbine support structure based on the use of long term monitoring of strain and operational and environmental data.

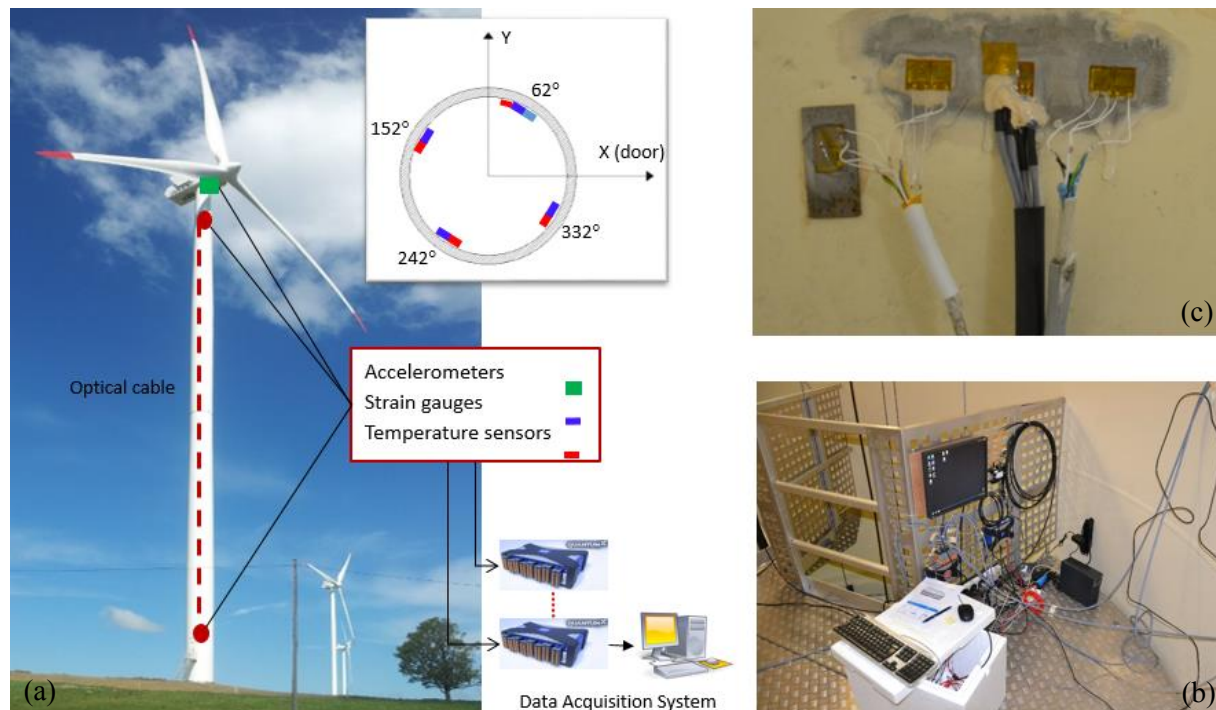


Figure 2. (a) Monitoring setup of the n°10 V90 wind turbine. Position of the stain gauges and temperature sensors at the top and bottom of the tower; (b) data acquisition installation on the first platform; (c) sensors glued to the steel mast at the bottom. Strain gauge in quarter-bridge with Pt-100 temperature sensors are compared with strain gauges in half-bridge configuration.

The monitoring system is installed on a Vestas V90 - 2.0MW wind turbine in the Swiss Jura mountains. The 95 m tall support structure is a conical S355 steel mast bolted to a concrete foundation. It is composed of four tower segments bolted together. Geometrical properties of the tower were measured in situ using a telemeter laser for the diameter and an ultrasonic device for the steel thickness

of the tower plates, as the fabrication drawings are not provided by the manufacturer. A first measurement of the tower eigenfrequencies was performed using a seismic recorder and measurement were confirmed by the accelerometers installed later on the tower. The first two measured eigenfrequencies are respectively $f_1 = 0.27$ Hz and $f_2 = 1.20$ Hz.

A first set of 4 strain gauges (3 longitudinal gauges and 1 rosette) is installed inside on the first platform, at 7.80 m from the tower foundation. Temperature sensors Pt100 are placed next to each strain gauge. The same set of strain gauges and Pt100 is installed at the top platform of the tower, with the addition of 3 accelerometers and one humidity sensor. Linear and rosette strain gauges are mounted in $\frac{1}{4}$ bridge and are protected from humidity. All sensors are connected to Data Acquisition Units (DAU) using 4-wire configuration to avoid temperature effect on the cable. DAUs from the top are linked to the bottom DAUs using a 100 m long optical cable. Data are continuously measured at a sampling rate of 50 Hz and saved on a local PC. 10 minutes series of operational data (nacelle angle, pitch angle, rotor speed and production) and environmental data (wind speed and orientation) are collected by the WT owner from the internal supervisory control system and data acquisition (SCADA) and automatically exported via a FTP server. After more than one year (385 days) of continuous measurement, 330 full days were recorded (86%). Missing days were a result of few power outage and synchronization problems.

Special attention was given to the signal treatment of the strain gauges, as the temperature is known to be the major cause of signal perturbation. Different configurations were tested (half bridge, half bridge with temperature compensation on a free steel plate and $\frac{1}{4}$ bridge) and the $\frac{1}{4}$ bridge configuration is finally chosen and the signal is post-processed to remove temperature effects. The strain gauge thermal output (difference in gauge temperature response and steel dilation) is removed by means of a thermal correction curve provided by the manufacturer, using the temperature measured on the steel surface. Eigenstresses generated by a non-linear temperature gradient (local heating of the sun) and drift of the 0 (induced by the fatigue of the gauge [11]) are canceled by using the two signals provided by the gauge couple installed at 180° . The drift of the 0 is in the order of $100 \mu\text{m/m/year}$ and the measured strain due to temperature go up to $35 \mu\text{m/m}$ and can sometimes be in the order of magnitude of the strain generated by wind induced actions [12].

After completing the 1st year of continuous measurement, the monitoring system is kept to the minimum. Accelerometers and strain gauges at the top of the wind turbine are removed. Only strain gauges at the bottom are kept. The strain is now recorded at 20 Hz and temperature sensors at 1 Hz. An accurate numerical analysis of the tower was performed with the multipurpose finite-element analysis software DIANA v9.6 and using the measured geometric properties, to determine the stress distribution in the steel plates along the tower height. Highest stresses are located at the junction between the tubes #2 and #3. Two extra strain gauges were then installed close to this critical detail in order to validate the numerical model.

3. Measurement of wind induced strains

Measurement of wind induced strains provide useful information regarding the Service Limit State (SLS) and the Ultimate Limit State (ULS) of the wind turbine tower during various events (e.g. normal operation, wind gusts, failure of the control system, etc.). Using two strain signals and the tower geometry, the force amplitude and the force angle can be back calculated. The calculated force angle compared with the nacelle direction provided by the SCADA system gives a perfect match and can be used for time synchronization between the two set of data.

Figure 3 shows the 10' average hub force versus the 10' average wind speed provided by the SCADA system during normal operation, in total 27'695 ten minutes series. The average force remains in a very narrow band around the average curve. After reaching the rated rotor speed of 14.8 RPM, the control system increases the blades pitch angle, keeping the lift force and rotor speed constant. The drag force which is acting on the rotor and is responsible for the tower deflection, is also reduced above the rated wind speed of 10.5 m/s. During the measurement period, the maximum average force is $F_{\text{hub,av}} = 256$ kN and the maximum recorded force is $F_{\text{hub,av}} = 420$ kN. Wind induced forces due to failure of the control

system (e.g. incorrect pitch) are in average lower than during normal operation. Highest wind induced forces always occur during storms, and the maximum force was recorded after 25 weeks of measurement.

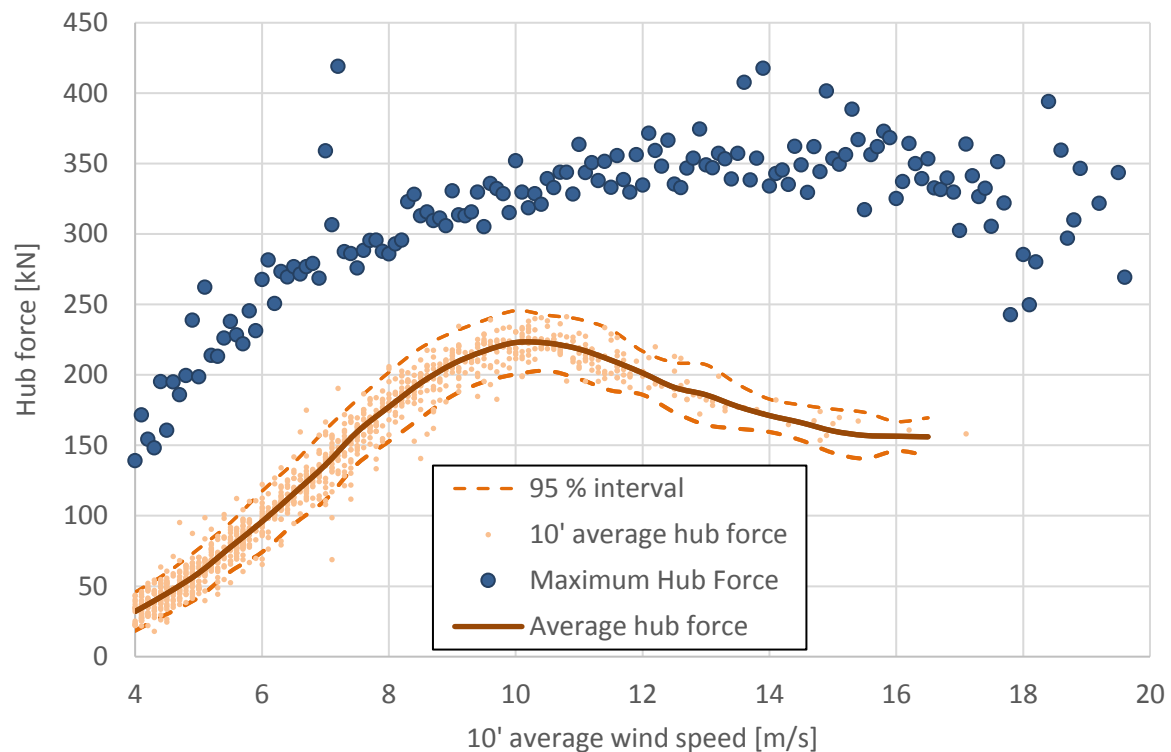


Figure 3. 10' average hub force measured during normal operation versus the 10' average wind speed. The maximum force measured for every wind speed is plotted.

4. Fatigue safety verification using long term monitored data

4.1. Fatigue damage calculation

Fatigue damage calculation is performed by combining the strain variations measured at the bottom with a FEM model of the tower. From the measured stress, a factor of 1.56 was found to obtain the nominal stress at the most fatigue relevant location, the detail between the tube #2 and #3, at 27.8 m from the foundation. This detail, used to link tower segments, is the welded connection of the tower plates with the flange. The considered detail category is 71, but further investigation in the literature could provide a less conservative value. The number of the category indicates the constant amplitude stress range (in MPa) for which the design value of endurance is 2×10^6 cycles.

Fatigue cycles are obtained by performing a rainflow counting algorithm on the measured strain data. A bin of $4.76 \mu\text{m/m}$ (1.0 MPa) was chosen to have a sufficient number of divisions. The Palmgren-Miner linear accumulation damage rule is used to calculate the total damage. The fatigue resistance of the critical detail is given by the S-N curves provided in [8]. This analysis is performed around the section (e. g. every 7.5°) for different windows length: over the full set of data, for every day and for every 10 minutes period. Figure 4 presents the 10' damage evolution over the monitoring period. It clearly shows that extreme events such as thunderstorm and wind gusts generate the highest damage. For example, 50 % of the damage happens in a duration of only 5 days. It is mostly due to emergency

shut-downs of the WT when the wind reaches 21 m/s and restarts at high wind speed (19 m/s). The total fatigue damage is shown in Figure 5 (a); the damage calculated with a 10' window is 10 % lower than the damage calculated with the daily window. This is explained by the fact that cycles with a period higher than 10 minutes are neglected, e.g. wind events of several days or slow change in wind direction.

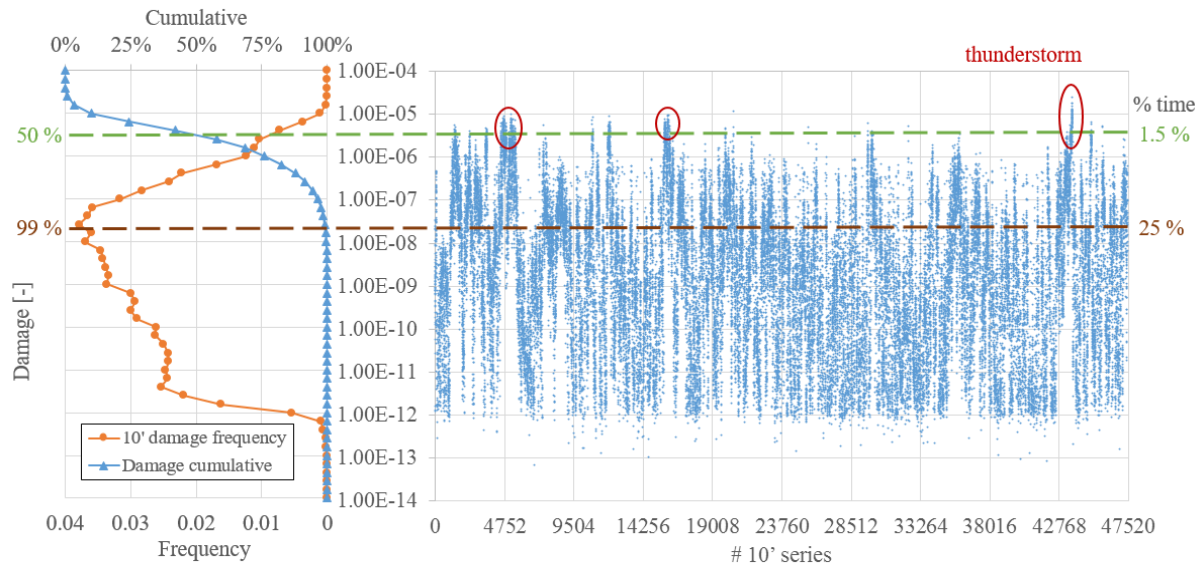


Figure 4. 10' fatigue damage calculated over the whole set of data for the 22.5° direction. The graph on the left shows the distribution and cumulative of damage.

From this calculated damage, the future service duration for the support structure can be estimated: a value of 135 years was estimated based on the data from the 330 days of measurement. This high value can be explained by the relatively slow wind speed in this area compared to the design wind speed. The average annual wind speed measured by the SCADA system for this wind turbine is 5.9 m/s, with an average turbulence intensity of 16.2 %. The estimated remaining service duration with increasing monitoring period is presented in Figure 5 (b) and clearly demonstrate that a monitoring period of only several weeks is not sufficient. The measurement period should be long enough to capture a sufficient number of extremes events (e.g. emergency shutdown during storms), e.g. several years. The future service duration will be more precisely estimated by using operational and environmental data since the wind turbine installation and will be updated after the monitoring period. I

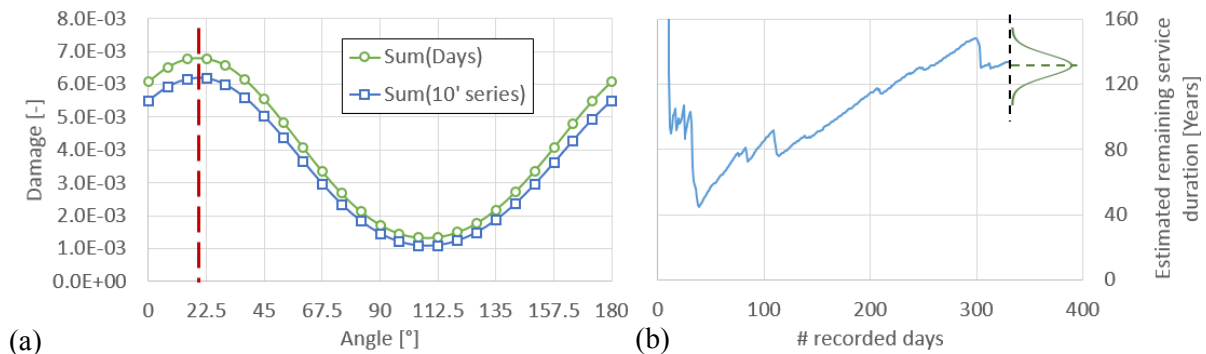


Figure 5. (a) Total fatigue damage calculated with 330 days of measurement and (b) estimated future service duration calculated over the monitoring period as a function of the number of days of measurement.

4.2. Fatigue damage, environmental and operational data coupling

One year of measurement provides an already sufficient amount of data regarding wind induced action and fatigue loading. However, the wind speed distribution can vary from a year to another, with stronger and weaker wind years. In order to consider these variations for a safe and reliable estimation of the future service duration of a wind turbine support structure, the measured data are coupled with operational and environmental data provided by the SCADA system, as these data are available since the WT installation. 10' series are clustered into different loading categories e. g. normal operation, normal operation plus fault (fault in pitch control for example) or icing on blades, by using environmental (wind speed and turbulence intensity) and operational data (power production, rotor speed and pitch angle) as shown in Table 1. Data collected since the installation of the wind turbine are used to determine the specific behavior of the wind turbine and provided useful information to design the monitoring system (e.g. main wind direction).

Table 1. Clustering of 10 minutes time series. Set of 28'360 values from December 2014 to June 2015

Operating conditions	LC	#	%
Power production $v < v_{rated}$	1.1	13'838	48.8
Power production $v \geq v_{rated}$	1.2	2'203	7.8
Power production plus fault	1.3	2'628	9.3
Start-up	2	1'711	6.0
Shut-down	3	982	3.5
Icing	4	1'779	6.3
Parked	5	4'979	17.6
-	0	240	0.8

Finally, a matrix of Wind speed – Turbulence intensity versus 10' damage series is built for the monitored wind turbine tower, including also various loading cases such as start-up, shut down, emergency shut down or icing. Figure 6 shows the capture matrix for the normal operation of the wind turbine. In order to have consistent data, the damage over the 10' window is calculated along the nacelle direction. If this information is not available from the SCADA system, the calculated angle of the wind force is used instead. Figure 6 also clearly shows that higher damage is correlated with high wind speed and high turbulence intensity. However, it takes several weeks of measurement to capture the essential data that leads to the largest part of the total endured damage.

For every specific wind speed and turbulence intensity, a normal distribution can be fitted to the – log of the damage. For example, a normal distribution with an average of 6.92 and a standard deviation of 0.41 describes the damage recorded for a wind speed of 10 m/s and 16 % of TI. With a sufficient amount of data recorded, a safe estimation of the remaining service duration can be made; this probabilistic method will be validated using the 2nd year of continuous monitoring, by using Monte-Carlo simulations for example.

Based on the 330 days of continuous strain measurement, the estimated theoretical remaining service duration (fatigue “life”) is 135 years, with a daily average fatigue damage of $2.08 \cdot 10^{-5}$. This result is the first estimation based only on the measurement period only. Some extremes events may have been neglected during the few days the monitoring system was off and could potentially modify this result. However, the use of the SCADA system can take this into account and provide a realistic estimation, by including every extremes events since the installation of the turbine. The methodology is still under validation and will be published soon after the 2nd year of strain measurement is over.

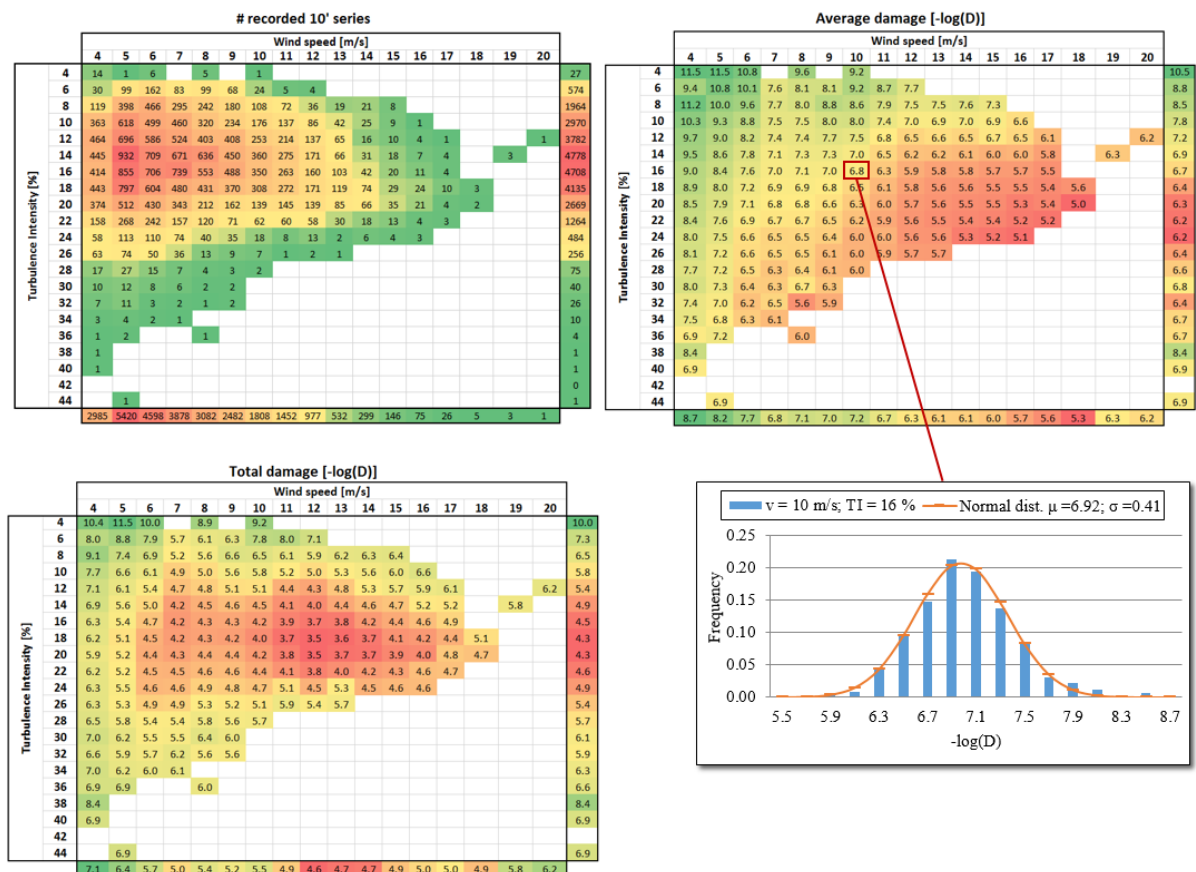


Figure 6. Capture matrix [Average wind speed – Turbulence Intensity – average damage] generated after 330 days of measurement for normal operation (# of recorded 10' series, average damage and total damage) and example of the damage distribution for a specific wind speed and turbulence intensity.

5. Conclusions and further work

Results from the measurement campaign clearly demonstrate that WT towers service duration can be extended safely beyond 20 years using a simple, robust and economic monitoring system. Monitoring provides a reliable estimation of the endured wind induced action effects and future service duration of WT towers because the in-situ wind regime, resonance phenomena, transient and extreme events as well as various failures in the control system are explicitly considered. Actual design codes are too conservative and the design assumption of a 20 year-service life should be altered. However, it is important to remember that wind turbines owners, manufacturers and insurance companies should be involved together in the process of an extension of the service duration.

Extending the service life beyond 20 years allows to continue to safely produce energy with existing wind turbine towers while enhancing the sustainability of the WT. Including the repowering from the design with conservation of the tower could also be a solution to reduce the long term cost and

environmental footprint of wind turbines. The method could also be used to increase maintenance intervals on the tower or to shorten the inspection duration by focusing on specific areas.

The large amount of in-situ data collected up-to-now from this wind farm will allow to develop realistic models for further numerical analyses and will allow for the design of new towers with a significantly longer service duration (up to 100 years). Cooperation with other laboratories from the Swiss Federal Institute of Technology in Lausanne (EPFL) and Zurich (ETH) will provide new research by combining recordings of tower deformation and wind field near the wind turbine.

Outlook: A more economic and sustainable solution for wind turbines is to develop support structures that last longer than 100 years. The exchange of the rotor/generator for a more powerful one obviously needs to be taken into account in the design process of such wind turbines. Steel towers could be designed for a longer fatigue life, but offshore environment would cause serious durability concerns of such structures in terms of steel corrosion. Wind turbines support structures built in Ultra High Performance Fibre Reinforced Cement-based Composite (UHPFRC) could overcome these limitations and allow for a more economical and durable solution for both onshore and offshore wind turbines. Further work and material testing will be pursued in order to investigate the fatigue behaviour of UHPFRC for an application to next generation of wind turbines.

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