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Farm-wide assessment of wind turbine lifetime extension using detailed tower model and actual operational history

A. Kazemi Amiri, R. Kazacoks, D. McMillan, J. Feuchtwang, W. Leithead

Wind Energy and Control Centre, University of Strathclyde, Glasgow, UK

Abbas. Kazemi-amiri@strath.ac.uk

Abstract. Lifetime extension is receiving increasing attention because of ageing asset bases, the need for efficient use of capital budgets, and the optimistic lifetime assumptions used at the project design stage. Based on the industrial attention and the overall observable reduction in subsidies for new investments and repowering, especially in onshore wind energy, lifetime extension is expected to become essential in the future. This contribution presents a methodology for life extension assessment of individual onshore wind turbine towers, as the key structural components, using the joint aeroeastic-finite element analysis and taking account of wind directionality and stress magnification around the tower door. The results demonstrate that the spread in the wind rose provide the potential for tower lifetime extension, however, the stress concentration around the tower door and site-wide variations of wind characteristics have to be also taken into account. The outcomes of this paper indicates that the wind rose dispersion can also provide a lifetime extension potential in addition to a more benign weather and operational conditions.

1. Introduction

Over the past years, wind turbine lifetime extension has been receiving increasingly attention. This is due to the fact that the European wind turbine fleet is aging and there are many farms with turbines close to the end of the design life. Moreover, the new subsidies and investments in wind energy has been shifted towards harvesting the offshore wind energy. Therefore, prolonging the service life of onshore wind turbines can be significantly profitable as an alternative for decommission. A useful review of the lifetime extension of the onshore wind turbines across Germany, Spain, Denmark and the UK can be found in [1]. The levelised cost of energy of onshore wind turbines and investment decision making for lifetime extension has been studied in [2]. Although the offshore fleet is comparatively younger than its onshore counterpart, nevertheless the lifetime extension studies are not limited to the onshore sites [3],[4].

Wind turbine lifetime extension is a very complex task and numerous factors and components have to be taken into account. The details of the life extension assessment procedure may differ from one component to another, but nevertheless, the general approach is the comparison between the estimated life under design loads with that under the site specific and operational loads. Several guidelines are available for the purpose of lifetime extension, which are mostly recommended by the industrial firms [5]–[7], but there is no commonly accepted procedure and a published standard, to date.

The existing lifetime extension guidelines propose a procedure, which is based on the assessment of the operational damage using the aeroelastic model [5]–[7]. The design reference fatigue evaluation by IEC61400-1 also recommends the same methodology. Such methodology as far as can be determined from the literature is based on unidirectional wind that leads to a conservative design. Consequently, the relation between wind directionality and life extension requires further investigations. This study applies a joint aeroelastic-finite element analysis and demonstrate the potential for lifetime extension due to the wind direction dispersion. Therefore, this study demonstrate that the lifetime extension is not limited only to a more benign operating and environmental conditions as mentioned by the existing lifetime extension guidelines. Moreover, this contribution shows that this lifetime extension potential also depends on the towers' own wind rose properties and tower door orientation relative to the prevailing wind. This is because the stresses around the tower door opening are magnified due to stress concentration effect, which can substantially increase the fatigue damage. This contribution develops and implements a methodology to evaluate the lifetime extension of wind turbines using the turbines' own SCADA data, taking account of the wind directionality and tower door opening stress concertation effect. According to the results, there is generally the potential for tower life extension under multi-directional wind as opposed to the unidirectional design assumption. However, this potential depends on the spread of the wind rose and also the tower door alignment relative to the wind seen by the individual turbine. Furthermore, the variations of wind properties across the wind farm and its influence on the lifetime extension potential is demonstrated.

2. Analysis methodology

Aero-elastic modelling is a powerful means for wind turbine response analysis under different load cases. The aero-elastic modelling is not intended for stress analysis, while finite element analysis is normally used for this purpose. As such, a joint aero elastic–finite element analysis is a reasonable analysis solution from the level of wind turbine load simulation up to stress analysis of different components under dynamic response. Figure 1 presents the flowchart of the applied procedure for tower lifetime extension evaluation in this study.

According to the flowchart, a validated aeroelastic model is required to analyse the hub loads under various fatigue load cases corresponding to different operational conditions (box 1). The hub loads are applied on the full-scale tower finite element model for dynamic response analysis, followed by stress time history simulation at different critical stress locations at tower base and around the door opening (box 2). The weather conditions information, including mean wind speed, wind direction (nacelle position), turbulence intensity, etc. can be obtained from towers' own SCADA data to evaluate the turbines' operational history (box 3). The tower fatigue life is normally controlled based on the largest damage of critical stress points under a unidirectional wind assumption [8]. As such, this is selected as the design reference damage. However, wind blows from different directions in reality, which implies that a critical stress location would be loaded at lower levels in contrast to the unidirectional design assumption. As such, the critical stress point with largest cumulative damage among various points on tower circumference and around the tower door under stress concentration effects should be identified. Finally, the damage indicator as a ratio between the reference and largest operational damage is utilised to evaluate the life extension potential (box 4). This procedure is repeated for other turbines within the wind farm. Through this procedure, the candidate turbines with the highest potential can be selected for the further detailed analysis and decision making process for the likely lifetime extension (box 5).

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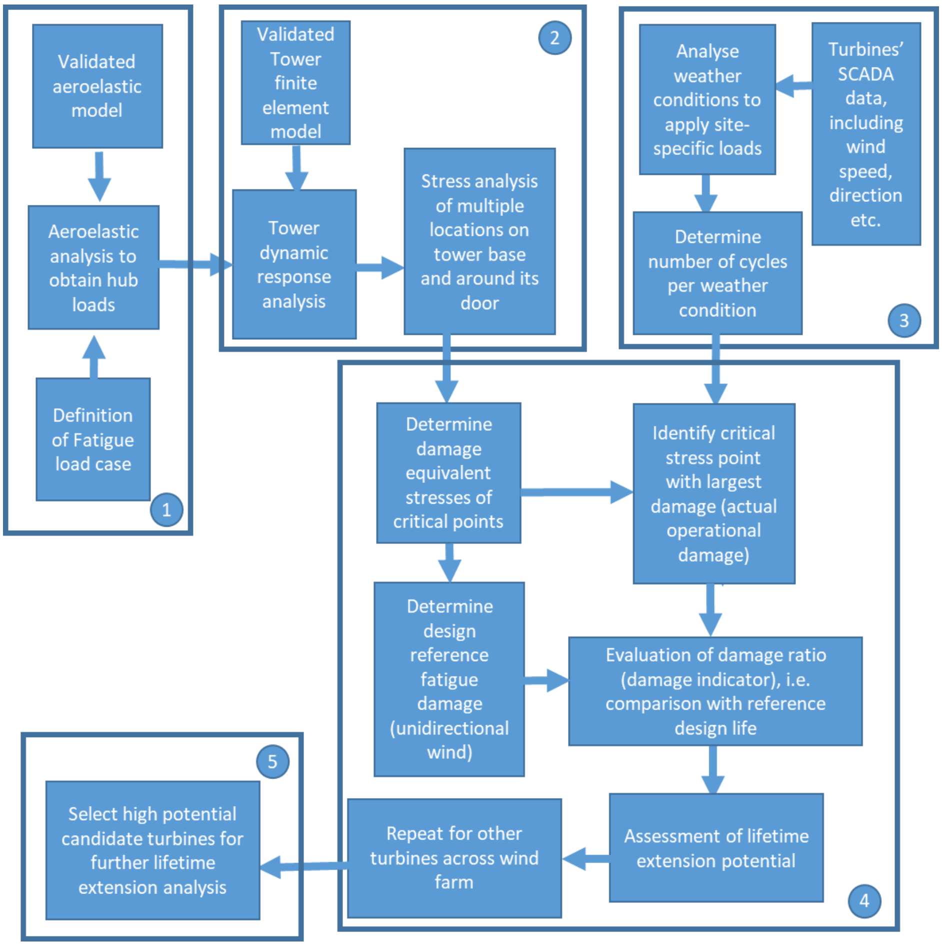

Figure 1. Step by step procedure of the applied of the applied methodology

2.1. Wind turbine Aeroelastic model and operational loads simulation

According to IEC 61400-1 standards [8], there are five design load cases (DLC) for evaluation of fatigue wind turbine fatigue damage and design life. These five DLCs correspond to design situation for power production without/with fault, i.e. (DLC 1.2) or (DLC 2.4), starts up (DLC 3.1), shut downs (DLC 4.1) and idling (DLC 6.4). In this study, the normal power production (DLC1.2) without any fault is used to produce time series. According to the base model of this study, the normal turbulence model (NTM) of IIB wind class is considered for the normal power production. DLC 1.2 characterises the wind turbine in its power production range and connected to the electrical load with normal turbulence model (NTM), where wind speed in the range from 4 m/s to 24 m/s with 2 m/s increments.

This study aims to replicate the power production loads of the actual wind turbines within an existing wind farm, to be able to evaluate the lifetime extension potential by use of the available operational data. Therefore, the base model of this study is an existing wind turbine, which is commonly used around the world. The aero-elastic model of base wind turbine model was developed by down scaling the generic upwind, variable speed and pitch regulated 3MW wind turbine model [9] by using the scaling rule with similarities [10]–[12]. The aerodynamic properties of down scaled model were adjusted according to the report developed by Carlen [13]. He performed the reverse engineering for the existing turbine to calculate the aerodynamic properties of blades of this turbine. His report includes the type of aerofoils, used in the blades of the existing turbine, and other aerodynamic properties. The key parameters of the base model are summarized in *Table 1.*

Table 1. The key parameters of base aero-elastic model

Parameter	Value
Rated power	2.3MW
Number of blades	3 blades
Rotor position	Up-wind
Control	Collective pitch
Speed type	Variable
Transmission gearbox ratio	91
Rotor diameter	101 m
Hub height	73.5 m
Cut-in wind speed	4 m/s
Rated wind speed	10.5 m/s
Cut-out wind speed	25 m/s
Rotor speed	6-16 rpm
Design tip speed ratio	9.5
Rated tip speed	75 m/s

The full model validation requires the envelope of high frequency data of the existing turbine, to see harmonic peaks and structural modes of different components of the wind turbine at the different operational conditions. Unfortunately, this information due to the confidentiality reasons cannot be published. The comparison of aero-elastic model and existing wind turbine demonstrates adequate similarities until 6P. This is sufficient for the model to be a good representation of the actual machine, as the significant fatigue loads occur at low frequencies. Additionally, the output of developed aero-elastic model is validated by using SCADA of the existing wind turbine model. Two full years of data is used for modelling in order to cover any possible weather conditions in different seasons. Figure 2 depicts two graphs that show the comparison between the output power and mean pitch angle from the actual wind turbine SCADA and the so-called artificial SCADA. The artificial SCADA is derived from the base aero-elastic model for the full envelope power production (DLC 1.2) wind speeds (from 4 to 25 m/s with 1 m/s increments) with 6 seeds per wind speed as specified in IEC standards. The artificial SCADA is obtained from the time series simulation outputs of aero-elastic model. The mean values of 10-minute time series are used for the artificial SCADA in Figure 2. The existing wind turbine is designed for the wind turbine class of IIB, which corresponds to 0.14 reference turbulence intensity and 0.2 wind shear coefficient. However, the SCADA data provided by the operator shows that the turbines also experience much higher turbulence intensities. Therefore, the simulation results of turbine operation under different turbulence intensities are also included in artificial SCADA data as shown in Figure 2. According to this figure, firstly, the operation under simulated SCADA data lies within the envelope of the turbine's power curve and secondly, the broad scattering due to the large turbulence intensity of the site is also reflected in the simulated data. As such, the developed model consistently represents the actual wind turbine.

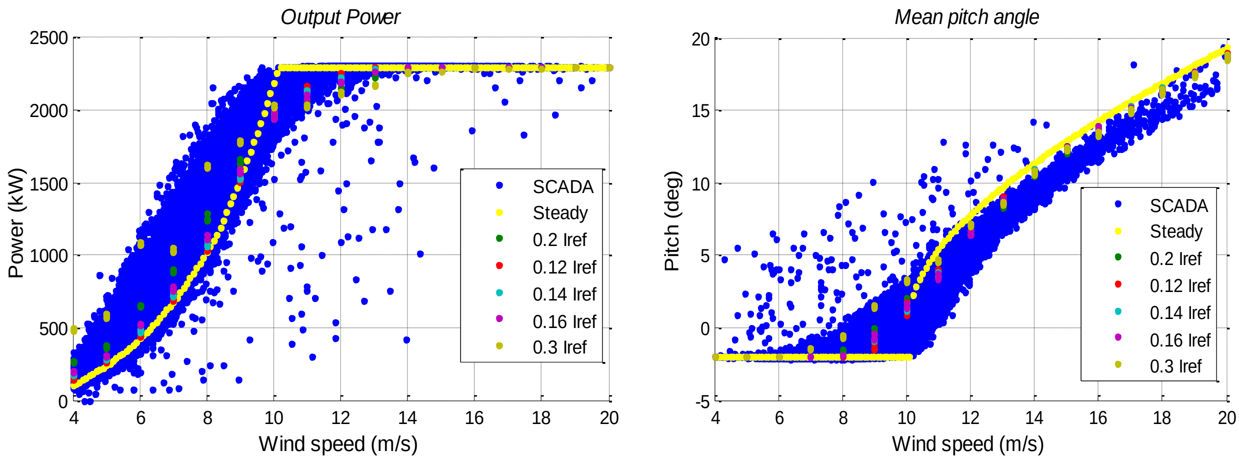

Figure 2. Power production (a) and mean pitch angle (b) against wind speed, comparison between the artificial SCADA of developed base model with SCADA of the actual wind turbine

2.2. *Tower stress analysis*

The wind turbine tower finite element (FE) model is used for tower dynamic response analysis under wind turbine loads, which is then followed by tower stress analysis for fatigue damage estimation. The tower loads are the power production turbine hub loads in different wind speeds, taking into account the tower door opening and wind directionality through rotation of hub load around tower vertical axis. The full-scale FE model of the wind turbine tower with the height of 71m is developed in ANSYS[14], based on the partially available information Figure 3. The door opening and its stiffener flange are modelled according to the detailed dimensions obtained from in situ measurements. There are some uncertainties with regard to tower FE modelling, since precise values for some parameters including rotor and nacelle mass properties, tower wall radius and tower wall thickness variations and actual mechanical properties of tower material are due to data protection policy of the manufacturers unavailable.

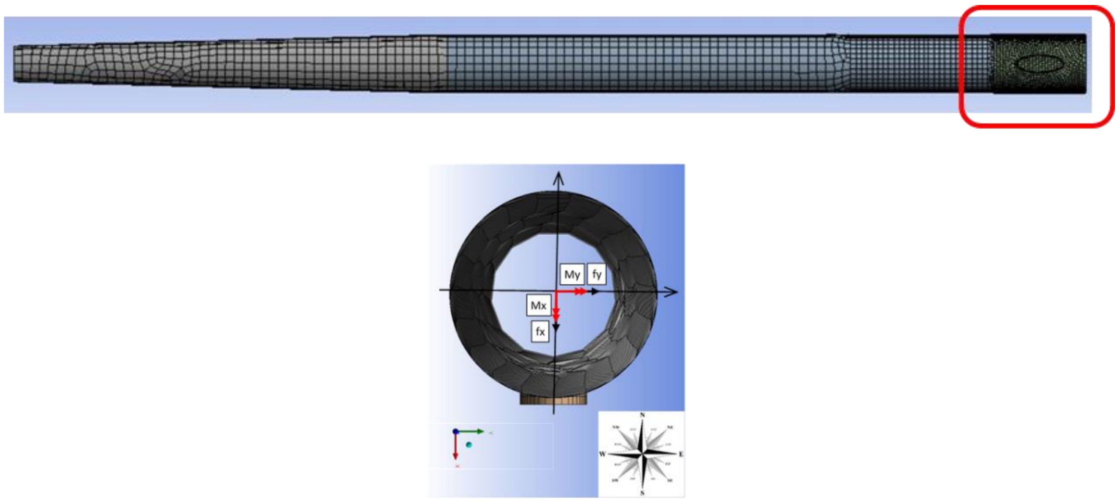

Figure 3. Tower finite element model (above), wind turbine hub loads and analysis coordinate system (below)

The tower FE model consists of about 13500 nodes and 7700 solid-shell elements (SOLSH190). Owing to the substantially large dimensions of the wind turbine model, high sampling rate of dynamic response analysis (25 samples/Sec) and long analysis time-windows (10 minutes), the finite element modelling has to be computationally efficient. Selection of a proper element type and meshing scheme for the tower model is specifically important to reach a sensible simulation runtime and disk space occupation. Sufficiently fine meshing is used in lower cylindrical part of the tower body, where higher accuracy for stress analysis at the tower base as well in the tower door surrounding areas is required. The sensitivity of the stresses in lower part of tower to mesh size is controlled. This showed that for this number of elements the average difference in stress values by reducing the mesh size is negligible. The samples of 20-second dynamic responses were simulated to find the average stress differences. Too small meshes caused too long runtimes and the storage exceedance of a normal PC. However, any approximation is expected to be cancelled out, since the proposed damage ratio (within box 4 in procedure flowchart) is the ratio of damage values.

The dynamic response is derived from expansion of the first four modal responses, i.e. two pairs of fore-aft and side-to-side modes, which capture the dominant dynamics of the wind turbine vibrations, required for fatigue damage analysis. The modal damping ratio is set to 5% for the first mode, to include the additional rotor aerodynamic damping, and 1% for the other three modes. The validity of the tower finite element model against the aeroelastic model is also checked. Figure 4 represents a sample of tower top total displacements derived from aeroelastic and finite element model at 15 m/s mean wind speed. The tower top displacement of the finite element model corresponds to the node on the tower top cross section that undergoes the largest deflection. The displacement time series as well as the power spectrum graph show adequate agreement between two displacements. The power spectrum graph demonstrates that for the fatigue damage analysis purpose, the dominant frequencies match sufficiently well, although two models are from different sources with different levels of complexity and details.

3. Results

For the estimation of the remaining useful life of the tower, the critical stress points that experience the highest fatigue damage have to be identified. According to the linear damage theory, Miner's rule [14], the cumulative damage is linearly proportional to the number of cycles, whereas it is exponentially proportional to stress levels. Consequently, it is required to check the damage at critical stress points, including the stress concentration points around the tower door, in addition to the points on the tower circumference. In order to evaluate the level of damage increase at the points around the door as compared to that at tower based, the concept of damage equivalent loads can similarly be applied to the stress time history to obtain an equivalent stress level with a constant amplitude (damage equivalent stress) [15], using the rainflow counting method with Woehler coefficient of 4. The number of cycles for the calculation of the damage equivalent loads is arbitrarily set to 600 cycles. The damage equivalent stresses are computed in 12 cardinal directions (30˚ interval) with the mean wind speeds from 4 to 24 m/s in each direction. Note that since the tower section has an axis of symmetry and due to the central symmetricity of the tower section, the damage equivalent stresses can be computed only for six cardinal directions and the Goodman's mean stress correction [14],[15] is conservatively applied where there is the tensile mean stress.

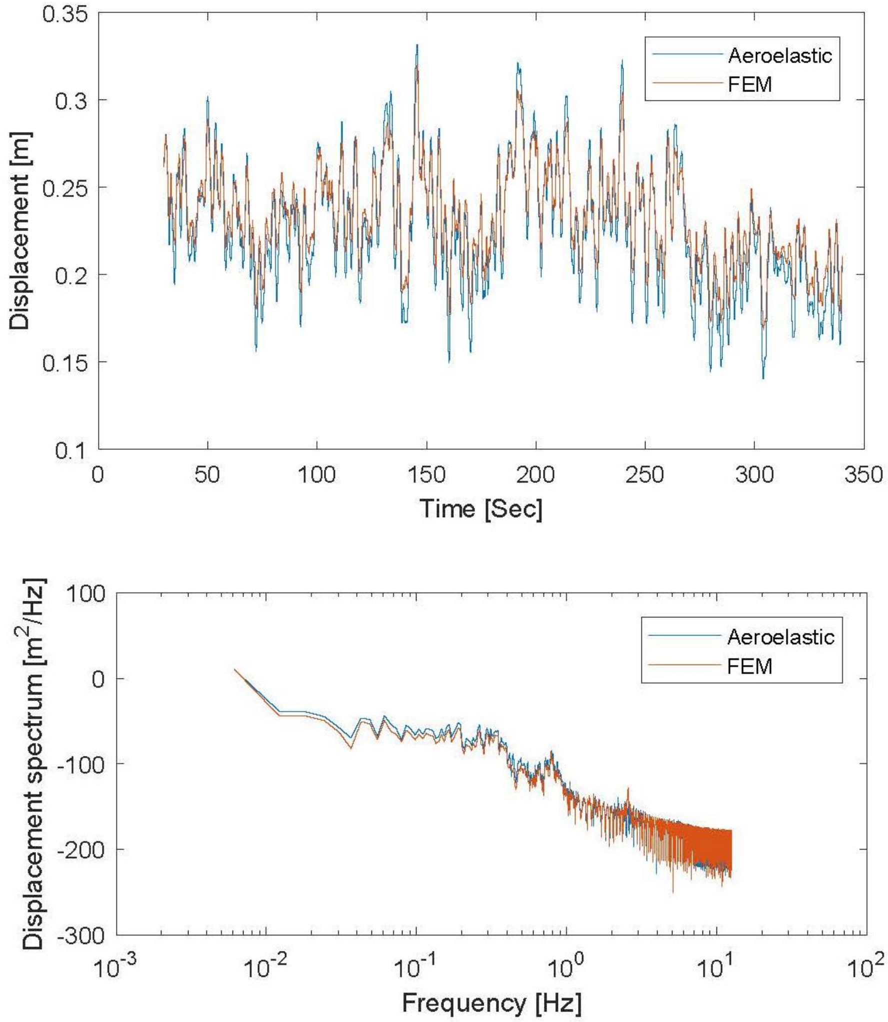

Figure 4. Comparison of aeroelastic model's tower top total displcament with that of the finite element model, time series (above) and power spctrum (below)

Through running a set of trial dynamic response analysis under wind blowing from each of the compass directions, four critical points around the tower door are detected to have stress values higher than that at the tower base within six wind directions. Two of those points are located above (DOA) and under (DOU) the door outside the tower, whereas the other two points lie inside the tower on the left (DIL) and right-hand (DIR) side of the door. Figure 5 represents the 10-minute damage equivalent stress at the critical stress points under southerly wind when the tower door faces south with and without mean stress correction. This figure compares the maximum damage equivalent stresses at tower base and other points around the door.

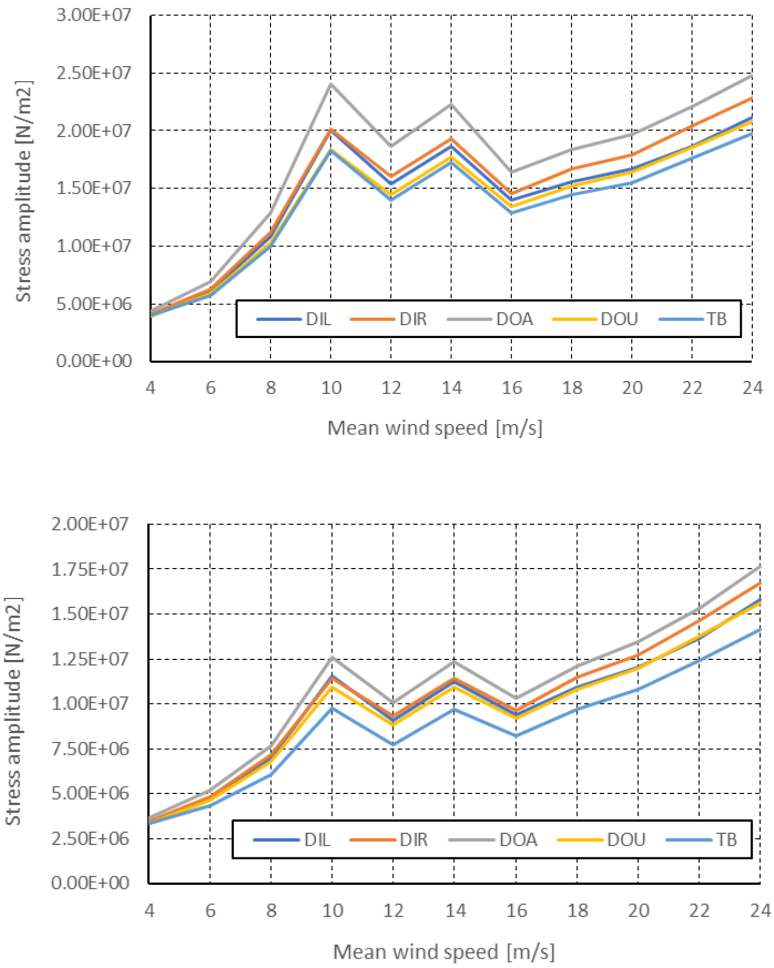

Figure 5. Damage equivalent stresses across different wind speeds with (above) and without (below) mean stress correction

This figure reveals the damage increase due to higher stresses at the points around the door as compared to that at tower base at each wind speed. The damage equivalent stresses are also higher where the mean stress correction is considered. This figure shows that DOA experiences the highest damage, while the lowest damage occurs at tower base. Nevertheless, the location of the point that experiences the highest damage will depend on the wind speed and direction distribution on site. Therefore, by changing the wind direction and the associated hub load on the tower top one can find a good picture of damage variations across different wind directions. Such an analysis helps to stablish the rosette plots of damage equivalent stresses at critical stress points around the tower door and at the tower base. The examples of theses rosette plot at 8 and 18 m/s mean wind speeds are presented in Figure 6. In the same figure, the tower top view with the red dots next to the rosette plots shows the location of the critical stress points, whose associated damage equivalent stresses are plotted. Note that the location of the point at the tower base is situated on the east compass axis on the tower circumference.

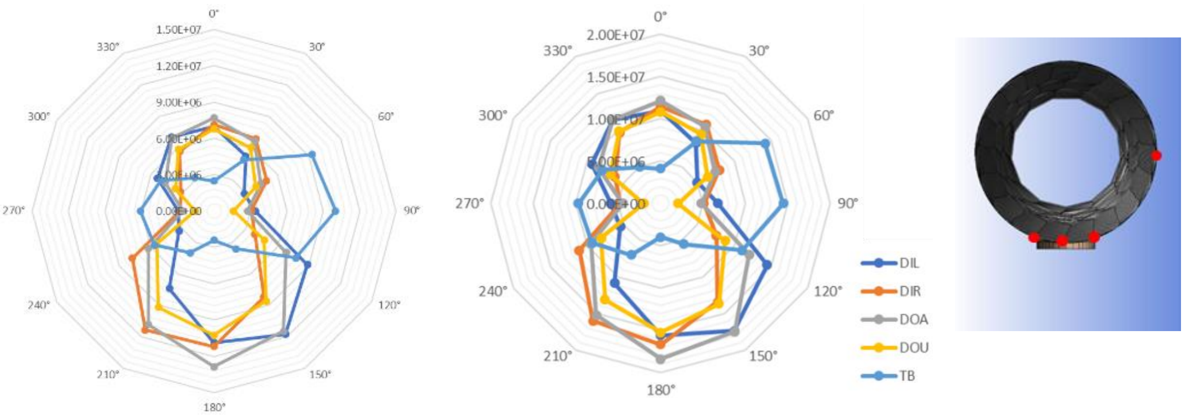

Figure 6. Samples of damage equivalent stress rosette plots at wind speeds of 8 (left) and 18 m/s (middle) together with the tower top view and representation of critical stress points (right)

Figure 7 shows the damage increase due to the stress concentration effect. This figure represents the ratio between damage equivalent stresses at DOA above the tower door opening (under multidirectional wind) and tower base (under unidirectional wind). Since the tower door has a fix orientation, it experiences different levels of damage in different wind direction. The plots with and without mean stress correction demonstrate that the damage at DOA is higher in six and three wind directions, respectively. Consequently, if the prevailing wind direction falls within these six or three directions the damage at DOA will be higher than that of tower base due to the stress concertation effect. Fatigue damage can significantly increase due to the stress concentrations, as it is exponentially proportional to the damage equivalent stress through the Woehler coefficient. Note that in case without mean stress correction the equivalent stress rosette plots becomes central symmetric, i.e. there is no differentiation between compressive or tensile stress.

The damage corresponding to the critical stress points on tower circumference and around the door opening is accumulated based on the procedure flowchart. The point with the highest damage is the driver for tower lifetime determination. An indicator is defined to be able to evaluate the lifetime extension potential (damage indicator). The damage indicator is derived by scaling the damage of the under multidirectional wind (operational condition) to the unidirectional wind along the door normal axis (design reference damage). It should be noted that according to the design guidelines the tower has to be designed for the highest possible damage, and selection of this point for the design reference is due to this fact. Hence, the damage at the point above the tower door under unidirectional wind along the door normal axis, which causes the highest damage above tower door (DOA) is assumed to be the fatigue design basis. The damage indicator indicates the amount of damage that has been spent under operational conditions. This means that the higher the damage indicator is the lower will be the lifetime extension potential.

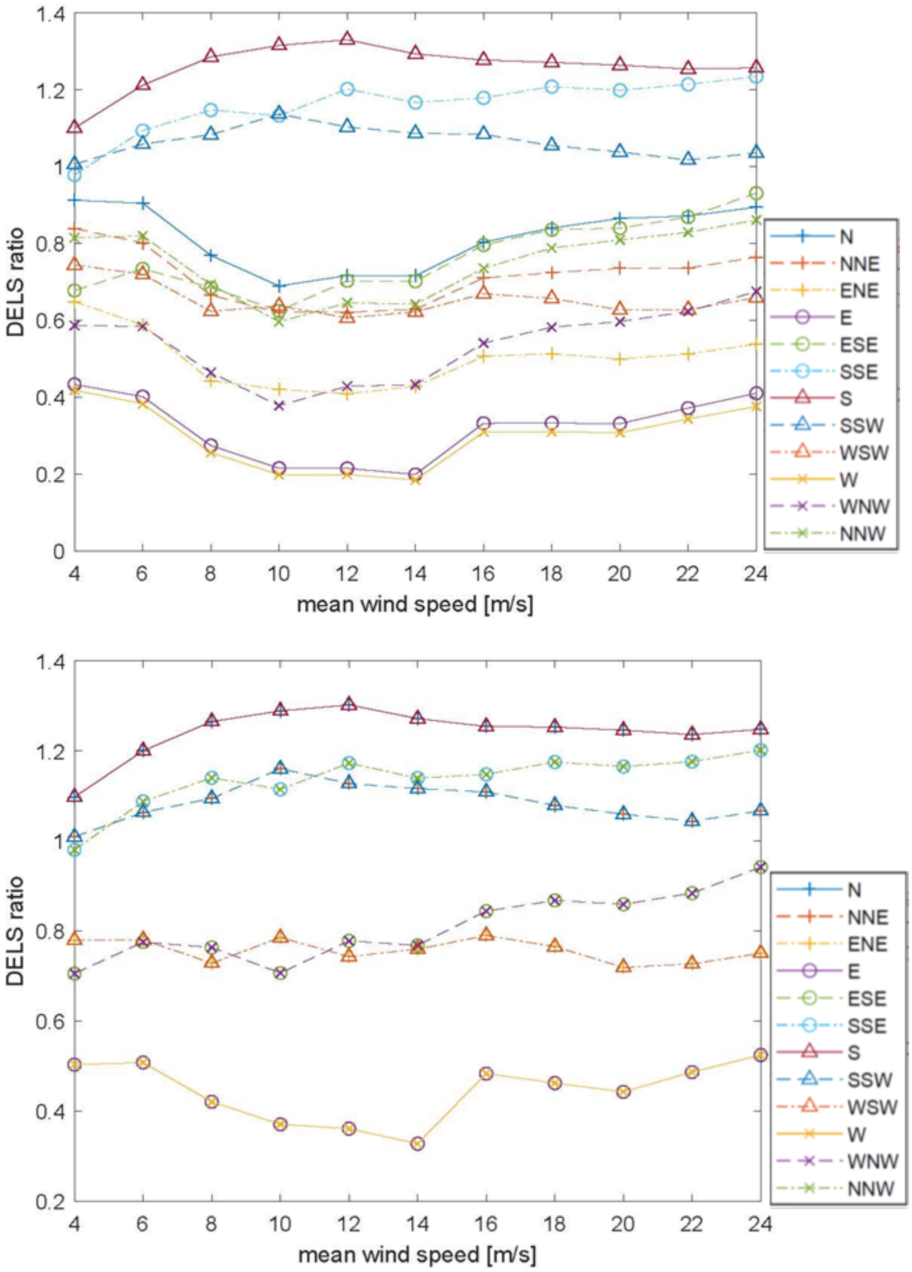

Figure 7. Damage equivalent stress magnification due to stress concentration around tower door opening, with (above) and without (below) mean stress correction

At this stage the proposed methodology for lifetime extension assessment is implemented. Firstly, the implementation results for two wind turbines are inspected in details. These two wind turbines, named T2" and T4 here, are picked from two different locations within an actual wind-farm. The damage indicators are evaluated with and without consideration of the mean stress correction, using the one-year weather conditions history from the turbines' own SCADA data. Inspection of the wind roses of these two turbines in Figure 8 indicates the wind speed properties and prevailing wind direction variations.
The damage indicators for turbine T2 and T4, applying the mean stress correction, are respectively 18% and 9%. These values correspond to critical tensile stresses of the points of TB2 and TB1, which expectedly fall on the axes of the turbines' prevailing wind directions. These values show that the tower has just spent 18% and 9% of its fatigue design capacity. The turbine towers' damage indicators for the case without mean stress correction are 60% and 37%, both relating to DOA. In this case the damage

magnification due to stress concentration around door opening is the driver for lifetime extension. Whether or not the mean stress correction should be considered for lifetime extension evaluation depends on the manufacture's methodology for fatigue analysis. Since the authors are not aware of the methodology used by the turbine manufacturer for fatigue reference design, the life extension potential results, considering both with and without mean stress correction are provided.

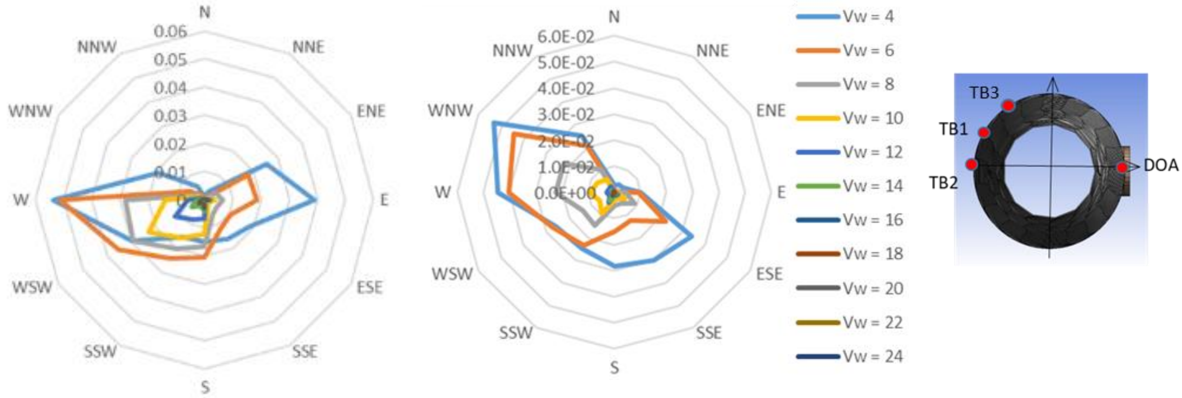

Figure 8. Wind rose plots of turbines T2 (left) and T4 (middle) and location of critical stress points (right) for damage estimation, wind speeds in m/s

In order to evaluate the variations of the lifetime extension potential across the wind farm, the proposed methodology is applied to five more wind turbines within a wind farm. Figure 9 compares the lifetime extension potential of all seven wind turbines. The wind farm has three main arrays and there are 3 rows of turbine in the first array, whereas the rest of arrays consist of two rows of turbine. The wind farm's layout cannot be displayed due to confidentiality issues. The turbines are purposely selected from different arrays and rows to reflect the wind speed properties variations in the results. The location of the stress points with highest damage are already shown in Figure 8. According to Figure 9, turbine T1 and T2 have undergone the highest operational fatigue damage. The wind roses of T1 and T2 are similar and both stretched along the tower door normal axis with a small spread. Turbines T4 and T5 have experienced significantly less damage in comparison to the other turbines, with and without mean stress corrections. Therefore, these two turbines have the highest potential for lifetime extension.

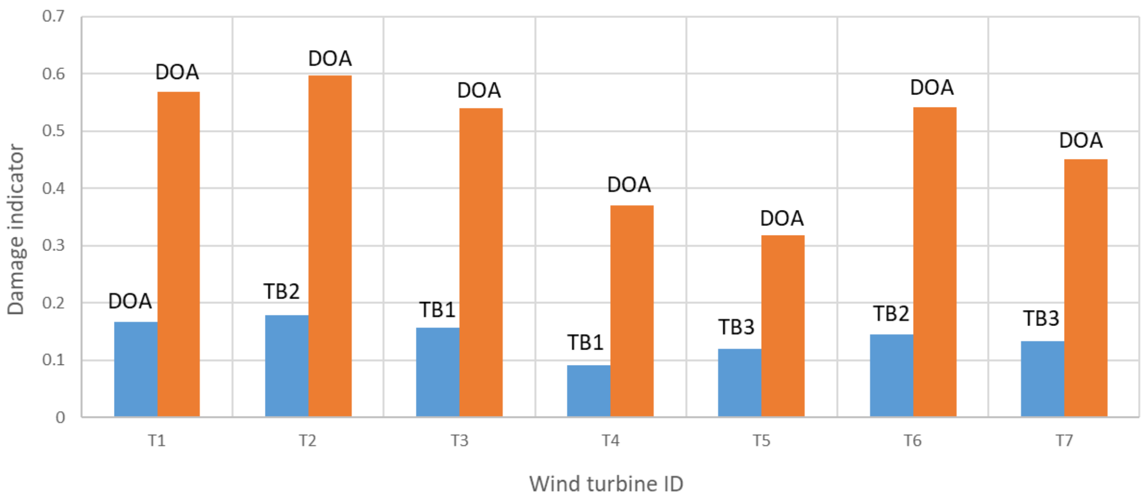

Figure 9. Comparison of lifetime extension potential of different turbines

4. Conclusions

Variation of wind direction implies the fact that the location of the maximum fatigue damage on the tower circumference is not fixed over the wind turbine life. Therefore, the point that undergoes the largest damage over the longest period of time under turbine's operational life will govern the tower lifetime. The shape of the wind rose and its spread will determine the potential for lifetime extension, in contrast to the design fatigue damage analysis that assumes a unidirectional wind direction. The damage equivalent stresses around the tower door are higher than those at tower base. Hence, the relative orientation of the prevailing wind direction and the tower door can also be limiting to the tower fatigue life.

The lifetime extension potential as a consequence of the wind direction dispersion holds true for all conventional large turbines. This is due to the fact that wind directionality distributes the operational loads over multiple points at tower base and around door opening, which causes distribution of fatigue damage as well. According to the results presented here, there is generally the potential for tower life extension under multi-directional wind as opposed to the unidirectional design assumption. However, this potential depends on the spread of the wind rose and also the tower door alignment relative to the wind seen by the individual turbine. Furthermore, the variations of wind properties across the wind farm influence the lifetime extension potential. Through the proposed methodology in this paper, the candidate turbines with the highest potential can be selected for the further detailed analysis and decision making process for the likely lifetime extension.

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