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COUPLED SIMULATION OF ICE-STRUCTURE INTERACTION OF OFFSHORE WIND TURBINES IN BHAWC USING VANILLA

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ABSTRACT

Offshore wind turbines at locations where sea or lake ice is present need to be designed to withstand ice-induced loading. For vertical-sided support structures, such as monopiles, the effects of ice-induced vibrations need to be considered in the design. Current practice is either to use approaches provided in design standards, or for example to apply pre-generated ice load time series in the wind turbine aeroelastic model. These approaches have the drawback that the coupling between ice failure behavior and structural motion is not included. The effect of omitting this coupling on predictions for fatigue and ultimate limit states is currently not known. To enable fully coupled simulations in the design of offshore wind turbines, an existing simulation model for ice crushing has been recently coupled (“VANILLA”) to the in-house aeroelastic software package BHawC. In this paper this fully coupled model is applied to simulate ultimate limit state design load cases (DLCs) for a recent design of an offshore wind turbine on a monopile foundation. The project that is chosen for this case study is situated in the Southern Baltic Sea. The loads obtained for ice- and wind loading with the VANILLA model are compared to wind- and wave-induced loading. It is found that intermittent crushing is the governing ice interaction mode for offshore wind turbine support structures and rotor-nacelle-assembly components.

KEY WORDS: Ice crushing; offshore wind; frequency lock-in; intermittent crushing.

INTRODUCTION

Ice loading on vertically-sided structures may result in the development of ice-induced vibrations. Past experience with oil and gas platforms and lighthouses has shown the importance of considering these vibrations in design (Bjork, 1981; Jefferies and Wright, 1988; Yue and Li, 2003). For offshore wind turbines on monopile foundations in cold regions, ice-induced vibrations may be relevant for both fatigue and ultimate limit states. Full-scale observations for such structures are not available due to a combination of most developments being relatively recent and recent prevalence of mild winters in the areas where offshore wind turbines are currently installed. Previous theoretical studies using simulation models suggest that the typical structural properties of offshore wind turbines, resulting from the slender pile design with a large mass at the top, allow for significant interaction between ice and structure to develop (Hendrikse and Nord, 2019).

In the offshore wind industry, the common approach to deal with ice-induced loading in design is to use pre-defined time series of the global ice load (ISO 19906, 2018; IEC 61400-3-1, 2019), or to generate time series of global ice load with numerical models developed by ice load consultants and apply these time series to the structural model of the wind turbine supplier or support structure designer. Both these approaches are uncoupled and as such do not capture the actual interaction between ice, structure, and wind. The downside of this is that the results are not always physically sound, e.g. ice loads increasing when the structure is moving away from the ice due to the wind. Therefore, assessing the safety of the structural design through such uncoupled approaches remains a challenge. In order to capture the interaction accurately, a fully coupled simulation model is required. The use of such models is suggested in IEC 61400-3-1 (2019), provided that the numerical model takes the effect of the dynamics of the structure, the dynamics of the ice, and the interaction between ice and structure into account. A particular emphasis is given to incorporating the forces from the ice being dependent on the relative motion between ice and structure.

Recently, Siemens Gamesa Renewable Energy (SGRE) and Delft University of Technology (TUD) completed the "Variation of contact Area model for Numerical Ice Load Level Analyses" (VANILLA) project. In this project, the ice crushing model developed at TUD (Hendrikse and Nord, 2019) was coupled to the SGRE in-house aeroelastic software package Bonus Horizontal axis wind turbine Code (BHawC), with the aim of developing a fully coupled simulation model for ice-structure interaction of offshore wind turbines. The implementation of the model and its compliance to relevant design standards have since been verified by DNV-GL.

In this paper, the application of the coupled model to simulate ultimate limit state (ULS) design load cases is presented. The aim of this study is to identify if ice-structure interaction can become design driving in an offshore wind project and which mode of ice-induced vibrations results in the governing loads. The study is based on a reference project in the Southern Baltic Sea with relatively mild ice conditions for which information on wind- and relatively mild wave-induced loading is also available, thereby allowing quantification of the relevance of ice loading in terms of ULS design.

APPROACH

The structural model is built in the in-house aeroelastic software BHawC which has been used in SGRE for almost sixteen years for producing loads for the design of wind turbines. The structural model in BHawC is built around the co-rotational formulation (Rubak and Petersen, 2005). Beam elements are used to model the support structure, shaft and blades. The ice crushing model used in the VANILLA software component coupled to BHawC is described in Hendrikse and Nord (2019) and implemented based on the reference implementation in MATLAB (Hendrikse, 2018). The model has been developed and validated against model-scale and full-scale data over the past ten years at TUD.

A simulation for ice crushing with VANILLA is defined using the crushing equation in ISO 19906 (2018). For a scenario defined in terms of ice strength coefficient C_R, ice thickness h, and projected structural width w, the peak global ice load F_G in continuous brittle crushing is first defined based on ISO 19906 (2018) as:

$$F_{\mathrm{G}} = C_{\mathrm{R}}\left[\left(\frac{h}{h_1}\right)^{n}\left(\frac{w}{h}\right)^{m}\right]wh$$
$$n = \min[-0.5 + h/5\,, -0.3] \qquad \text{(Eq. 1)}$$
$$m = -0.16$$

The ice model parameters in VANILLA are subsequently scaled such that the peak load F_{G} has a pre-defined probability of exceedance in a simulation of a standard crushing event. The standard crushing event is characterized by a drift speed v_{ice} and associated crushing length L_{crush} corresponding to a stable condition of continuous brittle crushing. In the VANILLA project the standard crushing event was defined based on full-scale data of the Norströmsgrund lighthouse and experience in the VANILLA project as: v_{ice} = 0.15 m s^{-1} and L_{crush} = 90 m.

In this study the ULS analysis is considered for which the design load cases including sea ice are defined as D3 and D8 from IEC 61400-3-1 (2019). D3 concerns the horizontal load from a moving ice sheet at relevant ice velocities. The Wind Turbine Generator (WTG) is in normal power production at operational wind speeds, with normal turbulence model (NTM) and normal current model (NCM). The extreme ice state of a moving ice sheet or floe is considered. This means that a combination of thickness and ice strength with a 50-year return period is considered and simulated for a range of ice drift speeds.

D8 concerns the horizontal load from a moving ice sheet at relevant velocities. The WTG is idling at the maximum 1-year recurrence 10-minute mean wind speed, with extreme wind model (EWM) and normal current model. Just as for D3, the extreme ice state of a moving ice sheet or floe is considered; i.e. a combination of thickness and ice strength with a 50-year return period is considered and simulated for a range of ice action speeds. In VANILLA this load case is appended with the wind speed where the smallest aerodynamic damping contribution is expected i.e. at 0 m s^{-1}. This is done as the fully coupled simulations are expected to result in the most severe load effect on the structure for conditions with the lowest possible damping.

The design load case setup and environmental conditions leading to the corresponding ULS results are directly extracted from the reference project load calculations. The reference project specific environmental input, load case setup, limit state analysis of the wind and wave-induced loading, and the structural properties of the WTG, are not further described in this paper. The simulations presented here concern a single position with the ice-interaction level at 1.09 m with respect to mean sea level (MSL). The equivalent outer diameter of the support structure at the ice action point is 6.3 m. Relevant parameters for the analysis presented here are h = 0.35 m, C_{R} = 1.1 MPa. The ice drift speeds considered are 0.01 m s^{-1} up to 0.4 m s^{-1} with steps of 0.01 m s^{-1}.

RESULTS

Two cases are compared:

1. The design load cases for wind and waves without ice, denoted with ‘No ice’;
2. The ice load cases D3 and D8 calculated using VANILLA.

A distinction is made between the support structure load effects and those of the rotor nacelle assembly (RNA). For the support structure the results at three relevant locations along the structure are shown in Table 1, being tower-top (101.7 m), interface (14.0 m) and mudline (-31.2 m). Values shown represent the normalized absolute maximum values of the design load cases that were included in the specific load set. The DLC to which the ice load effect corresponds is also indicated. Figure 1 further illustrates the comparison between ice and no-ice over the height of the structure.

Table 1. Governing bending moments and corresponding for 'No ice' and VANILLA simulations at three locations along the height of structure. The last column shows the relative difference between 'No ice' and VANILLA.

Location	Vertical coordinate w.r.t. MSL (m)	Normalized bending moments for 'No ice' (-)	Normalized bending moments for VANILLA (-)	VANILLA DLC	Relative difference
Hub height	101.7	0.11	0.10	D8	-4%
Interface	14.0	0.51	0.45	D3	-13%
Mudline	-31.2	0.81	1.00	D3	23%

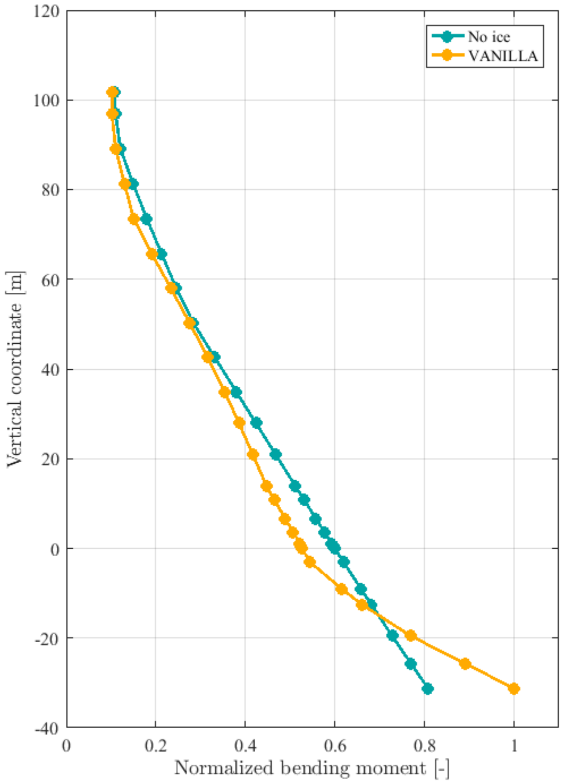

Figure 1. Comparison of governing bending moments over the height of the support structure between 'No ice' and ice DLCs simulated with VANILLA.

Results indicate that, for this example project, the ice load effects are governing over the wind and wave only DLCs, only in the part of the structure near mudline. Time series of the bending moments in the governing simulations for the three vertical coordinates are shown in Figures 2 to 4. For the interface level and mudline level it is found that the governing simulation contains intermittent crushing with a saw-tooth frequency close to the first natural frequency of the structure. This interaction mode results in the largest bending moments due to the increase in global ice load as a result of synchronized contact between ice and structure. It is different from a simple single-mode frequency lock-in, as the second mode of the structure plays a significant role in the transient oscillations and disturbs what would be a classical single-mode frequency lock-in response pattern. The speed of the structure at the ice action point reaches larger values compared to what is typically observed, up to 1.5 times the ice drift speed (Toyama et al, 1983). Nevertheless, a resonance-like effect does develop, causing large maximum bending moments in the structure.

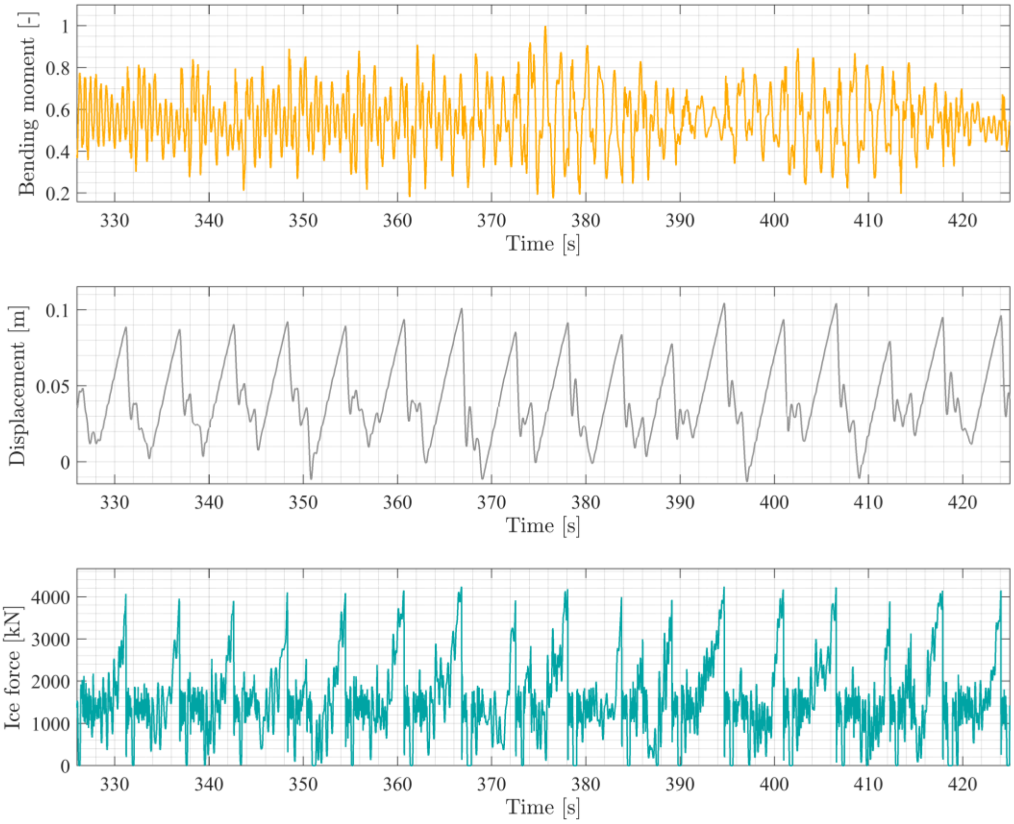

Figure 2. Time series of the load effect dominant simulation at **tower-top** (101.7 m). Turbine is in idling mode with an ice drift speed of 0.03 m s^{-1} and a mean wind speed of 33 m s^{-1}. Top: Tower top bending moment in fore-aft direction. Center: Displacement of the support structure at the ice-interaction point, in direction of the drifting ice. Bottom: Global ice force as a result of the ice-structure interaction.

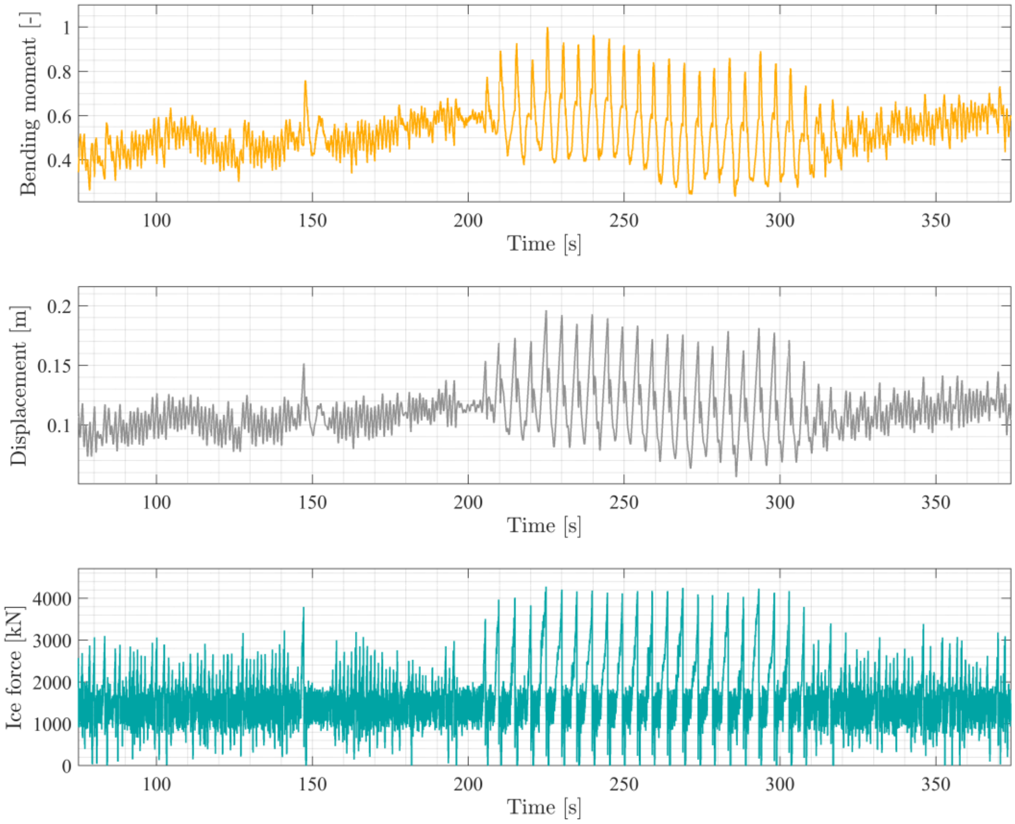

Figure 3. Time series of the load effect dominant simulation at **interface** (14.0 m). Turbine in production mode with an ice drift speed of 0.05 m s^{-1} and a mean wind speed of 13 m s^{-1}. Top: Interface bending moment in fore-aft direction. Center: Displacement of the support structure at the ice-interaction point, in direction of the drifting ice. Bottom: Global ice force as a result of the ice-structure interaction.

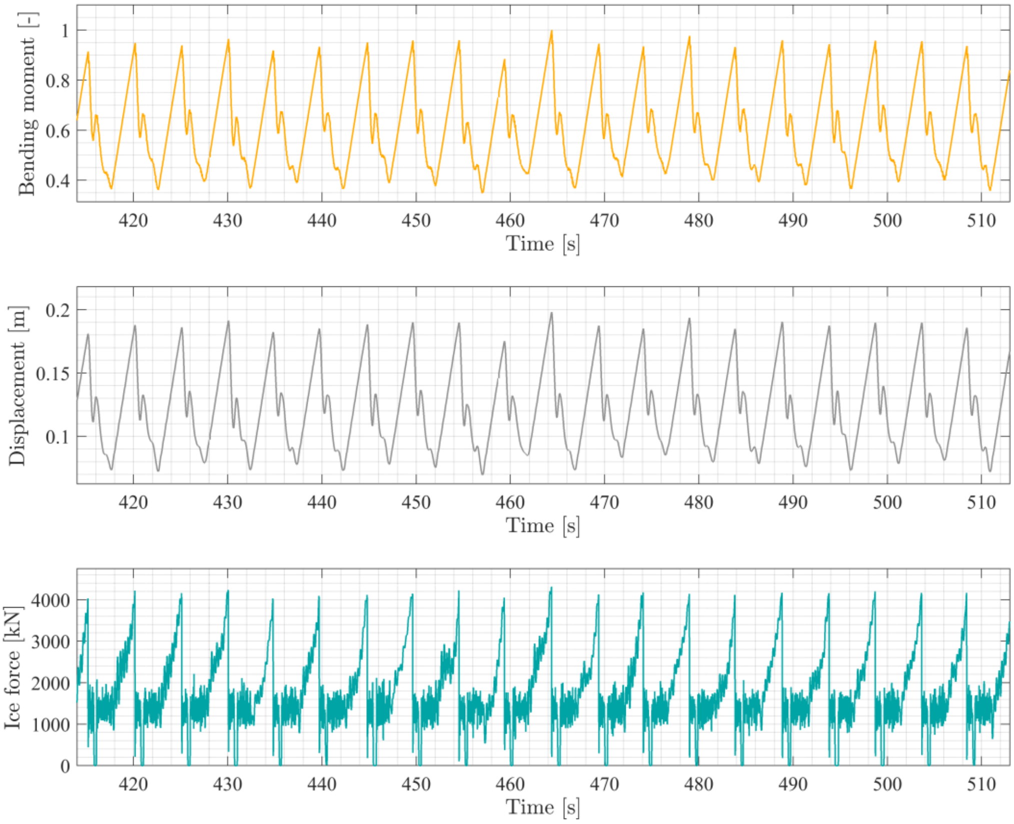

Figure 4. Time series of the load effect dominant simulation at **mudline** (-31.2 m). Turbine in production mode with an ice drift speed of 0.05 m s^{-1} and a mean wind speed of 13 m s^{-1}. Top: Bending moment in fore-aft direction. Center: Displacement of the support structure at the ice-interaction point, in direction of the drifting ice. Bottom: Global ice force as a result of the ice-structure interaction.

The bending moments for components of the RNA where the ice loading is found to be governing over the wind and wave only loading are shown in Table 2. Furthermore, Figure 5 shows the bending moment time series of the blade outer part in edge-wise direction.

The bending moment time series show a pattern that corresponds to rotation of the rotor: larger vibrations occur when the blade is pointing upwards compared to other azimuth positions. Further investigation into the waterline ice-structure interaction force shows that intermittent crushing is again the governing failure mode of the ice. The minimum edge-wise load effect in this part of the blade occurs when an intermittent crushing load drop coincides with the blade pointing in the upward direction. First a positive bending moment is observed shortly after the drop in the ice load. This comprises tension in the leading edge of the blade and occurs as the RNA accelerates into the opposite direction of the drifting ice. The ice load from brittle crushing then induces a deceleration of the RNA, resulting in a negative bending moment in the blade as it ‘flaps’ forward.

Table 2. Governing bending moment for 'No ice' and VANILLA simulations for the outer part of the blades.

RNA component	Normalized bending moments for 'No ice'	Normalized bending moments for VANILLA	VANILLA DLC
Blade outer edgewise bending moment (leading edge in compression)	1.0	1.28	D8
Blade outer edgewise bending moment (leading edge in tension)	1.0	1.08	D8

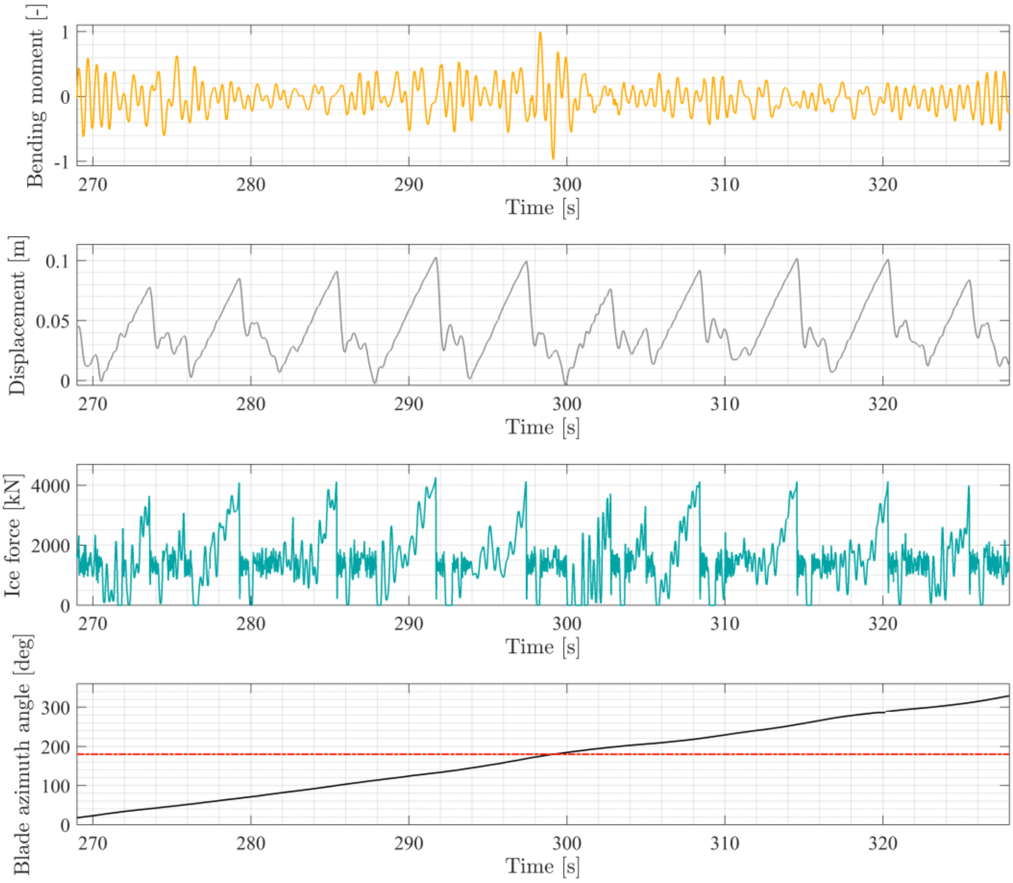

Figure 5. Bending moment time series of the outer part of a blade in edge-wise direction. The turbine is in idling mode with an ice drift speed of 0.03 m s^{-1} and a mean wind speed of 33 m s^{-1}. Top: Edge-wise bending moment; in fore-aft direction as blades are in pitched-out position. Second: Displacement of the support structure at the ice-interaction point in direction of the drifting ice. Third: Global ice force as a result of the ice-structure interaction. Bottom: Azimuth angle of the rotor in black. The considered blade is pointing upwards at an azimuth angle of 180 degrees, depicted with the red line.

DISCUSSION

It is found that, based on the reference project considered, intermittent crushing can be the most important scenario in ultimate limit state design of offshore wind turbines in ice prone regions. The reason for this is that during intermittent crushing the global ice load can reach a significantly higher maximum at the instance before global ice failure, compared to continuous brittle crushing. A factor of two has been often observed and used in design approaches (Finn et al., 1993; Gravesen and Kärnä, 2009; Kärnä et al., 2008, Kärnä and Muhonen, 1990). Unfortunately, the current design standards (IEC 61400-3-1, 2019; ISO 19906, 2018) do not explicitly define this load increase, which may result in the perception that frequency lock-in is the dominant case to consider, due to its more significant dynamic amplification. Despite the fact that these results are project specific the simulations presented here show that intermittent crushing, including the associated global load increase, should not be omitted in design.

CONCLUSION

A coupled simulation model for considering dynamic ice-structure interaction in design of offshore wind turbines has been developed. This model allows for simulation of DLCs related to ice crushing against vertically sided structures in compliance with governing offshore wind design standards. In using the model, the complex aerodynamics-ice-structure coupling can be included in design.

The model has been applied to simulate ULS DLCs for a Southern Baltic Sea project. It is found that intermittent crushing at small ice drift speeds has the most severe impact on the support structure. Intermittent crushing is shown to also be significant for the RNA load effects, where it could become the governing ice interaction mode for the blades in more severe ice conditions. In the reference project considered here the ice conditions are relatively mild, such that wind and (mild) wave only DLCs are design driving for most of the support structure.

The most severe case of intermittent crushing develops when the saw-tooth period in the global ice load comes close to the first natural period of the structure. An observation is that frequency lock-in does not develop in the first mode. Bending moments at mudline are governed by the large load build-up resulting from the large contact between ice and structure developing at low relative speed. Bending moments in the blades become governed by ice loading in case the large load drop during intermittent crushing coincides with a blade pointing upwards in idling conditions.

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