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Fatigue damage from dynamic ice action – The FATICE project

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ABSTRACT

In the FATICE project we have addressed the fatigue damage on fixed offshore structures exposed to drifting ice. This is an important challenge in the development of energy production from offshore wind in the Baltic and involves at least five element: a) define ice statistics, b) predict the structural response (ice-structure interaction simulations), c) estimate the fatigue damage and d) carry out scale-model tests. We have used the Copernicus database and simple analytical equations to define the large-scale ice statistics and studied down-scaling to structural scale by comparing with ice load data on the Norströmsgrund lighthouse (LOLEIF and STRICE data). The VANILLA model allows for ice-structure *interaction* simulations and has been validated against the full-scale LOLEIF and STRICE data and against the model-scale ice in HSVA. The fully coupled and the traditional methods are compared. In the fatigue estimations studies the assumption of linear damage accumulation is challenged and load combinations from wave, wind and ice studied by assessing simulated time-series of the different loads. The main results is that sea ice cause the higher loads than wind and waves do , but the cumulative frequency of ice loads is much smaller than for wind and waves. The traditional model-scale ice tends to be too soft and/or too viscous so that a realistic breaking pattern combined with realistic force-time series is not been obtained for large aspect ratios. HVA has developed a crushing model ice (ICMI) in which the ice crystals are larger and the texture more uniform

KEY WORDS: Offshore structures; Fatigue damage; Dynamic ice action

INTRODUCTION

There are several types of fixed offshore structures exposed to drifting sea ice, such as structures for exploitation of offshore wind energy or oil and gas, lighthouses and other aids for navigation. The environmental actions from current, waves, wind and ice may give both static and dynamic structural response and the structures need to be designed so that they are safe for people and the environment and at the same time cost-efficient. The dynamic response may give fatigue damage and a vital part of the design process is to ensure that fatigue induced failure does not occur in the lifetime of the structure. Much research has been carried out on wave-induced fatigue damage and well accepted industrial methods exists where a designer may use met-ocean data (from spectrums, remote sensing or other sources) and simulate the fatigue damage over the structure lifetime.

There are no well-approved methods for ice-induced fatigue, even though there has been a rapid development in the industry practice in the last years. The industry practice for the calculation of static and dynamic ice actions, including fatigue loads from dynamic ice loading, was primarily based on the ISO19906, IEC61400-3, and DNVGL-ST-0437 standards, and these suffer from a number of highly uncertain assumptions. On the one hand Bjerkås and Nord (2016) showed that several Baltic structures failed even if designed for higher static loads than recommended by the ISO19906, and on the other hand it seems as if the uncertainties in the standards may lead to a conservative design against fatigue. The industry practice for calculating design fatigue loads from drifting ice involved the following steps:

a) Defining ice conditions giving dynamic load on the structure including how often they may occur. In short, the relevant ice statistics.
b) Ice-structure interaction modelling, generating structural response.
c) Post-processing to estimate fatigue damage.

In addition, scale model tests are often done for both extrapolation of numerical results and for validation of industry practice.

RECENT PROGRESS

Ice statistics

The determination of the relevant ice statistics needs to balance between parameters that can be estimated and parameters that an ice-structure interaction model needs. Firstly, it is essential to identify the ice conditions that give dynamic ice action on the structure of interest. The presence of ice is not sufficient and here we find a vital difference to waves and wind. As long as there are waves and wind there is load on the structure. This is not the case for sea ice, it needs to move to produce dynamic ice action and if the ice concentration and floe sizes are small enough, loads will be negligible. Another vital complication with ice compared to waves and wind is the large spatial variability in an ice cover and this complicates the prediction of local conditions around a planned structure.

The ice-structure interaction model assumes certain mechanisms and requires corresponding ice properties. It is well known that drifting ice with even thickness, that is level ice or rafted ice, can give dynamic structural response. Ridges are often not considered do give sustained vibration. Nevertheless, this may be due to limited amount of full-scale data! Structures for Offshore wind are important in the Baltic and most of the planned and ongoing projects are in the south or central Baltic where one would mostly find level and rafted ice. Further, the state-of-the-art software that can simulate dynamic ice-structure interaction do not include ridges (see Section ”Predicting the structural response”). In other words, the ice statistics should include level ice thickness, velocity (speed and direction), their relative frequency of occurrence and some information on ice strength (or if ISO19906 is used, the C_R coefficient). In this paper, we focus on estimations of ice thickness, ice velocity and ice concentration.

Ice conditions are provided by Copernicus (https://www.copernicus.eu/en) or similar services for many areas worldwide. Inside these reanalysis products, the available data is combined with advanced numerical modelling and ice conditions such as ice thickness, ice velocity and ice concentration are provided. However, in some areas, only the met-ocean data (wind, air temperatures, precipitation, currents, etc.) are available and the ice parameters must be calculated by simple or advanced models. In any case, there is a challenge to determine which parameter combination may produce load locally on a structure. The lack of full-scale ice-structure interaction data and corresponding local ice measurements is an issue. The data from the LOLEIF and STRICE campaigns (Schwarz and Jochmann, 2001; Li, 2015) are to date the least incomplete available data set for fixed vertical structures. During the campaigns, the Swedish lighthouse Norströmsgrund was instrumented with load panels, accelerometers, tiltmeter, cameras, sonar and an EM antenna measuring the local ice thickness from 1999 to 2003. Load events at the structure were recorded during the period, along with the corresponding local ice conditions.

The recorded loads at Norströmsgrund have been discussed extensively in the past (Kärnä and Yan, 2009). However, to identify all combinations of conditions that could result in any significant structural loads, a complete analysis of all recorded ice conditions is required. To accomplish this, Hornnes et al. (2020) extracted and summarized all ice conditions that were recorded at the lighthouse during the campaigns. They found that 34% of the ice encountered at the lighthouse was thicker than the level ice in the region, signifying the importance of considering deformed ice in severe ice conditions. The results of the analysis provided a sample case of local ice conditions for simulations of dynamic ice-structure interactions, for a structure whose dynamic events have been extensively analysed (Nord et al., 2018). In addition, the data provided a validation case for output from Copernicus reanalysis products. Using the data, Turner et al. (2020) compared the output from Copernicus products with the locally measured ice and meteorological conditions during load giving events. They found excellent agreements for atmospheric parameters such as wind velocity, barometric pressure, and air temperature. There was favourable agreement between the two sources for sea ice velocity, but the ice thickness distributions differed greatly, likely due to areal averaging in the Copernicus output.

Let us examine the different ice parameters (h_i, v_i, and C_i) and start with ice thickness. When the ice is predominantly of local origin it can be estimated based on Stefan-law type of analytical model:

$$h_i^2 + ah_i = b(FDD - c) \tag{1}$$

Where *FDD* is freezing degree days, *a* is closely related to snow or ice-air heat transfer coefficient when there is no snow, *b* to ice thermal properties and *c* to oceanic conditions, especially water depth.

The parameters (*a, b* and *c*) may be calibrated to historical data on ice thickness, or one may apply data on air temperatures, precipitation and wind. The more local information one has the better estimates one gets. With only knowledge of historical air temperature records the ice thickness predictions may get conservative.

The ice drift is more difficult to find from analytical solutions. One may assume free drift, use wind data, some semi-empirical coefficients and estimate ice speed and direction. The ice drift speed is given in Eq. 2 and should then give an upper limit as any ice deformation will reduce the velocity.

$$v_i = v_w \sqrt{\frac{\rho_a C_a}{\rho_w C_w}} \tag{2}$$

Where ρ_a and ρ_w are air and water densities, and C_a and C_w are the air and water drag coefficients (the square root term is often called the Nansen number). In offshore, the ice drift generally deviates 20 – 30 degrees clockwise from the wind in the Baltic. However, care should be taken as many structures are located in coastal waters where the land and islands give physical limitations on ice drift direction. Ice mostly drifts along the coastline, may drift offshore, but rarely drifts towards the shore.

The ice concentration cannot be estimated from simple analytical solutions and one need to rely on local knowledge or numerical modelling in cases where Copernicus or similar reanalysis products do not give ice concentration.

The analytical models are simple and computationally very fast so they can easily be applied in probabilistic modelling, but they do not give any correlations between the parameters. Numerical modelling will of course give coupled thickness, velocity and concentration and enable estimation of ice thickness of non-local ice. The modelling behind the Copernicus products for the last 25 years can be used to find empirical statistics of h_i, v_i and C_i (Turner et al., 2021b). A derivation of the underlying distributions remains to be done. Especially in the southern and central Baltic this is challenging as ice forms not every year. This stresses the importance of combining all available data on several spatial and temporal scales, quantifiable physical processes and analytical and numerical modelling.

Finally, an approach to estimate the number of days in a season when a structure may be vulnerable to harsh in-induced vibrations (H-IVV) without quantifying the actual load, or response (Bjerkås and Gedikli, 2019). The starting point is the set of identified events in the unique full-scale LOLEIF and STRICE data from the Norströmsgrund lighthouse (Nord et al., 2019 a and b). Required met-ocean parameters are ice thickness, ice concentration, air temperature, ice drift speed and wind velocity. The ice thickness, and ice velocity were calculated from simple analytical expressions by the use of wind velocity and air temperatures (Eqs. 1 and 2), but the ice concentration must be available directly. Later, they further investigated the effect of individual met-ocean parameters on each other through a more in-depth parameter analysis and also updated their method (Gedikli et al., 2020). They concluded that met-ocean based H-IIV prediction method overestimates the number of H-IIV days in a season (but realistic). Gedikli et al. (2020) also observed that daily ice direction values in the northern Gulf of Bothnia may be highly variable, especially in the late and early winter seasons. The hypothesis is that because ice thickness is small, ice direction may be susceptible to the sudden fluctuations in the wind and surface current directions. One strong observation that supports this hypothesis is that sometimes stable strong wind speeds and directions do not result in IIVs. Gedikli et al. (2020) also identified several events where ice directions vary depending on wind directions and there are some discrepancies between wind directions and observed ice drift directions.

Predicting the structural response

Before 2017, there were limited possibilities to simulate ice-structure interaction, so that the ice was considered a completely external load. The industry practice was to generate ice load time series first, using limited information of the structure, and then to apply these on a detailed structural FE-model to compute the response to ice loading (Seidel and Hendrikse, 2018). The challenge with this approach is that the structural response is known to strongly affect the ice load (Hendrikse and Nord, 2019), and no accurate prediction of the development of ice-induced vibrations could therefore be done requiring difficult choices to be made in the design process. Though several models for simulating the complex dynamic ice-structure interaction existed at the time and had been applied in offshore projects (Karna et al., 1999, Hendrikse and Metrikine, 2016), they each suffered from limited validation against full-scale and model-scale data, giving rise to significant uncertainty in their ability to predict dynamic ice-structure interaction.

Over the course of the FATICE project, the model presented by Hendrikse and Nord (2019), in industry known as 'VANILLA', has been validated against full-scale data from the Norströmsgrund lighthouse and based on dedicated testing at the HSVA ice basin (Hendrikse et al. 2018) and since been applied in theoretical studies, both within FATICE (Milaković et al., 2019, Hendrikse and Koot, 2019) and outside (Popko, 2020). In parallel with FATICE the model has been validated by DNV-GL and since been used to determine the ice design loads in several offshore wind projects (for example: Willems and Hendrikse, 2019). Two studies as part of the FATICE project are still in progress: 1) determining the model parameters for the improved crushing model ice developed by HSVA as part of this project, and 2) a comparison between the 'traditional approach' of pre-simulating ice load time series and the approach using VANILLA in a fully-coupled setup with an offshore wind turbine model. First results of the latter study show that for some parts of the structure the bending moment amplitudes may be underestimated using the traditional approach as synchronization between ice failure and structural motion cannot develop (Fig. 1). The is especially true for frequency lock-in where an underestimation of the contribution of ice to fatigue damage is expected. This is not likely to be critical for locations with very mild ice conditions, such as the Southern Baltic Sea, but for the design of structures located in more Northerly waters this will have to be considered.

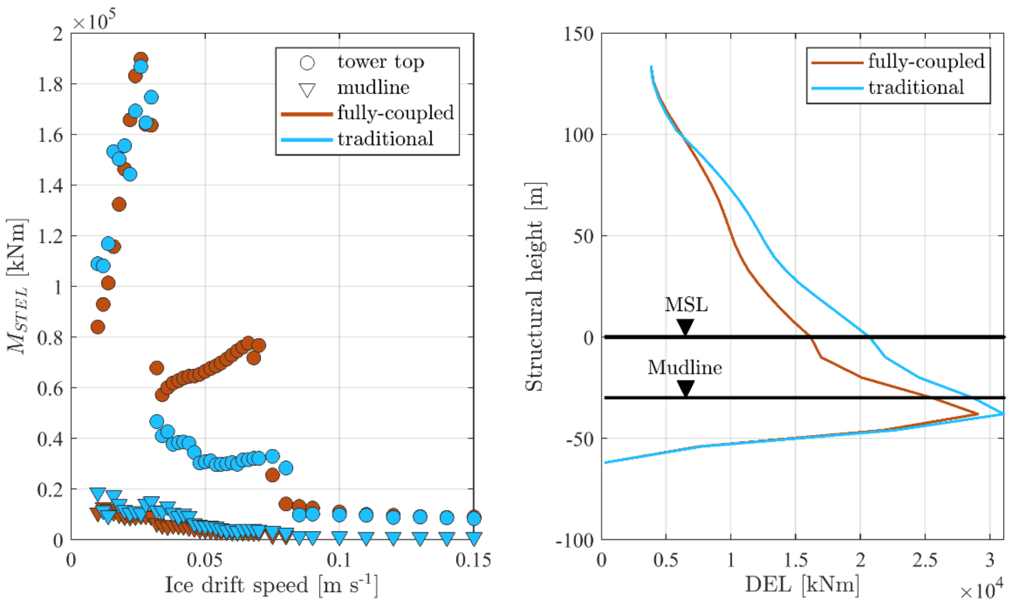

Figure 1 – Left: Short term equivalent bending moment plotted against ice drift speed at mudline and tower top. Results from 600 s simulations per ice drift speed are shown. When frequency lock-in develops, the traditional approach results in a short term equivalent bending moment up to a factor 2.5 smaller than the fully-coupled approach validated in FATICE. Right: Damage equivalent loads of an offshore wind turbine in power production

(DLCD4) are plotted against the structural height. The traditional approach exceeds the DEL in comparison to the fully-coupled approach by a maximum of 20%.

Simulated and measured recordings were used to assess the possibility to identify consistent modal parameters during ice-structure interaction and consistent system changes with observed ice conditions (Nord et al. 2019). Some consistency was noted between the ice failure mode and identified frequencies and damping. Some modes exhibited significantly higher damping than the other eigenmodes. These eigenmodes were mostly identified during events with significant ice actions. It is therefore suggested that these modes were highly influenced by the interaction process at the ice-structure interface. We suggested that some higher order modes with significantly lower damping were less influenced by the interaction process. For the sake of structural health monitoring, these eigenmodes insensitive to the interaction process significantly reduces the environmental variability and may turn out useful in selecting damage-sensitive features.

Estimating the fatigue damage evaluation response

The determination of the fatigue life for offshore structures such as offshore wind turbine (OWT) structures is usually performed by means of linear damage accumulation (Palmgren-Miner rule). If the long-term stress distribution for the entire service life is expressed by a load spectrum of linear elastic stress ranges, it is possible to calculate the fatigue life by dividing the load spectrum into a number of representative blocks with equivalent stress amplitudes. This allows the damage contribution of each block to be calculated individually. Consequently, the fatigue life is defined by the sum of the damage collected in each block independently. Load cases for OWTs take into account normal operating conditions (design load case (DLC12)), fault conditions or excessively high or low wind speeds (e.g. DLC64), as well as installation and maintenance.

For regions where seasonal sea ice may occur, two additional load cases with sea ice are considered for the fatigue design, distinguishing between normal operation (DLCD4) and turbine standstill (DLCD7). The current practice for calculating loads on WTGs, including dynamic ice action, is primarily based on ISO 19906, IEC 61400-3 and DNVGL-ST-0126 standards; however, those standards do not address effects of sub-zero temperatures on fatigue strength and effects of high ice loads on fatigue crack propagation (von Bock und Polach, 2019). To this day, the assumptions mentioned at the beginning regarding linear damage accumulation and the validity of Wöhler curves for sub-zero temperatures have not been verified or have been insufficiently verified so far. It is known that load cases with high mean or maximum stress may lead to changes in fatigue crack growth (Ehlers et al., 2015; Führing, 1977). Sequences with high ice loads, such as those occurring during the first winter, can cause such effects that violate the assumptions of independent damage accumulation. There is consequently a need to develop new methods to account for ice related variable load amplitudes (VAL) within fatigue design of OWTS.

A first step towards a combined load spectrum for wind, wave, and ice loading was done by assessing simulated time series for various load conditions of an OWT. This was performed for an exemplary OWT in the Baltic Sea designed by Siemens Gamesa. Using superposition and weighting of individual load conditions, a combined load spectrum for critical weld details was derived, see Fig. 2. It becomes clear that the load cases due to sea ice (e.g. DLCD7) cause the loads much higher than due to wind and wave loading (DLC12). On the other hand, the cumulative frequency of ice loads is much smaller than for wind and wave loads.

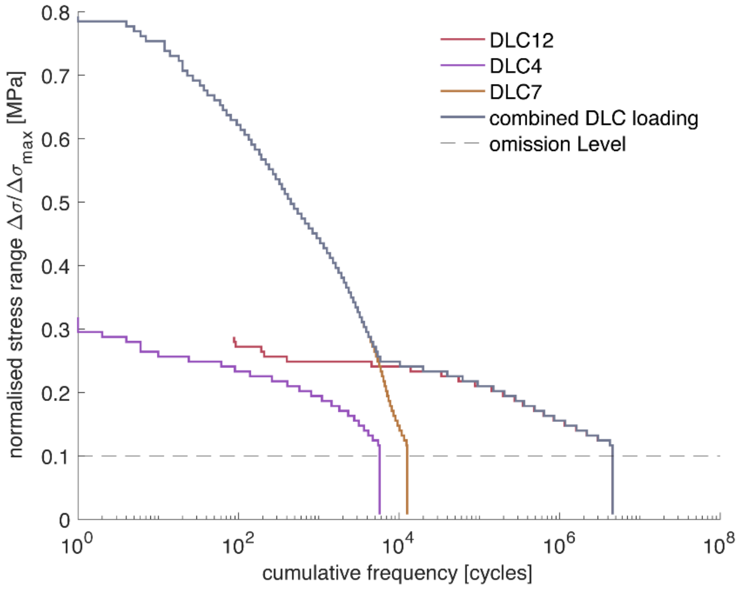

Figure 2: Superposition of individual load spectra to form a combined load spectrum with a 15 percent omission level (dashed line) according to the concept presented by Milaković et al. (2019), taken from Braun et al. (2021a)

In order to assess the effect of such complex VAL spectra on fatigue damage, fatigue tests are required using a truncated spectrum (by means of load omission) that also include the effect of sub-zero temperatures. In a number of recent studies, a nearly linear increase in fatigue strength with decreasing temperatures has been observed for welded joints (Braun et al., 2020a,b, 2021b).

Scale-model tests

Scale model tests are a common tool to investigate dynamic ice-structure interaction and to create validation cases for numerical models. Several model test campaigns for ice-induced vibrations of vertically sided structures have been conducted in recent years, and force-time series for different incoming ice velocities have been obtained (e.g. Määttänen, et al., 2012; Stange et al., 2020). However, the ice failure pattern and details of the ice mechanics have not always been modelled fully correctly. The model ice tends to be too soft and/or too viscous so that a realistic breaking pattern combined with realistic force-time series had not been obtained if the aspect ratio of structure and ice had been high. Generally, model ice deforms too much in bending if it interacts with a vertically sided structure. Especially in thin and soft ice, the crushing failure is frequently interrupted by global bending failure (Ziemer and Evers, 2016). Furthermore, the local pressures between ice and structure are not to scale if the model ice is thin, and a non-linear geometric scale effect exists (von Bock und Polach et al., 2020). Therefore, the nature of the model ice imposes limitations on ice and structure parameters if vertically sided structures are tested.

To overcome this limitation, HSVA attempts to develop a modified model ice more suitable for realistic representation of crushing failure. The core idea of improved crushing model ice (ICMI) is to aim for larger ice crystals and a more uniform ice structure than found in thin

HSVA standard model ice (MI), where the top layer resulting from the standard ice preparation procedure shows considerably different mechanical properties. Details of the HSVA standard model ice can be found in Evers and Jochmann (1993). In a first study, the crystal size was influenced by wave makers installed in the ice tank, keeping the water in motion while ice formed at the free water surface. Due to the waves, their size was naturally limited, and smaller than crystals which would form in calm open water exposed to cooled air. The procedure and pre-study steps are described in detail by Ziemer (2018). Several structures have been tested in MI and ICMI during the FATICE project. Direct comparison of compliant cylinders tested in MI and ICMI in Phase 1 tests confirmed improved representation of global and local failure mechanisms during static and dynamic ice-structure interaction tests. Figure 2 shows a visual comparison of the crushing failure. While the ice sheet bends and submerges during crushing in MI, it remains at the water level in ICMI. The extrusion of crushed ice appears more realistic. Tactile sensor records confirm formation of high pressure zones during continuous crushing in ICMI (Figure 4). The compliant structures were set into lock-in vibrations in both ice types.

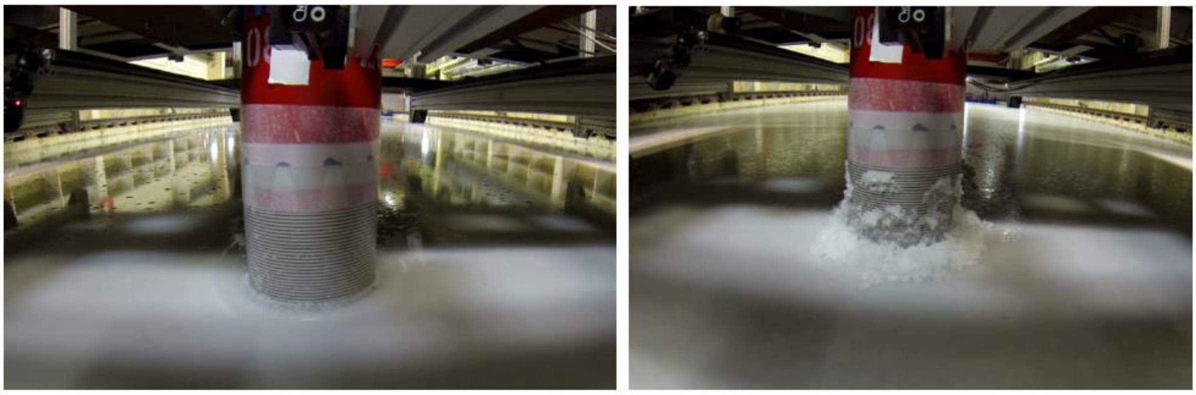

Figure 3. Cylindrical model during FATICE Phase 1 tests, left: Model in MI with submerged contact; right: Model in ICMI

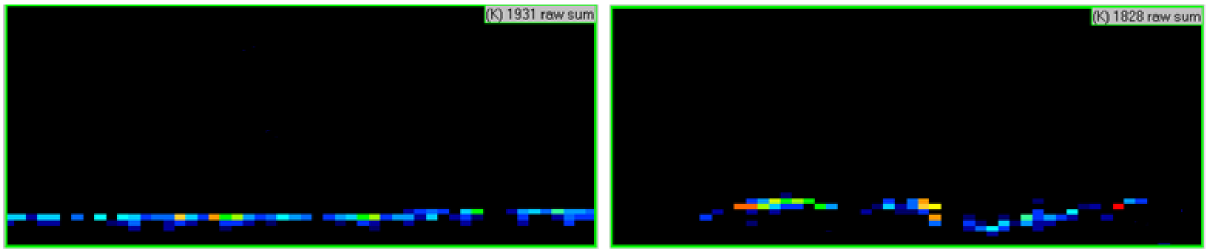

Figure 4. Local pressures measured with tactile sensors during FATICE Phase 1 tests, left: Crushing on a cylinder in MI with pressures concentrated in the submerged top layer; right: crushing on the same model in ICMI with irregular high pressure zone formation over the ice thickness.

Phase 2 model tests concentrated on the geometric scalability of ice loads. Results are presented in Figure 4. Tests with several models with different diameters proved that the mean ice load in crushing scales linearly in ICMI, regardless of aspect ratio. This is a major improvement compared to crushing tests in MI.

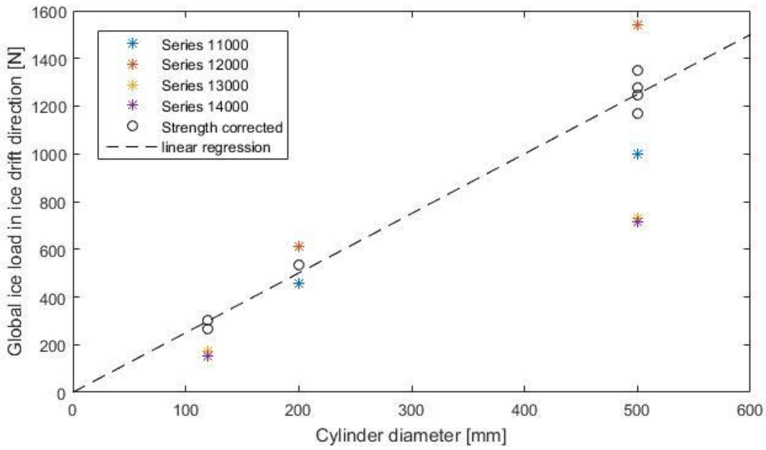

Figure 4. Mean global ice loads during crushing on cylinders with different diameters, tested in ICMI. Circles show corrected data accounting for compressive strength variation between the tests.

FUTURE CHALLENGES

Turner et al. (2020) has investigated how outputs from Copernicus products can be used to estimate the ice conditions in an area. Additionally, statistics of local ice and wind conditions have been explored (Hornnes, 2020, Gedikli et al, 2020). Moving forward, documenting and generalizing the complete range of ice conditions that could lead to ice actions is necessary. Additionally, to estimate ice actions in new areas, methods must be developed to enable the spatial and temporal transfer between “structural” and “Copernicus” scales The ice thickness output from Copernicus are areal averaged which reduces the presence of deformed ice, but the high spatial variability in ice thickness (due to ridging) makes this a challenge.

Bjerkås and Gedikli (2019) and Gedikli et al. (2020) used only five environmental parameters to estimate when a H-IIV could be expected at an offshore site in an ice infested region. However, this simplification does not tell us the full picture on the onset met-ocean conditions of IIVs. It is believed that the model can be improved further by including advanced geophysical models into the decision tools. Therefore, this method will highly benefit from 1) physical ice-drift model, 2) generalization of the criteria applied (i.e., including remote sensor data to the ice parameters that cover a larger area), 3) effect of surface current on the response and comparison of surface current with wind direction, 4) data calibration (i.e., comparison of the data obtained with other available datasets and numerical model results). Last but not least, reduced order modeling (Gedikli et al., 2019) can also be applied to ice statistics to further improve our understanding on the dynamics of met-ocean parameters (i.e. one can study the relative importance of each met-ocean parameter on H-IIV). This effort is expected to establish the bridging connection between the complex data and ice-structure interaction modeling research perspectives.

Upon completion of the FATICE project predictions of the structural response under ice loading are no longer a challenge, but this does not mean that everything has been solved. A fundamental understanding of the complicated physics and mechanics of ice-structure interaction is still missing. The “ice strength” should be estimated from available met-ocean or ice data. A first step could be to estimate ice temperatures from met-data and correlate it to ice mechanical properties. Furthermore, we are able to simulate the interaction in 1D accurately, but the question as to the influence of motions of the structure not in line with the ice drift direction remains, for example due to misaligned wind loading. Due to the phenomenological nature of the VANILLA model, and of any ice-structure interaction model, the model parameters can only be determined based on existing full-scale data, which is practically non-existing for many locations across the world. The solution to this has for now been found in using the ISO19906 crushing load equation, application of which gives an overestimation of the ice action in general. This is a safe approach from the perspective of designing offshore structures, but much can be gained still in the attempt to design optimal offshore structures at locations exposed to drifting sea ice.

In summary, the current design of OWTS for sea ice loading and low temperatures is subject to significant uncertainties. This is partly because forecasts of ice conditions are difficult, partly because temperature effects are not accounted for in standards, and partly because of the assumption of linear (or independent) damage accumulation, which seems questionable for ice loads and low temperatures.

The model ice improved for crushing (ICMI) can be used to create validation cases for numerical models. It provides ice force time series which do not suffer from exaggerated ice sheet bending. The static component of the global ice load is linearly dependent on ice thickness, strength and cylinder diameter. ICMI widens the range of possible combinations of ice and structure parameters to test in crushing. However, the larger ice crystals of ICMI have disadvantages compared to standard HSVA model ice when it comes to bending failure, which disqualifies ICMI for test cases that may include a combination of flexural and compressive failure. Furthermore, the tempering behaviour of ICMI results in a loss of ice quality if the strength reduces. Therefore, the limitations for ice and structure to model-test crushing scenarios have been widened significantly, but limitations still exist. Currently, possibilities are examined to further tune the crystal size and improve the tempering behaviour.

CONCLUSIONS

The FATICE project has introduced new methods to estimate ice-induced fatigue of fixed offshore structures, spanning from defining large-scale ice statistics and downscaling to local ice condition giving dynamic load on the structure, fully coupled ice-structure interaction numerical simulations, identifying and mitigating some and finally creating model-scale ice suitable for studying ice crushing and corresponding ice-induced vibrations in the model basins.

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