POAC'23
Glasgow, United Kingdom

Proceedings of the 27th International Conference on
Port and Ocean Engineering under Arctic Conditions
12-16 June 2023, Glasgow, United Kingdom

Application of the suggested ice strength coefficients in ISO 19906 to intermittent crushing

Hayo Hendrikse[1], Cody C. Owen[1]
[1] Delft University of Technology, Delft, The Netherlands

ABSTRACT

For offshore wind turbines on monopile or jacket foundations without ice cones, one of the relevant design load cases is that of ice floes or level ice crushing against the structure resulting in ice-induced vibrations. In relation to that design load case, a relevant question is which ice strength coefficient to use in the crushing formula in ISO 19906 for determining design peak loads during intermittent crushing. Despite the guidelines in the standard being relatively clear on this matter, there often exists uncertainty regarding if and how to account for velocity effects and compliance effects when defining the ice strength coefficient C_R. Ice tank tests were recently conducted to investigate the dependence of global peak loads on far-field ice speed for both rigid and compliant structures. Those tests revealed that the compliance effect and velocity effect on the global loads originate from the same strengthening effect in the ice. As a consequence, the absolute global loads on the rigid structure and compliant structure did not differ significantly. Applying these results to the challenge of defining the ice strength coefficient for intermittent crushing, it can be stated that if the velocity effect is accounted for in the ice strength coefficient, then there is no need for further increase due to compliance of the structure. ISO 19906 provides some suggested values for the ice strength coefficient which include provisions for the velocity effect and can therefore be directly applied to determine the peak loads during intermittent crushing, as the standard also suggests.

KEY WORDS
Crushing equation; Ice-induced vibrations; Global ice loads; Compliance effect; Velocity effect.

INTRODUCTION

For offshore wind turbines on monopile or jacket foundations without ice cones, one of the relevant design load cases is that of ice floes or level ice crushing against the structure resulting in ice-induced vibrations. A critical regime is that of low far-field ice velocity where intermittent crushing (see Figure 1) or multi-modal interaction develops, resulting in high-amplitude saw-tooth shaped load time series and significant dynamic response of the structure (Hammer et al., 2023). Intermittent crushing has, in the past, been observed for both small piles (Peyton, 1966) and wide offshore structures (Jefferies and Wright, 1988), and in model-scale campaigns with both freshwater (Sodhi, 2001) and model ice (van den Berg et al., 2022).

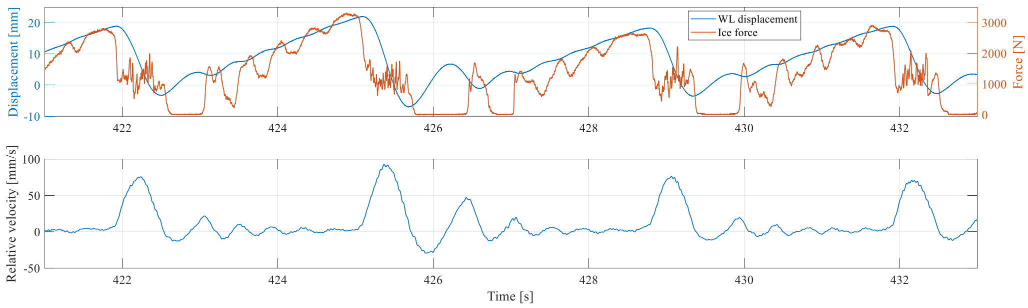

Figure 1 - Example of intermittent crushing in model tests from van den Berg et al. (2022) showing the characteristic saw-tooth load and displacement pattern.

Simulation models are often used in the design phase to assess the dynamic response of the structure in accordance with the guidance in Section A.8.2.6.1 in ISO 19906 (ISO, 2019). A key question arises: what is the maximum global ice load during intermittent crushing which should be used for simulation? ISO 19906 proposes as guidance to the user:

"The peak action, F_{max}, can be determined by the method described in A.8.2.4.3 as the static global ice action, F_G."

This refers to the 'crushing equation' or 'crushing formula' included in ISO 19906:

$$F_G = hwp_G \mathrm{F_G} = \mathrm{hwp_G} \tag{1}$$

where F_G is the peak global crushing load in continuous brittle crushing, h is the ice thickness, w is the structure width, or diameter in the case of a cylindrical structure, and p_G is the global pressure given by:

$$p_G = C_R \left[\left(\frac{h}{1}\right)^n \left(\frac{w}{h}\right)^m + f_{AR} \right] \tag{2}$$

with m an empirical coefficient equal to -0.16, n an empirical coefficient equal to $-0.5 + h/5$ for $h < 1.0\, m$, and -0.3 for $h > 1.0\, m$, C_R an ice strength coefficient, and f_{AR} an empirical term given by:

$$f_{AR} = e^{\frac{-w}{3h}} \sqrt{1 + 5\frac{h}{w}} \tag{3}$$

The approach is in fact relatively straightforward with the only difficulty being the determination of an appropriate ice strength coefficient C_R. ISO 19906 provides suggested values for the ice strength coefficient. These are region-specific values of 2.8 MPa for Arctic first-year (FY) and multi-year (MY) ice, 2.4 MPa for Subarctic regions (e.g. Okhotsk Sea), and 1.8 MPa for temperate regions such as the Baltic Sea where currently many offshore wind projects are being developed or considered. In addition, a table with values is included (see Figure 2) as an example on how the exposure of a structure to ice can be accounted for in the ice strength coefficient.

Table A.8-4 — Examples of ice strength coefficient C_R dependence on exposure to ice events

n	Total distance km	Return period	$F_P(p)$	C_R MPa
1	6	1 year	0,5	0,99
1	6	100 years	0,99	1,45
24	135	1 year	0,5	1,34
24	135	100 years	0,99	1,80
24	135	10,000 years	0,9999	2,30
100	563	1 year	0.5	1,49
100	563	100 years	0.99	1,96

Figure 2 – Table A.8-4 from ISO 19906 (ISO, 2019) showing an example of how the ice strength coefficient can vary with exposure of a structure to ice.

It is noted that a value of 1.80 MPa is provided as a 100-year return period value for a location with 24 annual ice events (*n*) and a total distance travelled by the ice of 135 km. This is not to be confused with the nominal value of 1.8 MPa proposed in general for temperate regions. The values do share a common basis in the high speed (> 0.1 m s^{-1}) data obtained from the Norströmsgrund lighthouse. Those data yielded a 1-year return period value for high-speed crushing of about 1.34 for the northern Baltic Sea as also included in Table A.8-4. The nominal value of 1.8 MPa was then introduced to make the crushing equation also apply for low far-field velocities. To be exact, the value of 1.8 MPa accounts for the 'velocity effect,' 'compliance effect,' and some 'dynamic magnification' by means of an empirical factor of approximately 1.4 (Kärnä and Masterson, 2011).

A nominal value of 1.8 MPa could thus be selected for Baltic Sea offshore wind developments and potentially reduced or increased by accounting for exposure to ice at the site of interest. This is a relatively clear and straightforward approach, but nevertheless, in the experience of the authors, there is often uncertainty as to whether or not this value fully accounts for all possible magnification effects on compliant structures. The effects mentioned during discussions are the 'dynamic amplification,' 'velocity effect,' and the 'compliance effect.'

Dynamic amplification, often expressed by the dynamic amplification factor, describes how many times the internal stresses should be multiplied to the stresses caused by static loads when a dynamic load is applied to a structure. This is a structure-specific factor which should be determined from a dynamic analysis by either using an ice load model or the prescribed time series for intermittent crushing and frequency lock-in in Section A.8.2.6.1 of ISO 19906 (ISO, 2019).

The velocity effect and compliance effect on global ice loads are treated in overview papers for full-scale events by Jefferies et al. (2008) and model-scale observations by Kärnä et al. (2008). A clear example of both the velocity effect and compliance effect on global loads from past experiments is found in the work by Singh et al. (1990) as shown in Figure 3.

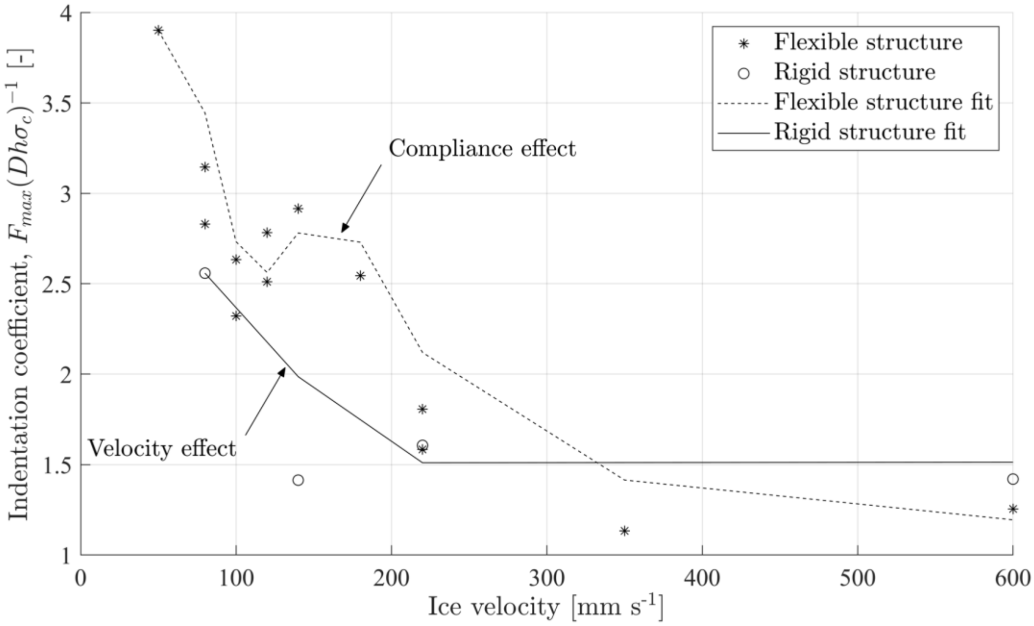

Figure 3 – Data replotted from Singh et al. (1990) showing the ‘velocity effect’ and ‘compliance effect.’ The indentation coefficient is defined as maximum excitation force divided by width, thickness, and (uniaxial) compressive strength.

Based on those referenced works the velocity effect can be defined as:

The observation that global peak loads on structures are generally highest at low far-field ice drift speeds around the transition where the failure of the ice changes from global creep to global crushing, sometimes also referred to as the ductile-to-brittle transition.

The compliance effect (see also: Kamesaki et al., 1996) can be defined as:

The observation that global peak loads on compliant structures are higher when intermittent crushing develops for those structures when compared to the global peak loads on more rigid structures at the same far-field ice drift speed.

Indeed, ISO 19906 contains some references to these two effects in Section A.8.2.4.3 such as:

“*The CR value recommended for the Arctic can be conservative, as it* ***potentially includes some magnification due to the compliance of the structure*** *in the referenced data from the Beaufort Sea.*”

and:

“*According to another data series from a stiff structure in the Baltic Sea, the ice strength parameter associated with the ELIE has been obtained as CR = 1,8 in conditions where the ice speed was higher than 0,1 m/s and the maximum waterline displacements in the direction of ice action of the structure were about 0,4 % of the ice thickness.* ***Under these conditions, the strength value CR obtained does not exhibit magnification due to the compliance of the structure****.*”

The latter statement seems to somewhat contradict what is written by Kärnä and Masterson

(2011) as therein they state that:

"*Therefore, the data that was used to obtain the ice strength value of* ***CR = 2.8 MPa for arctic conditions contains effects of ice speed and the compliance of the structure****. This is not the case for the STRICE data that was used for the strength value of CR = 1.8 MPa for the Bothnian Bay. Effects of ice speed and structure compliance are not incorporated in that part of [the] STRICE data that was used here.* ***Due to this reason, the value CR = 1.8 MPa was derived by applying a multiplying factor of 1.4 on the values that yield global pressures at the level of expected annual maximum...***

This increase in the ice strength parameter *is considered* ***sufficient to cover the influence of the ice speed and structure compliance*** *when the model based on STRICE data is used* ***for more flexible structures****.*"

In Section A.8.2.4.3.4 of ISO 19906, it is further mentioned that:

"*Pressures on compliant structures can be significantly higher than on rigid structures.*"

In a paper discussing the determination of an appropriate ice strength coefficient to use for the southern Baltic Sea offshore wind developments, the 'velocity effect' and 'compliance effect' are suggested as having to be accounted for separately (Gravesen and Kärnä, 2009).

It is therefore useful to better understand the velocity and compliance effects on global loads, with the aim to converge on answering the question if and how to account for these effects in defining the C_R coefficient for intermittent crushing. For this purpose, ice tank tests were conducted with rigid and compliant cylindrical structures over a range of ice speeds, allowing to establish both the velocity and compliance effects (Owen et al., 2023). The results of those tests are briefly summarized in this paper to demonstrate that the velocity and compliance effects are merely two observations of the same strengthening effect in the ice. Having established this, the method in ISO 19906 can be straightforwardly applied for defining peak loads during intermittent crushing, provided the C_R coefficient accounts for the velocity effect which applies to all structures, rigid or compliant. A reflection on if and how the velocity effect is included in the currently suggested values of—and methods for defining —C_R is included.

THE VELOCITY EFFECT AND COMPLIANCE EFFECT ON GLOBAL ICE LOADS

Ice tank tests were recently conducted at the Aalto Ice and Wave Tank to clarify if the global loads on compliant structures are indeed higher than those on rigid structures under the same ice conditions. Whether or not absolute global loads on compliant structures are higher than those on rigid structures over the same range of ice speeds is also assessed (Owen et al., 2023). To this end, a series of tests with rigid and compliant cylindrical structures of 200 mm diameter was executed, measuring the global loads for velocities ranging from 1 mm s^{-1} to 150 mm s^{-1}. The target model ice thickness for the experiments was 30 mm. The ice was kept cold during the tests by maintaining the ambient temperature at -11°C, resulting in an average flexural strength of 480 kPa and compressive strength of 610 kPa based on the International Towing Tank Conference recommended procedures and guidelines. The experiments from the test campaign are further described in Hendrikse et al. (2022a), including an explanation on how to obtain the data which are publicly available.

In the experiments, the velocity effect was observed for the rigid structures as shown for two test days in Figure 4. The figure shows the minimum, mean and maximum of the load time series recorded for a specific ice speed (v_{ice}), normalized by the mean load at the ice speed of 100 mm s^{-1}, as well as an 'x' marker for all peaks in the signal with a minimum prominence of 500 N (also mean-normalized). For the lowest indentation speed tested of 1 mm s^{-1}, the peak loads on both days were about 40% to 50% higher than those at higher speeds (> 5 mm s^{-1}). An interesting observation was that the increase in loads for lower speeds seemed to be mainly an increase in the mean load for which we did not find a direct explanation (Owen et al., 2023).

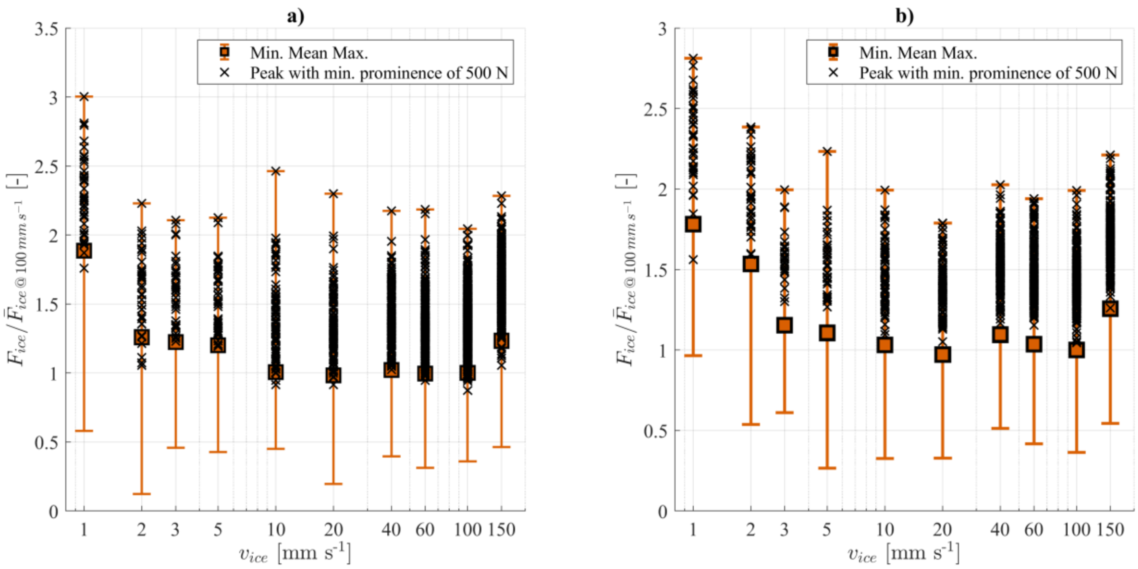

Figure 4 – Statistical measures of loads for the rigid structure tests on the a) 17th of June and b) 23rd of June showing the velocity effect. The loads are normalized by the mean brittle crushing load at an ice drift speed of 100 mm s^{-1} for each respective day. The minimum peak prominence is defined as the minimum relative height difference between peaks and determined by the *findpeaks* function in MATLAB.

Tests with compliant structures resulting in intermittent crushing were then performed in the same ice. An example of one of the constant deceleration tests during the campaign is shown in Figure 5. This test was aimed at reproducing the transition from continuous brittle crushing to intermittent crushing similar to the full-scale observations reported by Peyton (1966) and Jefferies and Wright (1988).

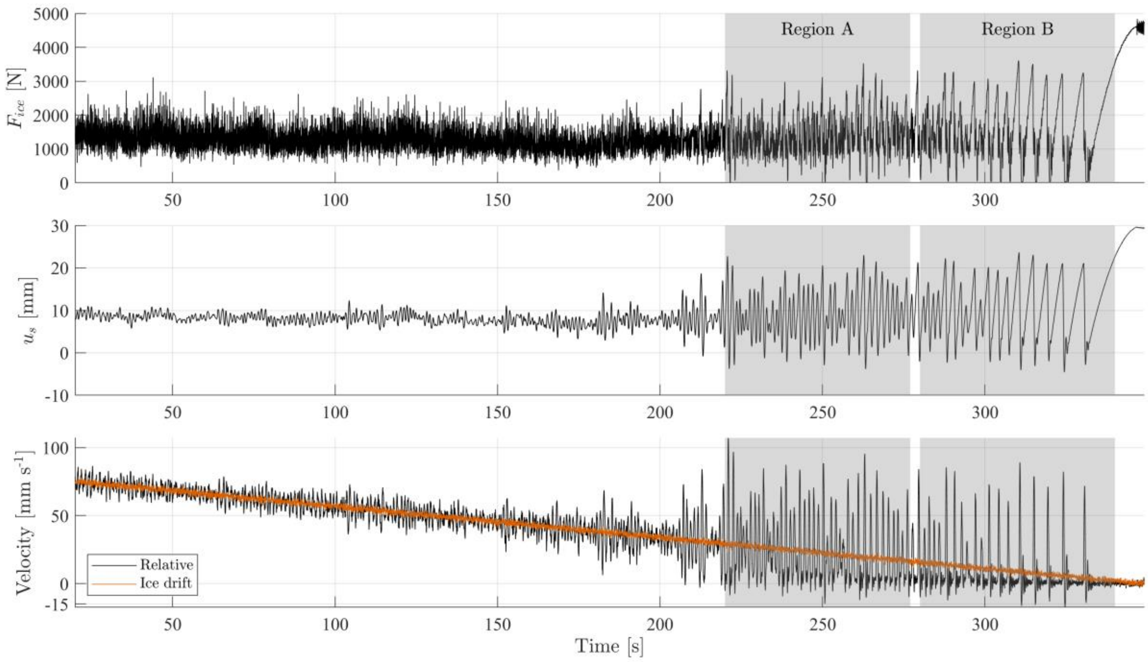

Figure 5 - Constant deceleration test with a single-degree-of-freedom structure on the 17th of June. Top: Ice load. Middle: Structural displacement. Bottom: Relative velocity between ice and structure, and ice drift speed. Region A indicates frequency lock-in and a transition to intermittent crushing. Region B indicates intermittent crushing.

The peak loads during this test are compared to those from the rigid structure on the same day in the same ice sheet in Figure 6. The same data are plotted in two ways. The top plot shows the peak loads plotted against the relative velocity between ice and structure (i.e. far-field ice speed minus structural velocity) at the moment of occurrence of the peak load. The bottom plot shows the peak loads plotted against the far-field ice velocity (penetration speed). The triangular markers are used to indicate if the relative velocity was increasing or decreasing prior to the peak load occurring, giving an indication if there had been some time of loading of the ice at low relative velocity.

The compliance effect is visible in the bottom plot where the peaks associated with intermittent crushing (Region B in Figure 5) exceeded those for the rigid structure at the same far-field ice speed. The effect was also observed during the phase where frequency lock-in and a transition to intermittent crushing were identified from the time series (Region A in Figure 5). Those higher peaks only developed after a period of low relative velocity between ice and structure as indicated by the rightward pointing triangles.

The top plot in Figure *6*shows the same data plotted for the relative velocity between ice and structure at the moment of the peak load occurring. It is seen that, when the relative velocity was used, the observed peak loads shifted left, towards the far-field speeds for which the velocity effect was observed for the rigid structures. More detailed analysis revealed that the higher peaks during intermittent crushing and frequency lock-in only developed after a period of near-zero relative velocity, which was the range where the strengthening effect occurred which defines the velocity effect (see Figure 4, and for more detail including controlledoscillation tests, see Owen et al. (2023)).

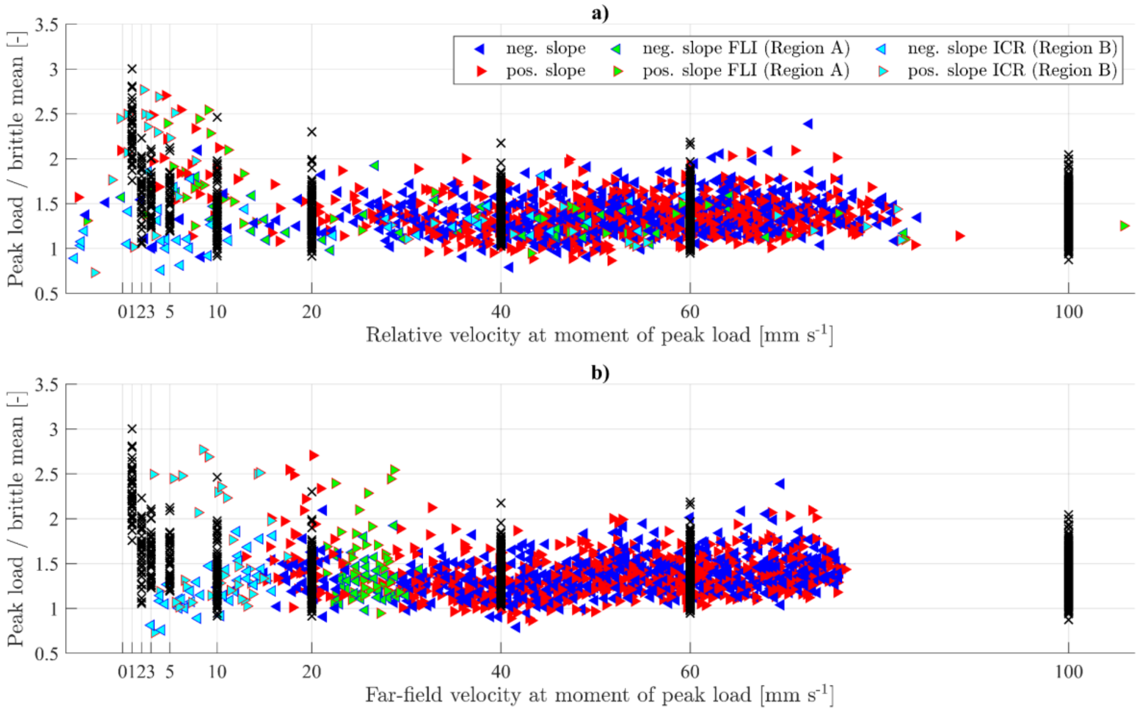

Figure 6 – Velocity and compliance effect example: a) peak loads as a function of relative velocity at the moment of peak load; b) peak loads as a function of far-field ice velocity at the moment of peak load, and normalized by the mean of the brittle crushing load between 20 s and 150 s in Figure 5. Peak loads from Figure 4 are represented by black crosses and normalized by the mean brittle crushing load at 100 mm s^{-1} ice drift speed. Arrows indicate the slope of relative velocity at the moment of failure. The peak loads from Regions A and B in Figure 5 are indicated.

The tests showed that both the velocity effect and compliance effect originate from the same strengthening effect at low relative velocity between ice and structure. Plotting the global loads as a function of constant penetration speed, or far-field ice drift speed, can be misleading as the motion of the structure plays a role in the rate of loading experienced by the ice. As the velocity effect is applicable to all structures, rigid or compliant, it seems most reasonable to account for that effect in design. When this is done, there is no need to increase the loads further to account for compliance.

An important note here is that this finding does not contradict the earlier works on the compliance effect (Kamesaki et al., 1996; Kärnä et al., 2008; Jefferies et al., 2008). The higher global peak loads on compliant structures are likely to be observed more often than high loads on rigid structures. In full-scale, there are simply more ice conditions where the high loads could develop for a compliant structure compared to a rigid structure when all ice drift speeds are assumed equally likely. In model-scale tests, one has to include rigid structure tests at very low penetration speeds, 1 mm s^{-1} or perhaps even lower, to observe the velocity effect. The fact that loads on compliant structures can be higher than those on rigid structures for the same far-field ice speed remains. But this fact should not be confused with the statement that extreme global loads on compliant structures are higher than on rigid structures for which there seems to be no direct evidence from full-scale and contradicting evidence from model-scale.

ACCOUNTING FOR THE VELOCITY EFFECT IN C_R IN ISO 19906

Based on the analysis presented in the previous section, it is recommendable to account for the velocity effect in the ice strength coefficient used to determine the peak loads during intermittent crushing. The currently suggested values for C_R and methods for determining C_R in ISO 19906 account for this in the way summarized in Table 1.

Table 1. Suggested values and methods for determining C_R and accounting of the velocity effect therein.

Value for of method of determining C_R in ISO 19906 (ISO, 2019)	Description and reference to ISO 19906 (ISO, 2019)	Comment on accounting for the velocity effect
1.8 MPa	Nominal value for temperate regions (A.8.2.4.3.3)	Based on high-speed crushing data (> 0.1 m/s) and accounts for velocity effect (and some dynamic magnification) by a factor 1.4 (Kärnä and Masterson, 2011).
2.8 MPa	Nominal value for Arctic FY and MY ice (A.8.2.4.3.3)	Accounts for velocity effect included in dataset used to derive the value (Kärnä and Masterson, 2011).
2.4 MPa	Nominal value for Subarctic regions (A.8.2.4.3.3)	No explicit reference about velocity effect has been found.
Table A.8-4 (Figure 2 in this paper)	Examples of ice strength coefficient dependence on exposure to ice events (A.8.2.4.3.3)	Derived from the same high-speed crushing data (> 0.1 m s^{-1}) as the value of 1.8 MPa at the top of this Table. Does not include a factor to account for the velocity effect.
$C_R = C_{R0} \cdot \frac{\sigma}{\sigma_0}$	Scaling method for C_R taking as input the nominal value of 1.8 MPa or 2.8 MPa as a reference area strength parameter C_{R0} (A.8.2.4.3.4)	Velocity effect included depending on which reference value is taken for scaling.

DISCUSSION

It is not the purpose of this paper to analyze or discuss the way the velocity effect has been accounted for in design standards. In general, for Baltic Sea offshore wind developments the nominal value of 1.8 MPa seems the most appropriate choice as a starting point, also given that no structure ever built in the Baltic would have failed if this value had been used (Määttänen and Kärnä, 2011). The value can still be changed for exposure to different locations in the Baltic Sea with, for example, the method proposed in Thijssen and Fuglem (2015).

The data collected during the LOLEIF and STRICE campaigns might reveal more information on what is an appropriate value for the crushing coefficient for low-velocity interaction. The data analyzed by Kärnä and Qu (2006) were limited to a selection of high-speed (> 0.1 m s^{-1}) brittle crushing events. Analysis of the low-speed data has so far been very limited, at least in the public domain. It is noted that, given the nonlinear nature of ice-structure interaction at low speed, the data should be interpreted using some theoretical framework as a basis.

A large part of the analysis in this paper relies on data from basin tests which should always be critically evaluated for their relevance to full-scale scenarios. In the test campaign that was conducted, this aspect was specifically addressed by running experiments aimed at reproducing characteristics of the dynamic interaction observed at full-scale for the Molikpaq platform and Norströmsgrund lighthouse (Hendrikse et al., 2022b). The results of those tests were qualitatively correct in terms of the development of ice-induced vibrations which give confidence in the relevance of this model test campaign for full-scale scenarios. It is emphasized that the focus here is on the effects involved during crushing on rigid and compliant structures and not on the determination of actual design values or design loads from the model tests.

CONCLUSION

When determining the design peak loads during intermittent crushing on the basis of the crushing equation in ISO 19906, it is important that the C_R coefficient used accounts for the velocity effect. The velocity effect herein refers to the observation that level or pack ice loads are generally largest for low far-field ice drift speeds or low relative velocity between ice and structure. For the Baltic Sea region, the nominal value of 1.8 MPa contains a factor to account for this effect. For the Arctic region, the value of 2.8 MPa also contains some provision originating from the full-scale data used to define this value which included the observations of the velocity effect.

It does not seem necessary to account for the compliance effect separately when defining C_R, if the velocity effect is included. It is shown with dedicated ice tank tests that the compliance effect is merely an observation of the same strengthening effect causing the velocity effect at different far-field ice drift speeds. Thus, when the velocity effect is accounted for, the compliance effect is also necessarily covered. This is in accordance with current recommendations in ISO 19906.

It is recommended to revisit the Norströmsgrund lighthouse data with the specific purpose of analyzing low-velocity interaction events which have so far not received as much attention as the high-speed brittle crushing events. The purpose of such study would be to obtain a relation between high-speed peak loads and low-speed peak loads which can help to substantiate the empirical factor currently used to account for the velocity effect in ISO 19906.

ACKNOWLEDGEMENTS

The author thanks the participating organizations in the SHIVER project: TU Delft and Siemens Gamesa Renewable Energy for supporting this work. The SHIVER project is co-financed by Siemens Gamesa Renewable Energy and TKI-Energy by the ‘Toeslag voor Topconsortia voor Kennis en Innovatie (TKI's)’ of the Dutch Ministry of Economic Affairs and Climate Policy.

I wish to thank everyone who initiated discussions on the topic of this paper in relation to offshore wind developments the past five years. Thanks to Florian van der Stap for posing the question that triggered the writing of this paper. Thanks to Richard McKenna for valuable insights on the development of the standard and reminding me that standards require expertise to apply and avoid misinterpretation. Thanks to Jan Thijssen and Mark Fuglem for their input on the C_R coefficient values in Table A.8-4 in ISO 19906 and helpful remarks about the available data from the Norströmsgrund lighthouse.

REFERENCES

Gravesen, H., Kärnä, T., 2009. Ice loads offshore wind turbines in southern Baltic Sea. *Proceedings of the 20th International Conference on Port and Ocean Engineering under Arctic Conditions*, June 9-12, 2009, Luleå, Sweden, POAC09-3.

Hammer, T.C., Willems, T., & Hendrikse, H., 2023. Dynamic ice loads for offshore wind support structure design. *Mar. Struct.*, 87, 103335.

Hendrikse, H., Hammer, T.C., van den Berg, M., Willems, T., Owen, C.C., van Beek, K., Ebben, N.J.J., Puolakka, O., Polojärvi, A., 2022a. Experimental data from ice basin tests with vertically sided cylindrical structures. *Data Br.* 41, 107877.

Hendrikse, H., Hammer, T.C., Owen, C.C., Puolakka, O., Willems, T, et al., 2022b. Ice basin tests for ice-induced vibrations of offshore structures in the SHIVER project. *Proceedings of the ASME 2022 41st International Conference on Ocean Offshore and Arctic Engineering,* OMAE 2022, Hamburg, Germany, OMAE2022-78507, 9p.

ISO, 2019. Petroleum and natural gas industries – Arctic offshore structures. *International Standard, Second edition*, 2019-07, ISO 19906:2019(E).

Jefferies, M.G., Wright, W.H., 1988. Dynamic response of “Molikpaq” to ice-structure interaction. *Proc. 7th Int. Conf. Offshore Mechanics and Arctic Engineering, OMAE’88, Houston, Tex.*, Vol. IV, pp. 201-220.

Jefferies, M., Kärnä, T., Løset, S., 2008. Field data on the magnification of ice loads on vertical structures, in: Jasek, M. (Ed.), *Proceedings of the 19th IAHR International Symposium on Ice. IAHR*, Vancouver, British Columbia, Canada, pp. 1325–1343.

Kamesaki, K., Yamauchi, Y., Kärnä, T., 1996. Ice force as a function of structural compliance, *Proceedings of the 13th IAHR International Symposium on Ice. IAHR*, Beijing, China, pp. 395–402.

Kärnä, T., Guo, F., Løset, S., Määttänen, M., 2008. Small-scale data on magnification of ice loads on vertical structures, in: Jasek, M. (Ed.), *Proceedings of the 19th IAHR International Symposium on Ice. IAHR*, Vancouver, British Columbia, Canada, pp. 1313–1324.

Kärnä, T., Masterson, D., 2011. Data for crushing formula. *Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions*, July 10-14, 2011, Montréal, Canada. POAC11-064.

Kärnä, T., Qu, Y., 2006. Analysis of the size effect in ice crushing – edition 2. Version 1.3, 26-08-2009. VTT Internal report. RTE50-IR-6/2005.

Määttänen, M., Kärnä, T., 2011. ISO 19906 Ice crushing load design extension for narrow structures. *Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions*, July 10-14, Montréal, Canada, POAC11-063.

Owen, C.C., Hammer, T.C., Hendrikse, H., 2023. Peak loads during dynamic ice-structure interaction caused by rapid ice strengthening at near-zero relative velocity. *Cold. Reg. Sci. Technol., 211, 103864.*

Peyton, H.R., 1966. Sea ice forces. *Proceedings of a Conference held at Laval University, Quebec, 10-11 November 1966,* pp.117-123.

Singh, S.K., Timco, G.W., Frederking, R.M.W., Jordaan, I.J., 1990. Tests of ice crushing on a flexible structure, *Proceedings of the 9th Offshore Mechanics and Arctic Engineering Symposium. OMAE*, Houston, Texas, USA, pp. 89–94.

Sodhi, D.S., 2001. Crushing failure during ice-structure interaction. *Engineering Fracture Mechanics*, 68, 1889-1921.

Thijssen, J., Fuglem, M., 2015. Methodology to evaluate sea ice loads for seasonal operations. *Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering*, OMAE2015, May 31-June 5, St. John's, Newfoundland, Canada. OMAE2015-42194.

Thijssen, J., Fuglem, M., Dolny, J., 2016. Pack Ice Loads on Seasonally Operating Semi-Submersible in the Labrador Sea. *Proceedings of the Arctic Technology Conference*, St. John's, Newfoundland, Canada, October 2016, OTC-27333-MS.

Van den Berg, M., Owen, C.C., & Hendrikse, H., 2022. Experimental study on ice-structure interaction phenomena of vertically sided structures. *Cold. Reg. Sci. Technol.*, 201, 103628.