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Rational structural criteria for ice design

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ABSTRACT

Structure performance in the ISO 19906 arctic structures standard is dictated by life-safety and environmental considerations without distinguishing between these objectives. Additional objectives can involve societal concerns such as reliability of energy supply and economic considerations (including business disruption) that underpin sound design. As part of an ongoing revision process, the scope of the ISO 19900 general requirements standard is expected to address reliability-based and risk-informed design approaches, deal more specifically with floating structures, expand on limit states in terms of functional criteria and damage states, and address support structures for wind turbines. In the paper, we look at how this expanded framework might be used to help set limit states criteria using structure performance with respect to adverse consequences, functional criteria and damage state concepts. As a way of illustrating the application of the design framework, examples are presented for a hydrocarbon production vessel in an iceberg region where life-safety and environmental damage are mitigated, and an offshore wind farm in an extensive ice cover where reliability of supply is to be ensured.

KEY WORDS Ice design; Structure performance; Limit states; Damage states

INTRODUCTION

Significant progress has been made in recent years on the design process for ice-resistant structures in a marine environment and much of this is encapsulated in the ISO 19906 Arctic offshore structures standard (ISO, 2019a). ISO 19906 relies on the ISO 19900 General requirements standard (ISO, 2019b) for common elements across structure type such as structural limit states, exposure levels (to be changed to consequence levels in the next revision), design situations, design approach (e.g. the partial factor semi-probabilistic approach) and other measures such as robustness that help to ensure safe structures. ISO 19900 is also the high level standard for the ISO 1990X series of structure standards that sets out a framework for future development of these standards along with ISO 2394 General principles on reliability for structures (ISO 2015). Work is also underway to coordinate the ISO 1990X series with the wind turbine standards IEC 61400-3-1 (Design requirements for fixed offshore wind turbines) and IEC 61400-3-2 (Design requirements for floating offshore wind turbines). The intent is for the ISO 1990X standards to deal with the support structure and foundation, while the IEC standards deal with the wind turbines and other infrastructure in a wind farm.

The ISO 19900 standard (ISO, 2019b) is presently under revision. The scope of these changes includes better coordination with the IEC wind turbine standards, integration of provisions relating to all structure types including floaters (present content is weighted toward jacket structures), the introduction of reliability-based and risk-informed design approaches, and additional provisions relating to damage states and performance with respect to different sources of risk (e.g. life-life safety, environmental pollution, reliability of energy supply and business disruption). The design process is constantly evolving and performance-based regulations that will rely on these standards are now being adopted (e.g. Canada 2024a, 2024b).

While the above framework is very broad, the present paper provides a high-level overview of how it can potentially help to improve design criteria for offshore structures in marine environments where icebergs and thermally-grown ice (sea and lake ice) are present. Unanticipated design or assessment situations are sometimes encountered, such as a short-term situation where a structure might be occupied temporarily for an unanticipated repair. The ISO 19906 Arctic structures standard (ISO, 2019a) allows some flexibility for reliability-based design (involving probability distributions for loads and resistance, and the probability that the limit states are exceeded) and this paper provides a framework that could be used to assist in its application. As well, there is a gradual move towards risk-informed design methods (in which the consequences of failing to meet design criteria are considered) in the offshore and the present framework can potentially be of assistance in this transition.

The first part of the paper deals with structure performance with respect to different sources of risk. The application of and distinctions between damage states, functional states and limit states are also described in a general sense for both fixed and floating structures. The last part of the paper addresses more specifically design situations involving iceberg interactions with floating structures and sea ice interactions with offshore wind farms.

To date, floating oil and gas production structures (Floating Production Storage and Offloading, i.e. FPSO) have only been used in marginal ice environments in which the primary hazard involves iceberg impacts. Although some sea ice can be tolerated by floating structures, this is generally limited to smaller floes or when larger floes are broken up using ice management vessels. The focus in the first example for an FPSO is limited to the iceberg impact situation and performance with respect to life-safety, hydrocarbon loss to the environment and business disruption. Affected parts of the structure can include the outer hull, stiffeners, framing, the inner hull, the ballast system and the stationkeeping system.

The second example addresses the design of bottom-founded wind turbine farms in a sea or lake ice environment. The main performance objective is the reliability of energy supply and avoidance of business disruption. In terms of the performance objectives, separate ice loading criteria might be used for individual turbine structures, multiple turbine structures and substations.

PERFORMANCE CRITERIA

Aside from fulfilling the purpose for which an offshore structure is designed, an important objective is to meet performance criteria relating to the various sources of risk to which it can be exposed. For offshore oil and gas structures and wind turbine structures, life-safety, environmental damage, reliability of energy supply and business disruption are generally the most important sources. In Table 1, some typical performance ranges are given, from no impairment, damage or disruption to unacceptable consequences or complete loss. In practice, the choice of performance ranges would depend on the particular design situation. Although five ranges are identified in Table 1, performance could be categorized using a different number of ranges, depending on the design situation. As well, the number of performance ranges need not be the same for different sources of risk as shown in the Table 1 example, and a performance range related to one source need not align with the same one for another. For example, significant loss of hydrocarbons to the environment need not occur with significant loss of life. Loss of hydrocarbons might be categorized as none, small quantity and large quantity, while human safety might be categorized into the five ranges shown in Table 1.

It can be useful to consider transitions from one performance range to the next, i.e. performance limits, that can be assigned an annual probability. For example, the long-term failure to supply a significant proportion of expected energy capacity might be assigned an annual probability not to exceed 10^{-3} or 10^{-4}. Performance limits could be set by a regulator based on acceptable values for an industry or society in general. When setting performance limits, it is important to acknowledge potential contributions of unanticipated factors, design errors and material/construction defects on the failure to meet these limits.

Table 1. Examples of performance ranges with respect to different sources of risk

Life-safety	**Environmental damage** [specifically related to hydrocarbon spills]	**Reliability of energy supply**	**Business disruption**
No impairment.	No release.	No impairment.	No disruption.
Discomfort or temporary impairment.	Small and finite release or continuous release with minimal flow. Generally containable.	Temporary or minor supply disruption.	Some downtime. Cosmetic damage.
Some injury potential.	Moderate finite release or continuous release with moderate flow. Partially containable.	Short-term failure to supply large part of capacity or long-term failure to supply small part of capacity.	Significant downtime. Repairable damage.
Major injury potential.	Significant release or uncontrolled flow. Partially containable.	Long-term failure to supply large proportion of capacity.	Permanent downtime. Unrepairable damage.
Unacceptable consequences, including loss of life.	Major release or uncontrolled flow. Not containable.	No supply.	Complete loss of structure.

FUNCTIONAL CRITERIA

Whereas performance criteria relate to potential sources of risk, functional criteria relate to the structure and critical systems that allow risk to be mitigated. The main kind of functional criteria involve limit states, which involve quantifiable states of the structural components, expressed as strains or other measures of structural response. Functional criteria can also involve issues such as the capability of systems for evacuation, heading control (for floaters), ballast control (for floaters) and operation of safety valves. Damage states are sometimes used instead of limit states when quantification of the condition of the structure is difficult or when the state of the structure is a starting point for subsequent short duration design situations, such as to secure hydrocarbons or make repairs. Damage states can be tied to the intensity of the interaction that is the source of the damage, as in impact or blast situations, based on analyses that allow calibration for these design situations. Limit states, often classified as ultimate and serviceability (e.g. ISO 2015, 2019b) and fatigue (e.g. ISO 2019b), lend themselves to circumstances when the state of the structure can be quantified. Strains in structural members associated with the onset of permanent deformation or buckling are sometimes used to represent limit states. Although limit states are quantified, this does not necessarily mean that an exact quantification is possible. The specification of limit states is often done by choosing strain limits that are known to be safe rather than attempting to characterize complex structural behaviour.

Examples of functional states are shown in Table 2 for fixed offshore structures and the hull and stationkeeping of floating structures. Fixed structures could include monotowers, jacket structures or concrete structures. Floating structures include floating wind turbines and floating oil and gas production vessels with disconnectable mooring, ballast control and heading control systems. Functional states begin with the intact structure and progress, as necessary, for different design situations, through different states of impairment, and often ending with complete loss of the structure. The functional states can be traditional limit states, damage states that extend the scope of limit states to significant amounts of damage, or strictly functional states of the various systems involved in the operation of the structure. As with the performance criteria in Table 1, the choice of five states is somewhat arbitrary and should be defined to best represent key functional issues relating to the design.

Table 2. Examples of functional states for offshore structures

Functional state	**Fixed**	**Floating**	
		Hull	**Stationkeeping**
No impairment	No damage.	No damage.	No impairment.
Minor impairment	Deflection; vibration; surface cracking.	Denting of outer hull; buckled stiffener.	Impairment of line/anchor or thruster.
Moderate impairment	Local impairment; loss of component capacity; partial loss of stiffness.	Damage to secondary framing or ballast control.	Line or thruster failure. Loss of heading control.
Significant impairment	Impaired ability to withstand actions; ability to withstand gravity actions and subsequent action of type that caused event.	Breach of outer hull; damage to major frame; permanent longitudinal deformation.	Complete loss without collateral damage.
Complete loss	Collapse; toppling; sliding failure.	Breach of inner hull; capsize; sinking.	Complete loss with collateral damage.

DESIGN SITUATIONS

As outlined in ISO (2019b), design situations for offshore structures are established for each type of hazard (e.g. wind, wave, ice, explosion) based on the associated actions (i.e. loads), structural configuration, limit states and other parameters. When establishing these design situations, it is helpful to make reference to the above performance and functional criteria that underpin the ISO and IEC offshore standards.

While performance and functional criteria for the structure are integral to the design process described above, they are separate concepts. Performance criteria are associated with the different sources of risk, whereas functional criteria relate to the structure and its critical systems (i.e. ballast and heading control systems for floating structures). Standard procedures for the design of offshore structures in ice environments typically do not distinguish between different sources of risk. For example, the design approach for oil and gas structures in ice (ISO 2019a, 2019b) does not distinguish between life-safety and environmental damage concerns. The design approach for fixed offshore wind turbines in IEC (2019), while ensuring structural integrity with respect to all hazards, does not deal explicitly with reliability of supply nor business disruption. When developing a rational set of design situations for any offshore structure, it is helpful to match project requirements with the various sources of risk and particular adverse consequences (see Table 1) with corresponding functional states of the structure (see Table 2).

In the following sections, we look specifically at iceberg hazards for floating oil and gas production vessels and sea ice hazards for bottom-founded structures in offshore wind farms.

DESIGN SITUATIONS FOR ICEBERG IMPACT WITH A FLOATING STRUCTURE

Potential sources of risk for an FPSO (floating production storage and offloading) vessel include life-safety for personnel on board and mobilized in emergency situations, loss of hydrocarbons to the ocean that pollute the environment, and either permanent business disruption or lost production time to allow for repair. In an iceberg environment, consideration is given not only for the FPSO itself, but also for the subsea infrastructure, which can include mooring lines, risers, wellheads on seabed and in-field pipelines. Iceberg interactions represent a very real risk for FPSOs, and relevant design situations are not well treated in open-water standards for floating production vessels and subsea infrastructure. The entire production infrastructure, including subsea, needs to be considered for iceberg design situations, as required in the ISO 19906 Arctic offshore structures standard (ISO, 2019a).

When considering iceberg risk to subsea infrastructure in the waters off eastern Canada, innovative design approaches need to be considered - iceberg interactions with equipment on the sea floor are infrequent (typically around 10^{-4} per year), the iceberg loading process is uncertain, and the behaviour under load of the wellhead, soil and conductors is complex. It makes sense to focus on the primary risk, that of hydrocarbon loss to the environment, as the design objective rather than consideration of, for example, strain criteria for the wellhead assembly. Subsea infrastructure can consist of many individual entities hundreds of metres apart that might not be impacted simultaneously. If partial action factors on an FPSO production structure are calibrated to a particular reliability level (e.g. annual target and maximum allowable probability of exceeding limit states), it might be appropriate to consider an equivalent annual target for hydrocarbon release from all subsea infrastructure. These circumstances provide a case for inclusion of reliability levels used for calibration in offshore standards as long as calibration procedures are well documented.

The choice of hydrocarbon release as the environmental risk metric is beyond the usual scope of limit states. Generally, hydrocarbon loss is the result of failure of downhole safety valves to close when loss of pressure occurs as a result of damage to the conductor, wellhead or riser. While impairment of these components can be described using limit states, it is difficult to characterize the performance of a safety valve in this way, which can either fail to function or only close partially under depressurization. Loss of hydrocarbons to the environment can be associated with a functional metric, such as failure of a safety valve to close on depressurization. When the next revision is implemented, ISO 19900 General requirements will allow reliability-based and risk-informed design approaches when their use is detailed in structure type standards such as ISO 19906 Arctic offshore structures.

For the hull of a FPSO, a more conventional design process is advocated in ISO 19904-1 Floating offshore structures (ISO, 2019c) and ISO 19906 (ISO, 2019a). Inherent in this process is the assumption that life-safety and pollution are dealt with together. In Table 3, an attempt has been made to identify the limit states and structural functions for these two different risk objectives. Particularly for the abnormal limit state (ALS) outlined in the ISO 19900 General requirements standard (ISO, 2019b), the structural functions associated with life-safety and hydrocarbon release are different. It therefore makes sense to consider separate design situations and structural limit states for each of them.

Table 3. Limit states, risk objectives and structural function for iceberg impact with the hull of a FPSO vessel

Limit State	Risk objective	Structural function
ALS[#] (Abnormal Limit State)	Ensure life-safety of personnel on board.	Maintain stability and remain floating until personnel can be evacuated. Avoid fire and blast. Avoid complete loss of hull integrity and maintain reserve capacity. Stationkeeping system impairment is factored into maintenance of other structural functions.
ALS[#] (Abnormal Limit State)	Avoid release of hydrocarbons.	No breach of inner hull. Maintain structural integrity to critical equipment (risers and gas piping). Stationkeeping system impairment should not lead to loss of containment. Maintain stability and remain floating until repairs can be made or FPSO removed from site and secured.
ULS[#] (Ultimate Limit State)	Avoid collateral damage, ISO 19901-7 (ISO, 2013).	If complete failure of stationkeeping system occurs, risk to adjacent infrastructure is acceptable.
ULS[#] (Ultimate Limit State)	Structure remains fit-for-purpose over design life.	Ability to sustain loading is maintained. Repairs can be made either on-location or off-location to continue operation.
# Note that the ULS and ALS will be changed in the revision to ISO 19900 to ULS_1 for local failure, ULS_2 for global rigid body failure and ULS_3 for progressive global failure mechanisms.		

The iceberg interaction example has been chosen to highlight the potential for creating effective and safe designs by separating the design process for different sources of risk. This means that, rather than considering iceberg interaction as a single design situation, one considers two separate ones - life-safety for an iceberg interaction and hydrocarbon loss for an iceberg impact, as illustrated in Table 3. In Table 2, functional states were shown for the hull and stationkeeping system of a floating structure. In the last column of Table 3, only some of these states are relevant. Individual structures can have different levels or categorization of structural impairment depending on the design, and the functional impairment threshold might be different depending on whether life-safety or pollution is considered. For example, a localized breach of the inner hull is likely to have a minimal effect on life-safety.

In this context, one might differentiate between a limit state and a damage state. Limit states are generally quantifiable measures of the state of the structure and are often represented in terms of material strains. Damage states can include impairment of several structural functions, in which some of them are not readily quantifiable. Damage states also apply more readily to circumstances involving subsequent steps such as evacuation of personnel or changes to the operation of critical marine systems.

For floating offshore structures, a common source of failure is loss of mooring capability. In the ISO 19901-7 Stationkeeping standard (ISO, 2013), single line failure can be accepted temporarily under limited circumstances. If neighbouring infrastructure (e.g. other platforms) could be impacted, design criteria need to be enhanced through consideration of a lower probability design event or through partial factor adjustment to meet a more stringent reliability target or limit. This last situation is an example of where the traditional design process is best amended to use a reliability-based approach.

Structural function in the last row of Table 3 includes the ability of the FPSO to withstand the loading for which it was designed. For example, denting of the outer hull or local inelastic damage to the framing should not impair the ability of the vessel to meet the original design requirements. Once this has been resolved, the potential need for repair can be assessed. The ability to sustain load can be dealt with via limit states, whereas the need for repair might involve a more complex assessment of structural function by means of damage states.

Stationkeeping (ISO 19901-7 – ISO, 2013) and ice management (ISO 35104 – ISO, 2018) can have significant effects on iceberg actions with the hull of a FPSO. Active elements include thrusters for heading control and passive elements, like mooring lines, can control offset and indirectly affect heading control. Because iceberg drift direction need not be aligned with wind and wave directions, it can be advantageous for the heading control system to operate in a way that minimizes the potential for impacts with the side of the hull and be consistent with the assumptions made in the design. The functional state of the stationkeeping system therefore needs to be part of the design process and needs to be considered in the limit state criteria. All existing hydrocarbon production facilities in the vicinity of the Grand Banks of Newfoundland, including two FPSOs, rely on iceberg management to reduce the frequency of iceberg interactions. The resulting interaction frequencies are less than 0.01 per year, obviating the need to consider ULS criteria and highlighting the importance of ALS criteria for hull design. Similarly, the functional state of the ice management system needs to be considered in the limit state criteria.

DESIGN SITUATIONS FOR WIND FARMS IN A SEA ICE ENVIRONMENT

In a sea ice or lake ice environment, fixed (bottom-founded) wind turbine structures can be subjected to interactions from drifting ice floes, continuous or near-continuous moving ice covers, and landfast ice covers with a connection to shore (e.g. Fuglem et al, 2025). An ice cover can vary in thickness due to deformation processes over the course of the winter and can contain pressure ridges and rubble fields with varying depths of consolidation (i.e. refreezing). Whether for moving or landfast ice, the loads experienced by multiple wind turbine structures in a wind farm would likely be correlated if the ice thickness were relatively constant. Shielding effects as a result of proximity to shore and to other wind turbines as well as whether the ice fails locally at the structures or fractures more regionally could influence correlation between the loads on different structures. For discrete floes and where deformed ice in the form of ridges and rubble fields are present, floe size and local thickness dominate the interaction, so one would expect less correlation between the loads on different wind turbine structures in a wind farm.

The ice load cases in the IEC standard for fixed offshore wind turbines (IEC, 2019) are summarized in the first three rows of Table 4, which represent a synthesis of the eight different load cases for ice loading in the standard. The focus of these load cases is the integrity of individual wind turbine structures.

Table 4. Load cases for offshore wind farm subjected to sea ice actions (adapted in part from IEC, 2019)

Design situation	Limit state (LS)	Structural function
Load on single wind turbine from temperature fluctuations, water level fluctuations spray ice accumulation and arch effects	Ultimate LS (estimated maximum effects)	Inability of wind turbine to function to full potential
Load from moving ice on single wind turbine in power production and parked modes	Ultimate LS (50-year ice action)	Inability of wind turbine to function to full potential
Load from moving ice on single wind turbine in power production and parked modes	Fatigue LS (load history)	Inability of wind turbine to function to full potential
Load from ice on multiple wind turbines in power production and parked modes	Ultimate LS (maximum effects or 50-year action)	Simultaneous inability of multiple wind turbine structures to function to full potential
Load from ice on offshore substation	Ultimate LS (maximum effects or 50-year action)	Regardless of ice loading source, inability to collect power from individual wind turbines and distribute to the power grid
Note – Shaded cells have been added to account for the considerations discussed in this paper.		

The performance criteria relating to the different sources of risk, as shown in Table 1, highlight the need to ensure reliability of energy supply from a wind farm. Significant loss of supply can result from simultaneous failure of a significant number of wind turbine structures or, alternatively, the loss of an offshore substation as a result of ice loading. Although the last two shaded rows in Table 4 represent design situations that are not considered in IEC (2019), they have been added because of their relationship with reliability of energy supply and business disruption. Depending on the energy supply strategy, the equipment used and repair times, the consequences of multiple wind turbine and substation failures might be different because of the time required to resume full or near-full wind farm production. Similarly, damage to cables from a substation to shore from ice ridges in shallow water or near the shore landing can have significant consequences.

Where multiple structures exist that are subjected to similar actions, simultaneous failure can be important. The issue is not necessarily that the failure of one structure leads to failure of another, it is that the magnitude of the action acting on multiple structures can be highly correlated because the ice is approximately the same thickness. Furthermore, if the reaction force to wind stress on the ice cover is shared by multiple wind turbine structures, failure of one structure can lead to shedding of a portion of the reaction force onto the other structures. This last situation would occur typically in landfast ice. For moving ice, structures don't have to be very far apart for loads to be independent (e.g. ISO 2019a, clause A.8.2.4.9), whereas wind turbines are always placed far enough apart that this is not an issue. Although turbine structures on the edge of a wind farm in a landfast ice regime are likely to be subjected to higher ice forces, load sharing is complicated by shoreline geometry, attachment points of the ice to the seabed or lake bed, to viscoelastic behaviour of the ice and to discontinuities in the ice cover (e.g. cracks and where there are out-of-plane displacements). When implementing the shaded load cases in Table 4, the above considerations will need to be kept in mind.

The different exposure levels, L1, L2 and L3, described in the ISO 19900 general requirements standard (i.e. ISO, 2019b) potentially provide a means of dealing with the different consequences for loss of single wind turbine structures, multiple wind turbine structures and offshore substations. Ongoing work with the revision to the ISO 19900 standard, for which the scope has been expanded to wind turbine structures, suggests that a single wind turbine be designated L3 (the least stringent exposure level) whereas multiple wind turbines and substations be designated L2. The most stringent exposure level, L1, is associated with life-safety and significant pollution considerations.

SUMMARY

Particularly for the offshore oil and gas industry but also for offshore wind farms, event-based and partial factor design methods have evolved that rely on structural limit states. For many structures and design situations, these have resulted in safe and efficient designs. Experience has shown that these methods have limitations for arctic offshore environments. This paper represents but a small step in describing a design framework for offshore structures in ice environments in terms of performance with respect to risk objectives and the functional characteristics of the structure. While elements of this framework are not new, they have not found their way into the ISO standards of oil and gas structures (ISO, 2019a; ISO 2019b) and the IEC standard for fixed offshore wind turbines (IEC, 2019). This situation will change with the implementation of the next revision for ISO 19900 General requirements (ISO, 2019b).

For floating (FPSO-type) structures in an iceberg environment, some of the limitations of a partial-factor design method have been addressed for the associated subsea infrastructure. Experience has shown that rational arrangement, placement and design of subsea wellheads cannot be achieved without resort to a reliability-based approach, an approach that goes beyond standard offshore practice. As well, hull design for iceberg interactions relies on structural design, the design and operation of critical marine systems, and on ice management assets and systems. In such cases, the functional characteristics of the structure and related systems are best tied to the major sources of risk, i.e. life safety and pollution.

To date, focus in standards for the offshore wind industry has been on individual wind turbine structures. While protection of assets is a significant concern, wind farms have an important role in the electrical grid and reliability of energy supply should be an area of focus in future. This paper has proposed that a risk-informed approach can be advantageous for addressing single and multiple wind turbine structures and offshore substations.

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