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RISK AND RELIABILITY IN THE DESIGN OF ARCTIC OFFSHORE STRUCTURES

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ABSTRACT

Risk and reliability, and consequential issues including exposure levels, action probabilities, limit states, and action factors, are integral components of the philosophy for safe and competitive design of offshore structures, as implemented in the ISO 19900-series of International Standards. These standards describe a limit state based design procedure that is intended to result in a structure with an appropriate level of reliability and acceptable performance. Despite recent clarifications to the general design approach, gaps remain in the general standards. This paper discusses the issues as relevant for arctic offshore structures. It identifies gaps that are closed and issues that need to be taken further in the specific standard for arctic offshore structures. These issues include reliability targets, "abnormal" environmental conditions, "beyond abnormal" conditions, and reserve strength of gravity-based structures. Risk and reliability in design can also depend on operating philosophy and practices (e.g. ice management, disconnection of floating structures) with consequent modification of design action hazard curves.

INTRODUCTION

ISO 19906 (2010), published in December 2010, specifies requirements and provides recommendations and guidance for the design, construction, transportation, installation and removal of offshore structures, related to the activities of the petroleum and natural gas industries in arctic and cold regions. Various overviews of ISO 19906 have been published, for example by Spring et al. (2011).

General and unifying principles for all types of offshore structures are provided in ISO 19900 (2013), first published in 2003 and updated with a second edition in December 2013. These principles include exposure levels, limit states design, and the partial factor approach, as well as considerations for structural configuration, robustness, reserve strength, hazards and environmental conditions.

ISO 19902 (2007) sets out detailed design requirements for fixed steel offshore structures based on the principles of ISO 19900. Although not formally limited by scope, the practice and the approach to "safety" is based on experience of steel lattice tower platforms as found in the Gulf of Mexico and the North Sea. ISO 19902 has shortcomings with respect to issues that are important for arctic offshore structures.

ISO 19906 is focused on supplementary provisions for conditions in arctic and cold regions, in particular with respect to ice actions and events. ISO 19906 relies on the "structure-specific" standards such as ISO 19902 for detailed structural requirements. ISO 19906 is obliged to extend some of the general concepts in ISO 19900 and ISO 19902 in order to address arctic offshore structures. Participation of all arctic nations in the development of ISO 19906 has ensured that consensus values of specific parameters are quantified and codified in ISO 19906 for all arctic and cold regions.

Work to revise ISO 19906 started in 2014, both to improve the content as more experience has been gained and to improve harmonisation with subsequent updates and publications related to other of the ISO 19900-series. A number of issues were raised in Thomas (2014), to which this current paper is a sequel. Experience to date indicates that there is a continuing need to fill gaps in ISO 19900 and ISO 19902 on issues that are particularly important for arctic offshore structures.

SOME BASIC CONCEPTS

Action and Load

The term "action" is used throughout ISO standards instead of the term "load". ISO 19900 (2013) defines action as "external load applied to the structure (direct action) or an imposed deformation or acceleration (indirect action)".

Extreme and Abnormal

The term "extreme" in ISO 19906 is reserved for events and actions with annual probability (of occurrence or exceedance) of 10^{-2}. In common parlance and in some technical publications, "extreme" is used as a generic adjective for design actions beyond the operational level, or as the maximum of a set of values within a defined time period, see Jordaan (2005). But in ISO 19906, and in this paper, this term has the precise definition described above.

Similarly, the term "abnormal" in ISO 19906 is reserved for events and actions with annual probability (of occurrence or exceedance) of 10^{-4}. A different term is required for describing very rare events with probabilities other than 10^{-4}.

ISO 19900 (2013) explains the relationship between return period and annual probability, in particular that return periods of 100 years and 10,000 years correspond to annual probabilities of 10^{-2} and 10^{-4} respectively. However, using the "annual probability" terminology, and focusing on annual probabilities expected during the design life, helps to avoid fruitless speculation about events 10,000 years in the future.

Limit states

ISO 19900 states that the performance of a whole structure or part of it shall be described with reference to a specified set of limit states beyond which the structure no longer satisfies the design requirements. The limit states are divided into the following four categories:

- serviceability limit states (SLS) that correspond to the criteria governing normal functional use;
- fatigue limit states (FLS) that correspond to the accumulated effect of repetitive actions;
- ultimate limit states (ULS) that generally correspond to the resistance to extreme applied actions;
- accidental limit states (ALS) that correspond to situations of accidental or abnormal events.

Abnormal environmental actions have design significance for arctic offshore structures far exceeding that for Gulf of Mexico lattice towers. Therefore ISO 19906 names the fourth set of limit states as “abnormal (accidental) limit states (ALS)”.

The ULS objective is to ensure that there is no reduction in structure reliability, with no significant structural damage and no repairs needed for restarting or continuing operation. The failure criteria relate to failure of an individual element or component, based on elastic analysis and factored resistances, although there can be nuances, e.g., around local plasticity.

The ALS objective is to ensure no loss of life or harm to the environment despite structural damage requiring repair or replacement of structure in order to restore reliability. The failure criteria relate to progressive collapse, beyond first failure of an element, such that plasticity, reserve strength, robustness, load shedding, energy dissipation etc., are considered.

This paper focuses on ULS and ALS with respect to risk and reliability of offshore structures.

RISK

As expressed by Jordaan (2005) among others, the concept of risk has two aspects: first, chance, and second, the unwanted consequences involved in risk; and the concept of “safety” conveys the overall objective of reducing risk to an acceptable level.

In the oil and gas industry, the concept of acceptable level of risk, or tolerable risk, is qualified by the over-riding imperative that no level of risk can be accepted, or tolerated, without a risk management plan. The further question, therefore, is at what levels do different risk mitigations and risk management plans apply. This is expanded below.

Chance and Probability

In a typical industry risk matrix, chance is usually expressed as likelihood and is quantified as either frequency or probability. Jordaan (2005) discusses the distinction. For structural design (ULS and ALS) probability is the important quantification. Design actions are calculated for design situations arising from extreme and abnormal events. ISO 19906 prescribes probabilities, in terms of annual probability of occurrence or exceedance, for these events.

Unwanted consequences and Exposure Level

In the ISO 19900-series of International Standards, unwanted consequences are addressed by Exposure Level.

ISO 19900 describes three exposure levels: L1, L2, and L3. The exposure level to be used in design or assessment of offshore structures is determined by considerations of “life-safety” and of environmental and economic consequences. The consequences are categorised into three Safety categories (S1, S2, and S3) and three Consequence categories (C1, C2, and C3), for which ISO 19900 provides a matrix for determining exposure level. Therefore exposure level is a categorisation of consequences.

L1 applies for a manned installation for which evacuation or shutdown is not planned in the face of extreme or abnormal situations. L2 and L3 can apply if increasing mitigation or elimination of risk to life safety and other consequences is demonstrated. This is explained further in Thomas et al. (2011) and the references from that paper.

Risk identification and management
It is common industry practice to identify, assess, and manage all risks that can reasonably be foreseen, however unlikely. This paper is concerned with risk events, defined in general terms as discrete, specific occurrences that negatively affect a decision, plan, firm, or organism. Risk events are identified, and can be assessed using a risk matrix to plot likelihood and consequence.

Requirements for risk mitigation and/or risk management planning are informed by the position on the risk matrix. A higher risk normally requires mitigation in order to reduce the risk to a level at which it can be managed. Although this could be considered as an "acceptable" level beyond which no further mitigation is required, the idea that the risk is then acceptable would be erroneous. This risk needs to be addressed and managed, normally by contingency response planning.

The underlying approach of ISO 19906 is that there is a break point at which risks transition from requiring mitigation by structural design, to being managed by other means such as operational planning. The break points are expressed as "reliability targets" for the structural design. The objective of the structural design is to reduce the likelihood of the risk event (such as element failure) to below the target for the exposure level. This is deemed to result in a structure with an appropriate level of reliability and acceptable performance.

Figure 1 illustrates the reliability targets in ISO 19906. These represent the break points between structural design and other planning. They are illustrated in typical risk matrix form.

		Likelihood of Risk Event - Reliability Targets							
		1	2	3	4	5	6	7	8
Consequence	S1, C1	Plan	L1	L1		Design			
	S2, C2	Plan		L2	L2		Design		
	S3, C3		Plan		L3	L3		Design	
Annual Probability		10^{-6} or lower	10^{-6} to 10^{-5}	10^{-5} to 10^{-4}	10^{-4} to 10^{-3}	10^{-3} to 10^{-2}	10^{-2} to 0.1	0.1 to 0.25	> 0.25

Figure 1 - Risk Matrix showing Reliability Targets for different Exposure Levels

The "S" and "C" consequence categories are described above. The most onerous is used to determine exposure level, where a level 1 (S1 or C1) is more onerous than a level 2, etc. Quantification of the reliability targets is discussed below.

RELIABILITY TARGETS - ISO 19906 APPROACH

"Reliability Target" as used in ISO 19906 is expressed as an annual probability of failure which is associated with global structural failure or with component failure leading to structural failure. ISO 19906 quantifies reliability targets as 1.0×10^{-5} for L1, 1.0×10^{-4} for L2, and 1.0×10^{-3} for L3, as illustrated in Figure 1. These reliability targets are provided for information and for optional use by the designer in specific circumstances such as those described below.

ISO 19906 emphasises that the reliability targets are for “single causes”, i.e., they apply the limit state combinations of actions for each design situation in isolation. They do not integrate reliability across different causes.

ISO 19900 (2013) recommends that “reliability targets should depend on the consequences of failure”, and states that the “chosen reliability targets should be consistent with established practice so as to maintain acceptable risk values”. It says that “Reliability targets for structural failure (e.g. for L1 and L2 exposure levels) have been established for the most relevant hazards” and refers to ISO 19902 for “extreme storm risk”. This is the “extreme” of common parlance, not the precise definition of “extreme”.

ISO 19902 (2007), unfortunately, does not establish reliability targets, nor does it provide information to differentiate the partial action factors. Instead, the designer is advised to perform a “calibration” of the partial action factors. ISO 19900 says that “separate calibration is generally required for each limit state and for each exposure level: L1, L2 and L3”.

The reliability targets in ISO 19906 were quantified by benchmarking industry practice for exposure levels based on life safety and consequence, as described in Thomas et al. (2011). The ISO 19906 targets were proposed by the ISO 19906 technical panel for Reliability, building on earlier research and codification for Canadian standards and for various North Sea countries, also influenced by research for API Load and Resistance Factor Design, and by other ISO Standards. The implementation in ISO 19906 was approved by the ISO committee responsible for ISO 19906, namely ISO/TC67/SC7/WG8.

The reliability targets can be (but are not required to be) used by the owner or designer in various ways, including:

- ISO 19906 gives permission for a site-specific calibration of the partial action factors. At some locations, this can result is more economic designs within the reliability targets.
- Ice actions can be mitigated by active measures such as ice management and, for stationary floating systems, disconnection. This can change the shape of an ice hazard curve due to, for example, towing large icebergs so that the probability of structural impact is reduced, or disconnecting so that it is eliminated. The reliability of the active measures needs to be considered with respect to the reliability of the system.
- Events of very low probability can fall below the threshold of the abnormal-level ice event, while having the possibility to cause the structure reliability to rise above the reliability target. The owner, advised by the designer, should consider if this risk is relevant to their design, as discussed below.
- Design of stationary floating structures in ice can be influenced by a variety of considerations, each being risk assessed in order to assess the overall reliability, as discussed further below.

Although the underlying philosophy of the ISO 19906 design approach is that of risk and reliability, with the objective of reaching a target. by means of structural design, explicit assessment of structure or system reliability is not required for design verification.

SAFETY FORMAT - ISO 19902 APPROACH

This section is a summary of the “safety format” approach detailed in document ISO/TC67/SC7 N749 (2014).

ISO 19902 follows a design route for ULS calculations where a distinction is made between:

- A system based design approach,
- A (traditional) component based design approach.

In ISO 19902 the prime safety measure is the system strength expressed as a Reserve Strength Ratio (RSR) value from which partial action factors for typical structures can be derived. This should mean that simple and complex structures will be equally safe if they have the same RSR.

The safety requirements in ISO 19902 can be met in two ways:

- By demonstrating that a structure has a certain minimum RSR,
- By following a partial safety factor design format.

According to ISO 19902, appropriate acceptance criteria (e.g. ULS equations with partial factors) in terms of a required minimum value of RSR for a given exposure level are in principle functions of the local wave climate and are thus geographically specific (not the same all over the world). And to maintain a requirement of a specified value of RSR for any type of structure it is in principle necessary to introduce a structure dependent value of the partial action factor. By extension to ISO 19906, partial action factors for arctic offshore structures would be a function also of the local ice climate.

When API developed an LRFD (Load and Resistance Factor Design) version of its WSD (Working Stress Design) code, the goal was to carry over the experience from many years of design of offshore structures mainly in the Gulf of Mexico. This was done by calibrating component behaviour in the new LRFD code to the mean safety index inherent in the WSD code. This way of thinking was reflected and supported in the works referenced in ISO 19902.

The partial action factors in ISO 19902 are therefore associated with typical space frame structures (Gulf of Mexico/North Sea). However, ISO 19902 does not provide partial action factors for environmental actions, perhaps because consensus on values with worldwide applicability could not be reached due to "lack of industry funding" for calibration. Instead, it is left to "jurisdictions" to optionally provide factors in the "regional annex". The "NW Europe" regional annex specifies 1.35 without qualification for exposure level, whereas the Canada regional annex specifies 1.35 for L1 structures. Other jurisdictions are silent, thus introducing uncertainty into the calculation of design actions for the ULS.

ISO 19902 was written to provide a "methodology that could be used for comparative purposes" for a specific design. The authors say that ISO 19902 was not intended to set, nor state, a target probability of failure for fixed steel structures.

BATTLE OF THE APPROACHES

The reliability target approach of ISO 19906 allows a consistent structural reliability to be applied to all types of offshore structure worldwide. The RSR approach of ISO 19902 is said to be dependent on region and structure type. In both approaches, the designer uses limit states equations with partial factors to achieve the intended "safety". The appropriate partial action factors are determined by "calibration". ISO 19900 defines calibration as "process used to determine partial factors using structural reliability analysis and target reliabilities".

ISO 19902 is written with experience of lattice steel structures in the Gulf of Mexico, so the underlying RSR approach is not much of a problem for ISO 19902. But because ISO 19902 declines to quantify targets, it is does not provide an auditable basis for calibrating partial action factors that are in conformance. Further “gaps” are that abnormal environmental conditions and abnormal limit states are not addressed adequately as would be required for arctic offshore structures, quantitative guidance on ULS partial action factors for different exposure levels is not provided, and the impact of operational measures is not considered.

With the participation of all experts from all arctic nations, ISO 19906 includes partial action factors that were calibrated to reliability targets and can be used for all structure types and environmental actions found in arctic and cold regions, see Thomas et al. (2011).

ISO 19902 identifies that partial action factors (and RSR) can depend on structure type, as well as action characteristics. Further thought should be given in ISO 19906 as to partial action factors relevant to structures in design situations where the structure is not “robust”, i.e. does not have multiple load paths and reserve strength. For example, the overturning of a gravity-based monotower structure under lateral load will exhibit minimal reserve strength, such that a greater partial action factor could be required in order to assure adequate reliability. Similarly, foundation failure of gravity-based structures could suggest larger partial action factors, however the conservatism in the estimation of foundation resistance is usually significant and would also need to be quantified.

To this date, the thinking in the governing ISO committee (ISO/TC67/SC7) has been heavily influenced by the ISO 19902 approach. For example, the committee has stated that its standards “cannot require or recommend specific target reliability levels”, despite the fact that ISO 19900 calls for calibration to such targets. This is a gap that ISO 19906 strives to fill.

EXTREME-LEVEL AND ABNORMAL-LEVEL

ISO 19906 requires that representative values for ice actions (and for other environmental actions) are determined both at extreme-level, and at abnormal-level, for all relevant ice-structure interaction scenarios. They represent different design situations, and are independently aimed at ensuring that the structure reliability target is achieved for each design situation. Figure 2, based on the risk matrix of Figure 1, shows the EL and AL actions for each exposure level, in the risk matrix space.

		Likelihood of Risk Event - due to Ice situations							
		1	2	3	4	5	6	7	8
Exposure Level	L1	Plan		AL		EL		Design	
	L2	Plan			AL	EL		Design	
	L3		Plan			EL		Design	
Frequency		10^{-6} /yr or lower	10^{-6} to 10^{-5} /yr	10^{-5} to 10^{-4} /yr	10^{-4} to 10^{-3} /yr	10^{-3} to 10^{-2} /yr	10^{-2} to 10^{-1} /yr	10^{-1} to 1 /yr	>1 /yr
Probability		10^{-6} or lower	10^{-6} to 10^{-5}	10^{-5} to 10^{-4}	10^{-4} to 10^{-3}	10^{-3} to 10^{-2}	10^{-2} to 0.1	0.1 to 0.25	>0.25

Figure 2 - Risk Matrix showing Abnormal-Level and Extreme-Level

Despite being shown together in Figure 2, it is important to not confuse the concepts of structure/system reliability (target 10^{-5} for L1) and design event occurrence probability (10^{-2}, 10^{-3}, or 10^{-4}). The former relates to structural failure (a risk event) arising from the overall design situation. The latter is a design event for which actions are factored for associated action combinations for design verification. Figure 2 positions the prescribed event frequencies, or probabilities, in relation to the reliability targets in order to indicate the effect of applying partial action factors and resistance formulations.

Specific reasons for requiring design verification of arctic offshore structures for both extreme-level and abnormal-level ice actions include:

1) The relative values of (factored) extreme-level and abnormal-level design actions depend on the slope of the action hazard curve. This can be site-specific and specific to the ice feature, such that either level could govern the design. One level is not a "factored" value of the other level.
2) The reliability target is achieved by action combinations, not an ice action in isolation. Design values of ice actions are combined with design values of other actions (gravity etc.) that are factored differently for ULS and ALS, and the limit state objectives and the approach to resistance are different as explained above.
3) The extreme-level ice action can be zero for some design situations. EL ice actions are not applicable for ice events having an annual probability of occurrence of less than 10^{-2} (these are obviously "discrete" events).
4) The EL ice action could arise from first year sea ice, while the critical AL ice action could arise from icebergs.

The first two bullets, (1) and (2) above, are illustrated in Figure 3.

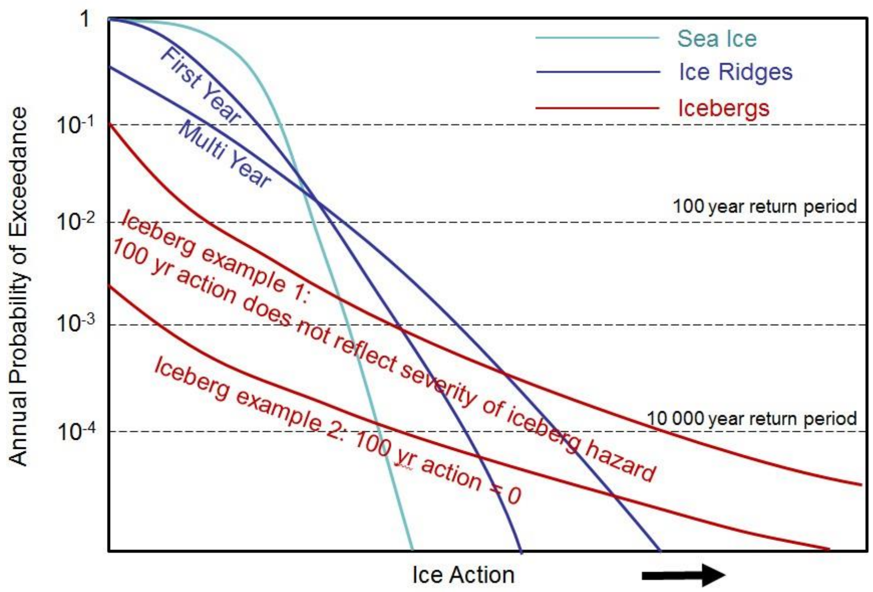

Figure 3 - Action-Hazard curves for various ice hazard scenarios

In Figure 3, firstly, hazard curves are illustrated for various ice scenarios including iceberg example 1, where there is both an extreme-level value and an abnormal-level value of characteristic ice action. With reference to OGP report 422 (2010) typical ratios can be 1.20 for first-year ice ridges and 1.35 for multi-year ice. For icebergs, a typical ratio could be 4, as shown for the Labrador Sea, in which case the 100-year value when factored by the partial factor of 1.35 does not reflect the severity of the hazard.

Secondly in Figure 3, a hazard curve is illustrated for iceberg example 2. This could be typical for some areas off the East coast of Canada, off Greenland and for the Barents Sea, where the iceberg encounter probability can be less than 10^{-2} per annum. Therefore the 100-year representative/characteristic ice action value is zero for this design situation, and the design verification will use only the ALS and abnormal-level ice action.

It is a myth, certainly in the case of ice actions, that the intention of the factored extreme-level ice action is to result in a value for design ice action with a notional 10^{-4} annual probability, thus emulating the value of the abnormal-level ice action.

Even if the annual frequency of iceberg or ice island impacts is greater than 10^{-2}, the 100 year action can be low and not generally representative of the severity of the action-hazard relationship with respect to overall structure reliability. Widianto et al. (2013) show that values of the "10,000 year" ice actions are up to 10 times the "100 year" values at the Hebron location, on the Grand Banks of Canada.

Modification of action hazard curves

Iceberg encounter probability can be modified by ice management, both for fixed (gravity-based) and for floating structures. The annual iceberg impact frequency associated with Grand Banks installations – Hibernia, Terra Nova, White Rose and soon Hebron – is about 0.02 in the absence of iceberg management and about an order of magnitude less with ice management. The corresponding actions or loads calculated at the 100 year level are minimal.

If a stationary floating structure is designed to be disconnectable, the hazard curve for environmental actions can be modified or limited by the pre-defined conditions and probability of success for disconnection. This can modify or limit the value of the AL ice action and, depending on the criteria for disconnection, the value of the EL ice action. Further discussion can be found in Makrygiannis et al. (2011).

The ratio of characteristic values depends on the slope of the action-hazard curve for the ice scenario, and can vary significantly or be mathematically infinite, and can be modified by operational procedures. The extreme-level partial action factor arises from calibrating the ULS action combinations to the structure reliability target, independently of any abnormal-level action. Therefore ISO 19906 requires that ULS and ALS both be satisfied independently for each design scenario.

BEYOND ABNORMAL EVENTS

There can be design situations of very rare events for which not only the extreme-level but also the abnormal-level ice action does not occur. Such ice events, of probability of occurrence less than the abnormal-level, are here termed "beyond abnormal".

Such events are an example of events not addressed by the design verification process. The limit states design method gives no insight into this issue, because ice actions for use in the action combinations are zero at the prescribed action probabilities.

An example of a “beyond abnormal” ice action-hazard curve is illustrated in Figure 4, labelled iceberg example 3.

There has been doubt as to whether “beyond abnormal” events can actually be characterized and calculated. As a reality check, an example is provided by Eik et al. (2013). For the Skrugard location in the Norwegian Barents Sea, the annual iceberg encounter frequency for a 100m diameter circle was assessed as 2.6 x 10^{-5}. Nevertheless, there can be significant uncertainties in estimating such rare events.

Discussion of types of uncertainty and approaches for taking this into account can be found in OGP Report 422 (2010) and Widianto et al. (2013). Although written with respect to abnormal-level ice actions and events, the principles of uncertainty apply equally to “beyond abnormal” actions and events.

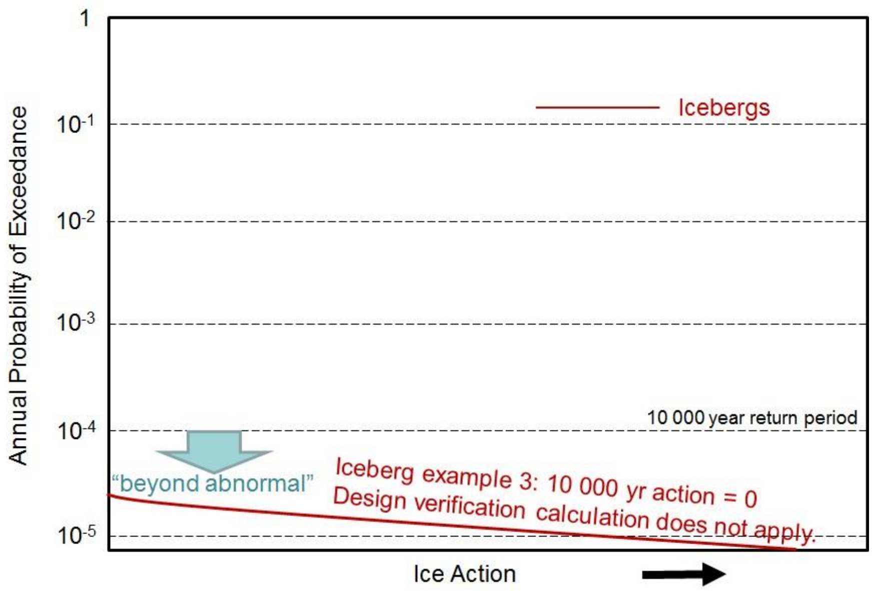

Figure 4 - Action-Hazard curve for “beyond abnormal” ice hazard

Categorisation of beyond abnormal events

Beyond abnormal events can be further categorised as follows:

- Events in design situations that result in structural reliability not meeting the reliability target relevant to the exposure level.
- Events in design situations that do not require structural reliability but result in risk that needs to be managed by other means.

In the first case, the event probability can be such that failure of the structure could be caused with a probability exceeding the reliability target. Owner evaluation of structural robustness and/or alternate operational measures to mitigate consequences of such events should be considered in order to demonstrate that the overall reliability targets for life safety and consequences are achieved.

As stated earlier, it is important to not confuse the concepts of structure/system reliability, and ice event occurrence probability. An ice event is either incorporated in a design situation with associated action combinations for design verification, or has a probability falling outside the design verification process. If the latter, the ice event could overwhelm the structural resistance that is provided for the design situations verified for ULS and ALS, and therefore cause catastrophic failure. The concept of “action combination” is then moot. If the ice event probability is above the reliability target, assurance of structure reliability can be achieved only if the risk of such events is recognised, and considered in an holistic design process. If the probability is below the structural reliability target, but can reasonably be foreseen, it should also be recognised, in an overall risk register with risks managed appropriately.

ISO 19906 (2010) attempts to address the case where the ice event is “beyond abnormal” but above the reliability target. But ISO 19906 can seem unclear on whether it is a design verification issue or a risk mitigation issue in order to achieve the reliability target. ISO 19906:2010 subclause 7.2.2.4 says “Iceberg and ice island impact events with an annual probability of occurrence between 10^{-4} and 10^{-5} for L1 structures (between 10^{-3} and 10^{-4} for L2 structures) and with high consequences should be considered for ALIE to ensure adequate reliability of the structure”. ISO 19906 recommends that the effect on structural reliability should be considered, but by using the term ALIE, it can be read as implying that an abnormal-level action should be calculated and used in the ALS design check. When ISO 19906 is revised, it is hoped that use of terms will be clarified and that the term “abnormal” will be strictly applied only for design events with the prescribed annual probability.

The author of this paper considers that the intention for “beyond abnormal” events is that owner evaluation of structural robustness and/or alternate operational measures including contingencies for shut-down operations, personnel evacuation, and measures to mitigate risks and consequences of such events should be considered in order to demonstrate that the overall reliability targets for life safety and consequences are achieved.

It is worth reiterating that the limit states design method using action combinations for design verification as implemented in the ISO 19900-series of standards does not apply to “beyond-abnormal” events.

DESIGN SITUATIONS

ISO 19900 (2013) defines “design situation” as “set of physical conditions representing real conditions during a certain time interval, for which the design demonstrates that relevant limit states are not exceeded”. This paper considers that the concept should be introduced into the next revision of ISO 19906 so as to enable a clearer exposition of a more holistic approach to the overall design.

Each design situation will be particular with respect to the hazard scenario and actions, and to the structural system resisting the actions. This will enable the description of extreme-level, abnormal-level and “beyond abnormal” design situations, and their associated risk events, in a manner that is separate from limit states and design verification. It will also allow the structural systems relevant to that design situation to be defined.

Description of design situation

Each design situation would be defined by including relevant particulars such as:

- Hazard scenario
- Manning levels
- Facility operations
- Exposure level(s)
- Structural systems
- Principal action

- Companion actions
- Limit state(s)
- Operational measures

Different operational measures such as ice management and, for floating systems, disconnection, could also be defined for each design situation, allowing more clarity on the effect of operational measures on mitigating the design values of ice actions for defined design situations.

If specific operational procedures are to be activated in some design situations (e.g., for a pre-defined abnormal-level event) but not for other design situations (e.g., for extreme-level events) then the associated risks could be mitigated differently and different exposure levels could be considered for the design situations, see below.

If operational procedures such as ice management or/and disconnection are a part of the design philosophy for a stationary floating structure, all relevant elements of the operational procedures which are required for an appropriate level of structural reliability need to be determined and documented.

APPLICATION OF EXPOSURE LEVEL

As discussed earlier, the reliability target, or break point between structural design and other risk management, is determined by exposure level. In the limit states design method, this is codified through the partial action factors for each exposure level.

ISO 19900 discusses the possibility of a reduction in partial environmental action factor for exposure level L2 and L3, but only in the context of (re)assessment of existing structures. It is probably intended that these reductions are additional to reduced factors (less than for L1) used for original design, but the wording is open to misinterpretation because the possibility of using different factors for original design is not addressed. It is stated as applicable to both ULS and ALS, implying that the partial factor for ALS could be less than the 1.0 specified for exposure level L1. And ALS remains ambiguous with respect to accidental vs abnormal.

ISO 19906 provides partial factors for all action combinations necessary for exposure levels L1 and L2, and makes reference to OGP Report 422 (2010) for exposure level L3.

Assigning exposure level to components and sub-structures
ISO 19906 recognises that some components or sub-structures can be categorized differently from each other and from the overall structure with respect to risk and consequences, in which case their exposure level can be different.

Assigning exposure level to design situations
This principle should be extended to recognise that the same structure, sub-structure or component may have an exposure level that is particular to a specific design situation, subject to project-specific assessment if, for example, the risks and their consequences are managed and mitigated.

Consider a structure that is generally categorised as L1 because it is normally manned during operational conditions including extreme-level environmental conditions. If a specific design situation is defined in which, for example, specific structural systems or operational measures are implemented with sufficient probability of success, such that the L2 criteria for life safety and other consequences can be met if that event were to occur, an L2 designation should be permitted for this design situation. This could result in ensuring life safety and environmental protection in accordance with the standard, but at significant cost savings as design requirements are replaced by other measures.

In the case of a design situation based on the hazard curve for iceberg example 1 illustrated in Figure 3, the structure could be considered for L2 categorisation specifically, and only, for the abnormal-level iceberg design situation. The structure would therefore be designated L1 for the extreme-level iceberg actions and the design verified for the relevant ULS with a partial action factor of 1.35, while being designated L2 for the ALS and the design being verified for an iceberg action with an annual probability of 10^{-3}. If the design situation were based on the hazard curve for iceberg example 2 illustrated in Figure 3, an L2 designation could be applied for all iceberg hazards, while being designated L1 for all other hazards.

The risks associated with the measures required to meet the L2 criteria would need to be assessed with respect to achieving the overall structural design reliability targets for life safety and other consequences. Such measures, such as including hazard detection, monitoring and forecasting, success of ice management, staged shut-in of wells and shut-down of production and export facilities, evacuation of personnel under prevailing conditions, etc., are likely to require significant resources to be available for deployment as necessary. Within the inviolable constraints of life safety and other consequences, the owner should be permitted to weigh this against the risks of less economic design or increased economic loss. If all life safety and other consequence criteria are satisfied, the decision on assigning exposure level by specific design situation becomes primarily a commercial decision by the owner, although there may be national strategic interests also to be considered and negotiated.

CONCLUSION

Designers need to consider risk and reliability in the design of arctic offshore structures in order to ensure an appropriate level of reliability and acceptable performance. ISO 19906 (2010) encodes the design approach into a limit states design format for design verification appropriate for arctic offshore structures, and also discusses issues for further consideration. This goes beyond what is specified for traditional lattice tower structures, because some of the traditional implicit assumptions are not valid (e.g. abnormal actions with no extreme value).

All risk events that can reasonably be foreseen, including those from very rare environmental events beyond abnormal-level, need to be characterised in order to assess risks and ensure appropriate planning, documentation and management. Reliability targets define a break point between risk mitigation by structural design and by other planning and management.

ISO 19906 represents a significant step forward from the traditional approach to the design of offshore structures. Design for arctic and cold regions necessitates pushing the traditional boundaries on the use of reliability targets, consideration of both “abnormal-level” and “beyond abnormal” environmental events, and modification of action hazard curves due to operational procedures. More work in other ISO 19900-series standards is required in order to define exposure levels and partial action factors so that those standards can be used without further calibration by the user. The arctic “community” needs to communicate these issues and gain a consensus in ISO/TC67/SC7 that methodology appropriate for arctic offshore structures should be codified and used appropriately.

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