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Design Situations and Limit State Verification for Arctic Offshore Structures

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ABSTRACT

Standardized solutions for the design and assessment of arctic offshore structures have evolved a long way from the sometimes empirical, pragmatic solutions that were originally developed for offshore structures in well-known regions such as the Gulf of Mexico. This paper discusses the modern codification of the limit state design and verification approach embedded in the most recent 2019 editions of ISO 19900 and ISO 19906, the International Standards for the design of offshore and arctic structures.

A flexible and risk-consistent limit state design and verification approach is especially relevant for the design and assessment of safe and economic arctic offshore structures. Structural integrity is verified for the relevant limit states in design/assessment situations arising from operational, extreme, abnormal, and accidental events and actions. The approach also accommodates the effects of operating philosophy and mitigating measures such as ice management, and disconnection of floating structures.

The limit state verification procedure addresses uncertainty, risk, and structural reliability through the use of combinations of actions with specified probabilities, partial factors for actions and material properties, and limit states which are established for each design/assessment situation. The ultimate limit states for each design/assessment situation, including component failure and complete loss of structural integrity, depend on the specific situation.

The verification process now codified in ISO 19900 and ISO 19906 is shown to be a specialized version of broader risk-informed design/assessment approaches codified in ISO 2394, which provides anchoring and support for structural integrity and risk management involving arctic-specific hazards and situations.

KEY WORDS: ISO 19906, Arctic offshore structures; Hazardous events; Design situations; Limit states.

INTRODUCTION

New editions of ISO 19906 Arctic offshore structures and of ISO 19900 General requirements for offshore structures, have been prepared for publication in 2019. The new editions incorporate an additional 6-9 years of experience and development, the previous editions having been published in 2010 and 2013 respectively. The revision of ISO 19906 is described in Muggeridge et.al., 2019, and was approximately a year ahead of the 19900 work. Because the work was performed in different working groups under ISO/TC67/SC7, ISO 19906:2019 is based on ISO 19900:2013 which was the stable version available.

Nevertheless the 2019 edition of ISO 19900 has not changed the basic approach to design and verification. However, it now clarifies and reinforces provisions in the 2013 edition, and uses more consistent terminology such as "design/assessment situation" in place of "design situation" in order to make clear that these situations apply both for new design as well as for assessment of existing structures. It has improved interfaces with the other International Standards on offshore structures developed by ISO/TC 67/SC 7, for which the relationships are illustrated in Muggeridge et.al., 2019. And there is further alignment with general codes for civil and structural engineering.

This paper focusses on the verification of structural reliability of arctic offshore structures using the limit state verification procedure embodied in ISO 19900:2019 and ISO 19906:2019. Key concepts in this approach are establishing design/assessment situations, and verifying that in each design/assessment situation the structure and its components have adequate reliability against exceeding a limit state.

A number of background issues related to risk, reliability, and exposure levels were previously discussed in Thomas, 2017. This paper includes a brief update on these issues.

THE DESIGN PROCESS

The design process starts with concept development. The drivers are the functional requirements for the structure, such as number and type of wells, production rates, support systems (water injection etc.), stabilisation and processing of fluids, power and utilities, safety systems, accommodation, and export requirements. Key issues for the resulting structure are water depth, ice scenarios month by month, and seabed conditions.

The art of structural design is to select and configure a structure to perform safely and economically. Figure 1 shows some typical arctic offshore structural solutions.

Figure 1 – Typical Arctic Offshore Structures (left and centre courtesy GazProm)

ISO 19906 is not a textbook on how to create the concept for an offshore structure. However, it provides considerations when selecting type and configuration. Most importantly, ISO 19906 provides a procedure for verifying the structural reliability of a structure when configured and designed. Conversely, it leads the designer to select and adjust solutions (such as sizing components) so that they are verified as achieving adequate structural reliability.

DESIGN SITUATIONS USED FOR VERIFICATION

The concept of "design situations" is now clearly introduced into the revision of ISO 19906 as part of a more holistic approach to the overall design process, see Thomas, 2017. This reference also summarises the relevant parameters and criteria which ISO 19900:2013 describes as characterising “design situations”. ISO 19900:2019 clarifies that these are “design/assessment situations” as previously explained.

Design/assessment situations

ISO 19900:2019 requires that a design/assessment situation is established for each hazardous event and for each dominating source of action. The limit state verification procedure is applied for each design/assessment situation in turn, to ensure that structural reliability is adequate in all situations.

Hazard

A hazard is a potential source of harm: human injury, damage to the environment, damage to property, or a combination of these. Hazards can include environmental hazards and potential accidents. ISO 19900 requires that all reasonably-foreseeable hazards are identified.

If an environmental hazard can be identified and monitored, such as for an iceberg or a hurricane, planned operational measures such as ice management, or shutdown and evacuation, can be initiated. Such measures for floating structures are addressed in Makrygiannis et.al., 2019.

Hazardous event

A hazardous event occurs when a hazard interacts with a structure, either alone or in combination with other conditions. ISO 19906 defines ice event as ice-structure interaction for which ice actions are calculated. If the action effects are of sufficient magnitude, a limit state can be exceeded and damage or collapse can occur.

Environmental actions *E*, for example, can be plotted against return period (i.e. probability of exceedance) on an action hazard curve, such as shown in Figure 2 which is based on ISO 19900:2019, Figure A.1. Figure 2 shows various types of environmental actions including three ice action curves for 100m wide, vertical-sided GBS structures. The three curves are selected to illustrate that different types of ice can have very different hazard curve shapes and slopes.

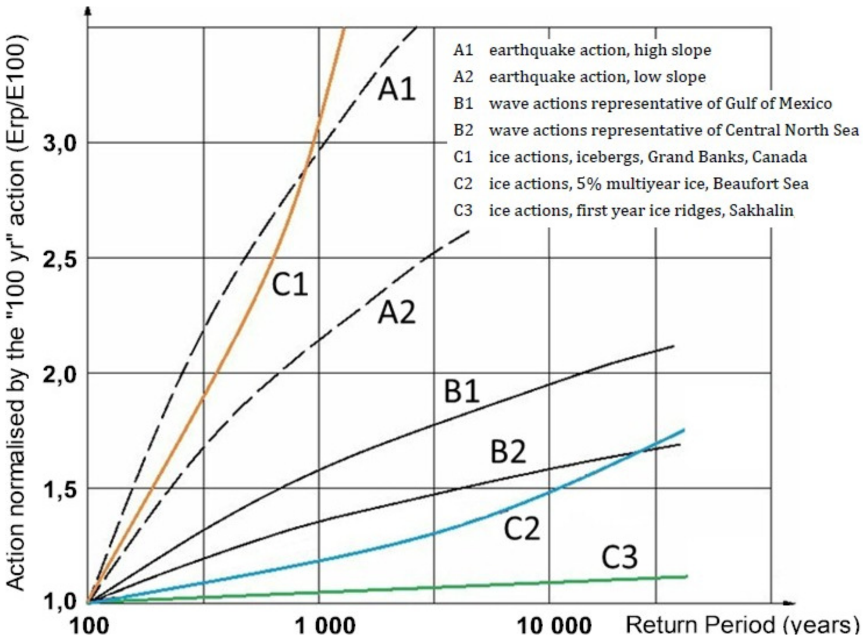

Figure 2 – Example action hazard curves from ISO 19900:2019

If a hazard curve has been developed, different levels of hazardous event can be selected at different points on the hazard curve. The most commonly used are the extreme-level environmental action for use in an extreme design/assessment situation, and the abnormal-level environmental action for use in an abnormal design/assessment situation.

The term “extreme” is reserved for events and actions with annual probability (of occurrence or exceedance) of 10^{-2} (100 year return period). This differs from some general use, where, “extreme” can be used as a generic adjective for severe environmental actions beyond an operating level, or as the maximum of a set of values within a defined time period.

Similarly, the terms “abnormal” and “accidental” are reserved for events and actions used for abnormal and accidental design/assessment situations respectively. The actual annual probability (of occurrence or exceedance) depends on the exposure level, see below, and is 10^{-4} (10,000-year return period) for exposure level L1.

Ice events and ice actions are further addressed in Matskevitch and Thomas, 2019.

Other dominating sources of action

Design situations should also be established for each dominating source of action. This includes operational design situations for operational actions, combined with permanent actions. Operational actions are variable actions related to operations and functional use of the platform. They can vary in magnitude, position and direction during the period under consideration.

Actions and representative values

The term “action” is used throughout ISO standards instead of the term “load”. ISO 19900:2019 defines action as “external load applied to the structure (direct action) or an imposed deformation or acceleration (indirect action)”.

Values of actions termed “representative values” are the actual (unfactored) values, such as actual weights and environmental loads calculated from actual parameters.

The “principal” action is the action arising from the hazardous event or other dominant source of action for which the design situation has been established.

“Companion” actions arise from phenomena of the same type which can act simultaneously. If ice provides the principal action, wind and ocean current can provide companion actions. The sum of all environmental actions provides the overall environmental action used in the limit state verification applicable to the specific design/assessment situation.

Classes of design/assessment situation to ISO 19900:2019

Five classes of design/assessment situation are set out in ISO 19900:2019 as relevant for the “ultimate” (or strength) limit states. They are as follows:

- Operational
- Extreme
- Abnormal
- Accidental
- Short duration

Operational and extreme design situations

Operational and extreme design situations are established to ensure that, provided that a limit state is not exceeded, the probability of undesirable consequences is sufficiently low. This aims at maintaining acceptable structural reliability, avoiding significant structural damage and repairs needed for restarting or continuing operation.

The global behaviour of the structure is essentially elastic, even though local stress concentrations can exceed yield stresses and some nonlinear behaviour (e.g. pile-soil interaction) is expected. Some components may behave inelastically if their capacity to resist action effects is not reduced, e.g. plates in membrane action.

Abnormal and accidental design situations

Abnormal and accidental design situations serve to ensure that, provided that a limit state is not exceeded, the probability of life-safety consequences or harm to the environment is sufficiently low despite a likelihood of structural damage requiring repair or replacement of structure in order to restore adequate in-service structural integrity. Structural integrity at the limit state needs to be assured to enable evacuation following the event, and repairs.

System and component ductility and reserve capacity may be taken into consideration in determining the ultimate resistance of the structural system. Structural analysis may be non-linear and progressed to complete loss of structural integrity or collapse, with design resistance of individual components being exceeded and action effects being redistributed.

Short duration design situations

If structural damage occurs, e.g. if a structural component is deemed to fail, or actually fails in service, but the structure does not experience overall collapse, a short duration, post-damage design situation can be defined and fitness for continuing service can be assessed.

The design process can comprise establishing different design/assessment situations which can occur sequentially both in time and in space. Structural components can be damaged before the overall collapse limit is reached, but a "damaged structure" configuration representing component damage at the overall collapse limit can nevertheless be specified for use in one or more short duration design/assessment situations.

LIMIT STATES

ISO 19900 states that the performance of a structure, in whole or in part, shall be described with reference to a specified set of limit states beyond which the structure no longer satisfies the design criteria. In essence, it no longer satisfies the Equation (1) of the limit state verification procedure explained below. This definition is illustrated in Figure 3.

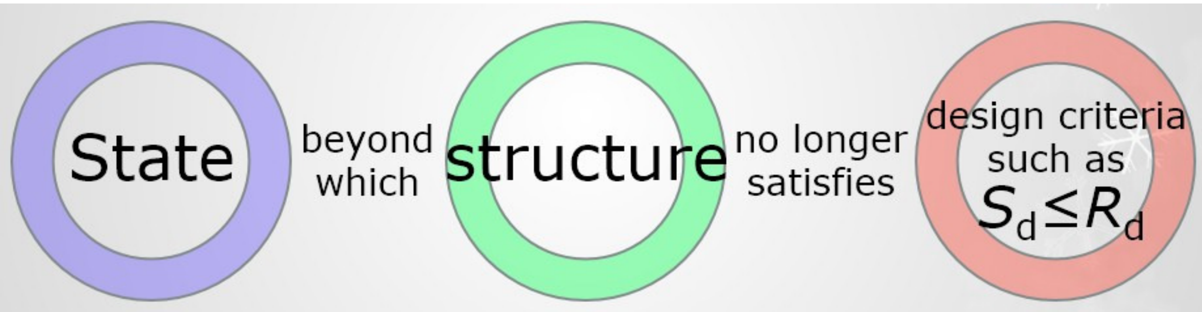

Figure 3 – Illustration of the definition of limit state

If design action effects S_d exceed design resistance R_d, the structure or structural component has failed the verification check. This does not necessarily result in physical failure, but it represents a structural reliability which is below a level acceptable for the outcome of the codified design (or assessment) process; further work such as design changes is needed.

A key clarification in ISO 19900:2019 is to decouple the concept of limit state from the design process. An approach had developed in the oil and gas industry to consider that the "Accidental Limit State" was a two-step process comprising firstly damage due to an accidental (or abnormal) event, and secondly a post-damage assessment. The clarification is that a limit state is simply a limit. The limit is either satisfied (not exceeded) or not satisfied (exceeded) in each design situation.

In the 2019 edition of ISO 19900, the limit states are divided into the following three categories:

- ultimate (or "strength") limit states (subdivided into ULS_1, ULS_2, and ALS);
- serviceability limit states (SLS);
- fatigue limit states (FLS).

Ultimate limit states

Ultimate limit states are considered in three categories as follows:

a) ULS_1: action effects in individual structural components exceeding the resistance (in some cases reduced by deterioration), including loss of structural stability (buckling, etc.). It is noted that resistance can include the ultimate strength or the ultimate deformation of the component;

b) ULS_2: loss of static equilibrium of the structure, or of a critical part of the structure, considered as a rigid body (e.g. overturning, sinking, or capsizing);

c) ALS (for abnormal and accidental limit states): complete loss of integrity of the structure or of a critical part of the structure, when there is no further system ductility or reserve strength e.g. from energy dissipation or load shedding between components. ALS include transformation of the structure into a mechanism (collapse or excessive deformation) and loss of stationkeeping (free drifting);

The additional system resistance between the point at which the first structural component no longer satisfies the ULS_1, and the overall collapse with respect to ALS, is an essential aspect of "robustness". Also, in this region (between ULS_1 and ALS) damage could occur for which, as part of the overall design process, short duration situations can be established for assuring adequate structural integrity pending repairs.

LIMIT STATE VERIFICATION PROCEDURE

The limit state verification procedure verifies that a structure has adequate structural reliability with respect to specified limit states in each design situation. Exceeding the limit state would result in no longer satisfying the design criteria for avoiding damage and/or collapse. The steps can be outlined as follows:

Establishing design situations

- Hazards, hazardous events and other sources of actions are identified and quantified;
- Individual design situations are established for each hazardous event and for each other source or cause of a principal action;
- For each design situation, criteria and other parameters are established or selected for design verification, including:
    - structure configuration;
    - exposure level (see risk section below);
    - relevant limit states.

Evaluating actions, see also Figure 4

- Representative values of actions are derived from basic variables;
- The principal action is calculated by evaluating the hazardous event or other source of principal action;
- Companion actions are assessed;
- Representative values of action types are derived by combining representative values of principal actions and companion actions;
- Actions accompanying the principal action type are evaluated. The four action types are permanent *G*, operational *Q*, environmental *E*, and accidental *A*;
- Partial factors are quantified, depending on exposure level, limit state and design situation;
- Design values for the design situation are calculated by factoring representative values;
- Design actions are applied in a combination of action types dependent on the design situation, for input to the modelling and analysis.

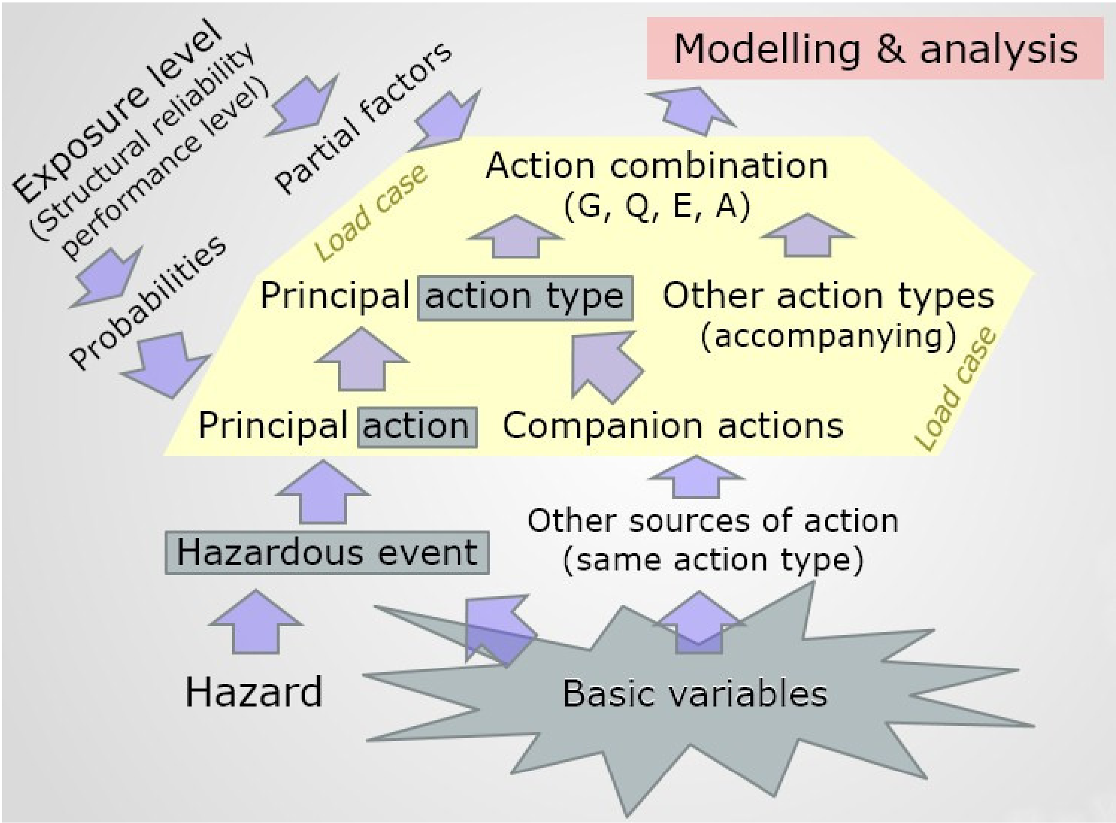

Figure 4 – Evaluating and combining actions for a hazardous event

Evaluating resistance, see also Figure 5

- Representative values of resistance are derived from basic variables, geometry, and structural configuration;
- Partial factors are quantified, depending on the limit state and design situation;
- Design values for the design situation are calculated by factoring representative values;
- Resistance is modelled using design values, or directly by factoring resistance formulations, for the structure as a whole and for each structural component, for input to the modelling and analysis.

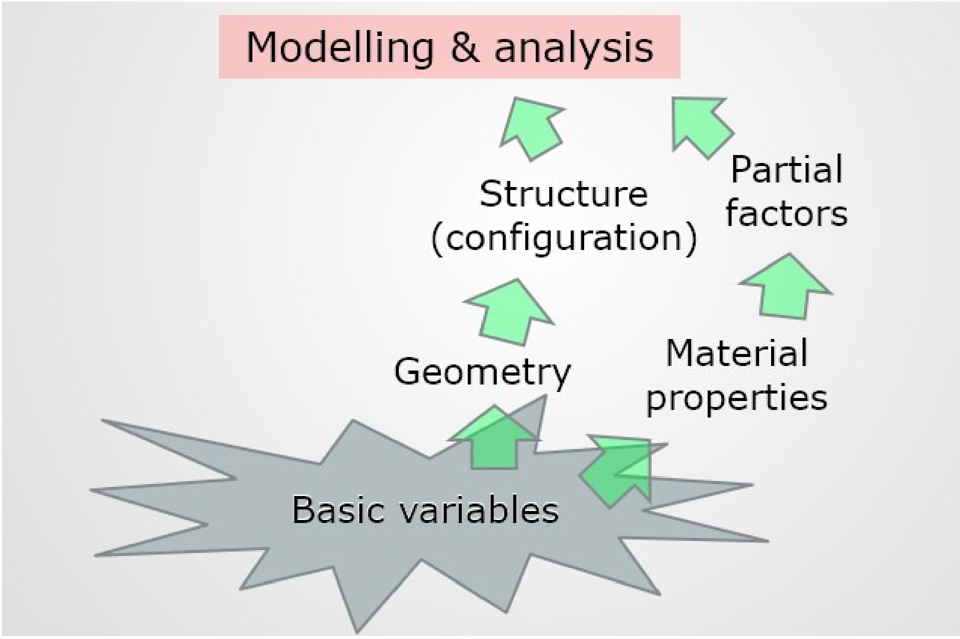

Figure 5 – Evaluating resistance

Limit state verification, see also Figure 6

- The structure is modelled and analysed to obtain the total design action effect, S_d, for the structure as a whole and for each structural component;
- Design resistance, R_d, is calculated with regard to failure modes and limit state(s);
- The structure is verified for the each relevant limit state by applying Equation (1):

$$S_d \leq R_d \tag{1}$$

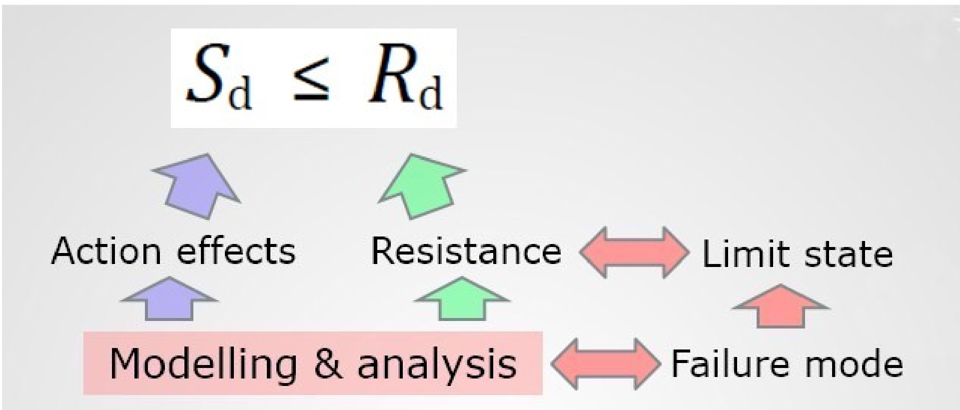

Figure 6 – Limit state verification to Equation (1)

Structural reliability

The concept of structural reliability underpins the limit state verification process. Figure 7 illustrates how reliability (i.e. the probability of avoiding the domain of possible failure) is derived from the probability density functions of action effects S and resistance R.

For ISO 19906 the probabilities of basic variables and actions, and the partial factors for actions and material properties, have been calibrated to reliability targets as described in Thomas, 2017 and in Maes and Thomas, 2011. The verification procedure of applying deterministic probabilities and partial factors, and combining action types to verify that Equation (1) is satisfied, is a surrogate for the full probabilistic modelling illustrated in Figure 7, see next section.

The deterministic formulae for combining the action types for extreme and abnormal design situations are also shown in Figure 7.

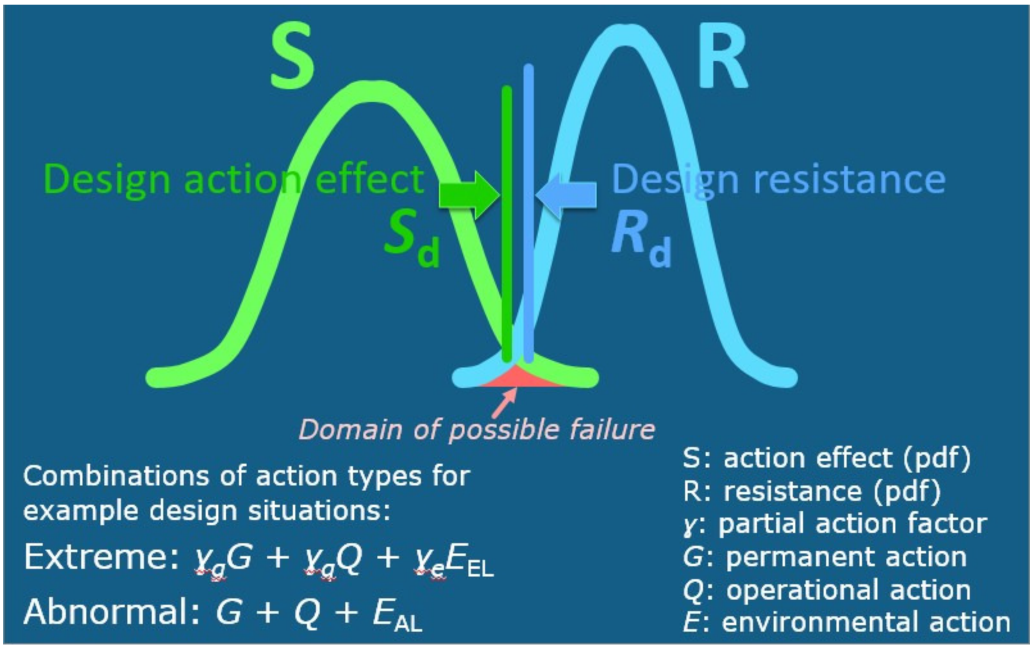

Figure 7 – Probabilistic illustration of Equation (1)

RISK APPROACH

Risk-informed decision making

In a world marked by increasing complexity and interconnectivity, risk has become a truly holistic concept. Triggers for risk are ubiquitous and risk spreads very rapidly in large systems: This makes the role of standards developers more and more challenging as assessment, control, and mitigation of "global" risks conflicts with the unavailability of a solid risk-based codified framework for structural design and assessment.

This is especially true for Arctic offshore engineering where it is often a challenge to account quantitatively and transparently for any type of "non-structural" risk (in terms of both operational risk and strategic risk) (Maes, 2016). It also becomes increasingly difficult to harmonize inspection, maintenance planning, and asset integrity management, using a consistent across-the-board treatment of risk as opposed to a large number of distinct narrowly-scoped standards and regulations.

In addressing some of these challenges, the latest edition of ISO 2394 (2015) "General principles on reliability of structures", generally viewed as the international standard for developers of structural codes, offers three valid hierarchical approaches to design/assessment:

(a) the overarching approach is **risk-**informed
(b) when failure consequences are well understood, a narrower **reliability**-based assessment may be used
(c) a further simplification is permitted when familiar failure modes and common variables allow a suitably calibrated **semi-probabilistic** format such as limit state design/assessment verification.

The preferred/ideal approach (a) uses the supple framework of scenario-based risk assessment and decision making/optimization subject to life safety and environmental constraints.

While the latest revisions of ISO 19900 and ISO 19906 are not explicitly embracing a fully risk-informed approach there is implicit and indirect recognition of the fact that design/assessment based on these two standards is in some sense a trickle-down version of a higher and broader design/assessment context in which risk plays the lead role. ISO 19900 and ISO 19906 employ approach (c), however partial factors for ISO 19906 were calibrated to explicit reliability targets, as described in Maes and Thomas, 2011.

Risk events and reliability targets

It is important to not confuse the concept of risk event, which captures both the extent and the likelihood of undesirable consequences resulting from exceeding a specific limit state, with the concept of hazardous event (or ice event) for which actions are established for design/assessment verification.

It is common industry practice, to identify, assess, and manage all risks that can reasonably be foreseen, however unlikely. Risk events are identified, and can be assessed using a risk matrix to plot each event by its likelihood and consequence. 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 simply be accepted, or tolerated, without a risk management plan.

In the design and assessment of offshore structures, the objective is to reduce risk by design so that the probability of "failure" is less than a target. In this context, probability of failure means the probability that the limit state criteria are no longer satisfied. There is a point on the probability axis at which risk management transitions from reduction by design, to being managed by other means such as operational contingency planning. This transition point, also known as the "reliability target", depends on the severity of consequences, which is taken into account by specifying "exposure levels" for the structure of L1, L2 or L3, where L1 has the most severe consequences and the highest reliability target.

ISO 19906 suggests structural reliability targets (R_T) of $1\text{-}10^{-5}$, $1\text{-}10^{-4}$, and $1\text{-}10^{-3}$ for L1, L2, and L3 structures respectively, with due regard to life safety and environmental protection. This is illustrated in matrix form in Figure 8. If engineering work during the design (or assessment) process indicates probabilities above these targets (e.g. if Equation (1) is not satisfied), the design or supporting measures need to be changed until it is verified that the targets are met (e.g. by satisfying Equation (1)).

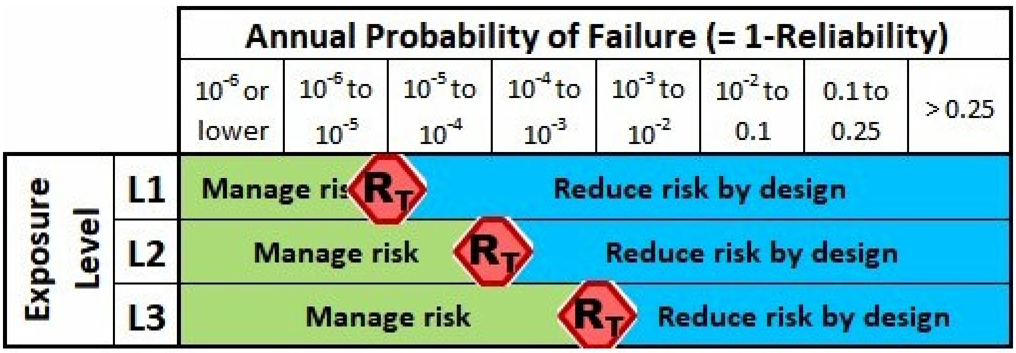

Figure 8 – Matrix showing approach to risk, based on ISO 19906 reliability targets (R_T) for different exposure levels

In this way, risk is reduced to a level acceptable as an outcome of the codified design process. Residual risk is then mitigated or managed by other means.

Design to reduce risk to an acceptable design target

ISO 19900 and ISO 19906 aim to ensure that risk events are very unlikely, by confirming that the structure and its components are designed with adequate structural reliability. The limit state verification procedure is based on hazardous events with occurrence probabilities of 10^{-2}, 10^{-3}, or 10^{-4} (except for earthquakes, for which a more analytical approach applies).

Figure 9 shows the probabilities specified for extreme-level ice events (ELIE) and abnormal-level ice events (ALIE), see Matskevitch and Thomas, 2019. These are denoted by E and A in Figure 9 for each exposure level, in a matrix space defined by likelihood of ice event.

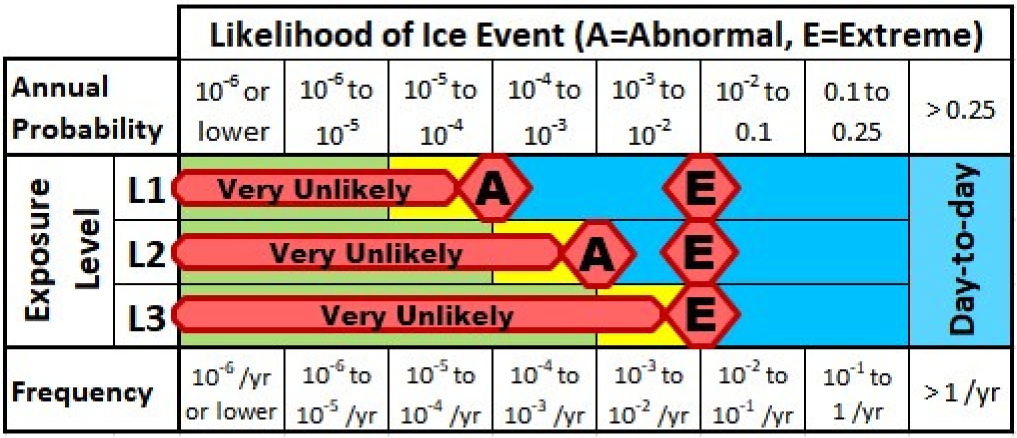

Figure 9 - Matrix showing categorisation and terminology of ice events with respect to probability for different exposure levels

Manage and mitigate residual risk

The limit state verification procedure does not require a design/assessment situation to be established and design-verified for “very unlikely” ice events. These are events with a probability less than that for the ALIE (and ELIE). But there is a low, residual risk which needs to be identified and assessed. At probabilities below those of the ALIE (and ELIE), a very unlikely ice event, of potentially severe magnitude for which the structure is not designed, could cause complete loss of the structure. This would be a risk event.

An ice event could have an event probability between 10^{-4} and 10^{-5} (for L1 structures), see Figure 9, which is less than that for the ALIE. If this results in a risk event which is complete loss of the structure, then the structural reliability is less than the $1\text{-}10^{-5}$ target. Therefore an emergency response plan is required in order to address potential consequences for life safety and environmental protection for which the structure is not design-verified, if needed to reduce risk further.

And at yet lower likelihoods, there could be a risk events for which the owner can assess the risk and can plan for emergency response and other operational measures.

CONCLUSIONS

ISO 19906 represents a significant step forward from the traditional approach to the design of offshore structures which has been largely derived from steel jackets and lattice tower structures.

Design for all types of structures in arctic and cold regions requires that all foreseeable hazards and all relevant hazardous events are identified and evaluated. Limit state verification is required for three types of limit states and for five classes of design situations.

The underlying philosophy of both ISO 19900 and ISO 19906 is to ensure that the structure has the appropriate level of structural integrity. This is achieved for structural design by using the limit state verification procedure with appropriate partial factors and probabilities and, where applicable, operational measures, to demonstrate that structural reliability is achieved.

The requirement of ISO 19900:2019 and ISO 19906:2019 to define design/assessment situations specifically for both extreme and abnormal events and actions, with associated ultimate limit state design criteria, brings more clarity to the design process.

Reliability targets establish a transition point between risk being reduced to level acceptable as an outcome of the codified design process, and residual risk being managed by planning. ISO 19906:2019 addresses risk management by design using the codified limit state verification procedure to achieve adequate structural reliability.

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