Integrity management of offshore structures and its implication on computation of structural action effects and resistance

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Abstract. An overview of integrity management of offshore structures, with emphasis on the oil and gas energy sector, is given. Based on relevant accident experiences and means to control the associated risks, accidents are categorized from a technical-physical as well as human and organizational point of view. Structural risk relates to extreme actions as well as structural degradation. Risk mitigation measures, including adequate design criteria, inspection, repair and maintenance as well as quality assurance and control of engineering processes, are briefly outlined. The current status of risk and reliability methodology to aid decisions in the integrity management is briefly reviewed. Finally, the need to balance the uncertainties in data, methods and computational efforts and the cautious use and quality assurance and control in applying high fidelity methods to avoid human errors, is emphasized, and with a plea to develop both high fidelity as well as efficient, simplified methods for design.

1. Introduction
The oceans contribute to energy [1], mineral resources [2] and food [3] and provide means for transport and other infrastructure. About 1/3 of hydrocarbons, 15% of the total energy supply in the world, are produced from subsea reservoirs. Moreover, the energy industry, like other man-made activities, is challenged by the demand for sustainability [4]. New solutions for attaining clean and renewable energy combined with cleaning of fossil energy are required. Sustainable energy, especially from wind, is expected to be a part of this. Subsea rare minerals also represents a potential for a new ocean industry. Due to the stagnation of wild fish catch at about 90 mill tones, the world has to rely on aquaculture which already produces about the same as wild catch and annually increases by 8%.

The exploitation of the oceans takes place in increasingly harsh environments, including oil and gas production and transport in arctic conditions. Moreover, the demanding industrial environment of, e.g., in the oil and gas industry, has an inherent risk of blowout, severe fires/explosions and other undesirable events.

Figure 1 shows some structures used for various functions. The variety of shapes and sizes clearly shows the many opportunities for innovation. The use of the oceans requires approaches that are socially, environmentally, economically and energetically sustainable. The success of marine technology in the future requires exploration and implementation of relevant enabling technologies such as information and communication technology, automatic control, materials, fabrication and logistics.
The continuous innovation to deal with new serviceability requirements and demanding environments as well the inherent potential of risk of fires and explosions in the offshore oil and gas industry, have led to an industry which has been in forefront of development of design and analysis methodology for ocean systems, applicable to other ocean industries.

This paper deals with structural integrity management during the life cycle - design, fabrication, installation and operation (Figure 2), mainly referring to the oil and gas industry. Various types of offshore structures experience different failure modes which ultimately can lead to fatalities, pollution or property loss.

Current industry practice is implemented in standards for design and reassessment of structures, e.g. [6-14] for offshore oil and gas platforms and [15-18] offshore wind turbines and [19] for (floating) bridges. It is noted that the standards for offshore wind turbines and floating bridges are emerging, and refer to a large extent to the principles and methods specified in the standards for offshore petroleum facilities, however, with different target safety levels due to different consequences of failure. In addition, many classification societies have specified design codes and guidelines. The most advanced standards and codes are characterized by:

- design criteria formulated in terms of serviceability and safety limit states, considering payloads, environmental and accidental actions
- semi-probabilistic methods for ultimate strength design which have been calibrated by reliability or risk analysis methodology
- fatigue design checks depending upon consequences of failure (damage-tolerance) and access for inspection
- explicit accidental collapse design criteria to achieve damage-tolerance for the system
- global and local structural analysis by finite element methods for ultimate strength and fatigue design checks
- nonlinear analyses to demonstrate damage tolerance in view of inspection planning and progressive failure due to accidental damage
- life cycle feature, with strong link between design, and inspection, monitoring, maintenance and repair (IMMR)

Moreover, reassessment of design is required during operation, for instance, because of planned change of platform function and, hence, the need to increase payload or over-load damage due to hurricanes in the Gulf of Mexico, subsidence of North Sea jackets, after accidental loads such as e.g. explosions, fires and ship impacts, as well as in connection with extension of service life.

Basically, the reassessment involves the same assessments as carried out during initial design. However, depending upon the inherent damage tolerance ensured by the initial design, the measures that have to be implemented to improve the strength of an existing structure may be much more expensive.
than for a new structure. This fact commonly justifies a more advanced mechanics and probabilistic
assessment than in the initial design [1, 8, 13, 14, 20].

![Figure 2. Life cycle phases of offshore structures](image)

The offshore industry early recognized that design took place under uncertainty and adopted risk and
reliability methods to make more rational decisions. In addition to the uncertainties affecting the
predicted behaviour under extreme and fatigue conditions, inspection is subjected to uncertainty.
Reliability methods are, hence, crucial to support decisions about safety and economy of degrading
structures. Significant developments of structural reliability methodology, including Bayesian updating
techniques, have taken place since the 1980s, as outlined e.g. in [21-25].

While current design and inspection procedures have been established on a reliability basis of the
generic information available at the design stage, it is important that information obtained during
operation of individual structures, e.g. by inspections during operation, is used to update the inspection
plan. This fact implies dedicated IMMR efforts to each individual structure, in contrast to ultimate limit
state (ULS) criteria that are based on a generic code calibration. However, service experiences from
other structures with similar geometry, loading and site of operation could obviously also be utilized to
update IMMR plans for a given structure, e.g. Moan [26-27]. In particular, fatigue depends on very local
geometrical features, and gross errors might appear as relatively small geometrical deviations (Section
3.3). To justify a probabilistic approach addressing normal uncertainties it is important that such
anomalies are corrected based on the results from inspection of the as-built structure.

Moreover, service experiences show that accidental actions and abnormal strength due to gross errors
or omissions made during design, fabrication or operation, contribute significantly to the risk. Clearly,
control of the risk associated with those kinds of events needs a broad safety management approach
during the life cycle, including a proper measure of the risk; with considerations of the expenditure to
achieve the desired safety level, e.g. [28].

In the following sections the basic requirements and in-service experiences of oil and gas structures
are briefly described, followed by a formulation of the structural integrity management approach. This
includes a quantitative limit state for robustness to limit the likelihood of progressive failure, as well as
quality assurance and control (QA/QC) of the engineering process, fabrication and operation. Use of
probabilistic methods to aid the design and decision process during operation is addressed, considering
the fact that human errors play an important role on the safety.

2. The basic requirement to offshore structures
The design is the crucial life cycle phase (Figure 2) in which important decisions can be made regarding:
- serviceability during operation
- fabrication and installation
- safety during fabrication, installation and use
In the design phase, the optimal choice of layout, materials and equipment is to be made based on the fulfillment of requirements with regard to serviceability, ease of fabrication and installation as well as safety.

Serviceability of a petroleum production facility requires among other properties, a structure with proper payload capacity and deck area, limited motions and station-keeping to avoid damage to risers and ensure an efficient drilling or production process [29]. Moreover, platforms for exploratory drilling need to be mobile and thus have limited resistance in transit.

To achieve competitive fabrication costs, design for producibility is also crucial. This especially implies designing and outfitting the structure with a simple geometry, preferably as a system built up by repeatable modules to facilitate parallel production and cost savings through serial production. Another issue is the design for automated fabrication. This goal can only be achieved if powerful processes and tools are used for the design, production and planning/logistics based on computer tools to allow efficiency, speed and reliability.

Production yards are becoming increasingly “digital” by using numerical methods to predict imperfections and residual stresses, and logistic methods for integrating product and production information that reduce costs and error potential. [30].

A description of design and engineering analyses of different offshore oil and gas structures, such as jackets, semi-submersibles, tension-leg, spar platforms may be found in [29].

The metocean, seismic and hydrocarbon hazards make safety an important issue for oil and gas platforms. Safety requirements are specified to avoid fatalities, environmental damage and property, and are related to the following failure modes:

- overall, rigid body instability (capsizing) under permanent, variable and environmental loads
- failure of (parts of) the structure, foundation or mooring systems, considering permanent, variable, and environmental as well as accidental loads

The location far off shore makes evacuation and rescue difficult, but on the other hand accidents on offshore facilities do not affect the general public in the same manner as accidents on land do.

3. In-service failure experiences

3.1. General

Safety may be defined as the absence of accidents or failures. Hence, useful insight about the safety features can be gained from the detailed investigations of catastrophic accidents, as described e.g. in [26-28] for offshore oil and gas structures. In addition, statistics about offshore accidents, regularly compiled in WOAD(-),[31] which provides an overview of accident rates. Data for wind turbines are found e.g. in [32-33], essentially referring to the rotor-drivetrain assembly for land-based turbines.

Detailed investigations have been carried out for accidents with significant consequences in the oil and gas industry; e.g. namely the three-legged jack-up Ranger [34], semi-submersibles Alexander Kielland platform [35] and Ocean Ranger [36], P-36 [37], jacket. Piper Alpha [38] and the semisubmersible Deepwater Horizon [39].

Capsizing/sinking and global structural failures normally develop in a sequence of technical and physical events. Structural damage can cause progressive structural failure or flooding, which may result in capsizing of buoyant structures. However, to fully explain accident event sequences, it is necessary to interpret them in view of the human and organizational factors (HOF) of influence as advocated in [40] for structures in general and for offshore structures in [41-42].

Basically structural failure occurs when the resistance, R is less than the load effect, S. From an HOF point of view this can be due to too small safety factors to account for the normal uncertainty and variability in R and S relating to ultimate limit state (ULS) and fatigue limit state (FLS) criteria. But the main cause of actual structural failures is abnormal resistance or accidental or abnormal loads due to human errors and omissions.

Design errors materialise as a deficient (or excessive) resistance, which cannot be derived from the parameters affecting the “normal” variability of resistance. Fabrication imperfections (such as cracks, plate misalignment, etc.), which also affect the resistance, are influenced by human actions. The
“normal” variability of welders performance, environmental conditions, etc. lead to a “normal” variability in the imperfection size, characterised by a smooth variation of the relevant imperfection parameter. Sometimes an abnormal deviation from this behaviour occurs, e.g., caused by using a wet electrode, etc. or another gross fabrication error. Thus, the initial fatigue failure of a brace in the Alexander L. Kielland platform was due to lack of fatigue design checks as well as inadequate inspection [43]. Even though the fatigue failures that had occurred in semi-submersibles in the period 1965-70 resulted in fatigue requirements, the requirements were not properly implemented even for platforms built in the 1970’s. Many platforms built in the 1970s had joints with design fatigue lives as low as 2-5 years. Fatigue failure has been rediscovered many times, even in marine technology, since Wöhler’s initial “scientific” discovery more than 150 years ago.

3.2. Overload damages and failures of hull structures

Man-made live loads have a “normal” and an abnormal component, while some loads, notably fires and explosions, ship collisions, etc. do not have a normal counterpart. They are simply caused by operational errors or technical faults. The mobile platform Ocean Ranger capsized offshore New-foundland in 1982. The accident was initiated by control room window breaking due to wave slamming. The water entering the control room lead to short circuit of the ballast valve system, thereby leading to spurious operation of ballast valves. The resulting accidental ballast condition could not be controlled partly because of lack of crew training and partly because of inadequate ballast pumps, and open chain lockers [36].

The significant damage to the jacket in Figure 3a was caused during the hurricane Lilli in the Gulf of Mexico by waves hitting platform deck due to apparently too small deck clearance.

The catastrophic explosion and fire on the Piper Alpha platform (Figure 3b) in 1988 was initiated by a gas leak from a blind flange of a condensate pump that was under maintenance and not adequately shut [37]. The gas ignited and the initial explosion lead to damage of an oil pipe and subsequent oil fire and explosion.

In 2001 the platform P-36 in Brazil experienced a burst collapse of the emergency drainage tank, accidental explosion and subsequent flooding, capsizing and sinking. A series of operational errors were identified as the main cause of the first event and also the sinking. [38]. Other accidents and structural failures are discussed e.g. by Vinnem [43].

3.3. Fatigue and other degradation of hull structures

Degradation due to corrosion and fatigue crack growth would normally develop slowly to failure. However, fatigue can cause catastrophic accidents if the fatigue life is not sufficient to make IMMR effective or if there is lack of robustness, as for the Ranger I [34] and Alexander Kielland [35] platforms.

Crack is the most critical degradation phenomenon, because it could result in rupture. The stages of crack growth depend upon the layout of the structure. For a frame or truss structure consisting of slender members, it is natural to consider crack growth in the following stages: visible crack, through-thickness crack, and failure (rupture) of member. In monocoque structures the situation is different in that cracks in the main hull girder can grow continuously until global rupture of the hull [45]. Fatigue failure, as inferred from SN curves, is normally taken to be a crack through the plate thickness. In this case it is desirable to have a criterion for rupture (for large cracks).
Cracks are for instance always present at welds. The development of cracks depends on their initial size (normally a fraction of a mm), uncertainties in the stresses driving the crack, fatigue resistance and the inspection method used to detect the crack. Due to the very nature (small size) of initial (fabrication) defects, an abnormal size of such defects often have been the cause of fatigue cracks. Hence, cracks have been caused by e.g. [26-28].
- not carrying out proper fatigue design checks and inspections and possible repairs, e.g. [35]
- abnormal initial defect size, e.g. due to wet electrodes
- abnormal crack propagation e.g. due to corrosion fatigue effects
- fatigue caused by overprotection or loss of protection
- abnormal local geometry due to deviation between as-built structure deviating and design or bad design. Hence inspection engineering should always refer to the as-built condition
- error in load (stress) analysis (environmental conditions, method, stress concentration factor) and particular phenomena like VIV.

During fabrication the QA/QC addresses control of material and geometry, especially tolerances relating to misalignment etc., possible damage that could occur etc. It is noted that defects in welds are primarily controlled indirectly by the specification of welding procedure, environment etc. This is because the normal defect depth, say of the order of 0.1 mm are not likely to be detected by non-destructive examination (NDE) inspections with a mean detectable crack size which is significantly larger. However, gross errors, like cracks of a depth 2.0 mm or more might be detected by NDE. Larger defects than the 0.1 mm could be due to e.g. wet electrodes or other deviations from normal welding procedures. Figure 4 shows an example with a 2 mm deep initial defect. The implication is a 80-90% reduction in the fatigue life for this plate under membrane stresses. Based on underwater inspection results for tubular joints in jackets Moan et al. [46] back-calculated the initial crack depth to be 0.9 mm. The collected experience data [47] clearly show shortcomings in local design and fabrication quality than normally accounted for in fatigue management based on traditional fatigue analyses

Extensive experiences regarding cracks in North Sea jacket platforms and semi-submersible drilling platforms have for instance been reported in [26-27, 46-48].

The occurrence of cracks in jackets have been correlated to fatigue predictions. The most important lessons learnt are that the initial methods used in general were conservative, but 2-3 % of the cracks detected were not predicted. The latter fact indicates that gross fabrication defects occur. The average crack depth of propagating cracks detected was 4.8 mm, with a small percentage of through thickness cracks. Another lesson was the significant difference in relative crack occurrences in platforms installed before and after 1978.

All data for semisubmersibles have not yet been correlated with predictions. However, comparisons made show a generally good agreement, but that deviation between observations and predictions are especially due to discrepancies between design drawings and specification and as-built structural geometry as well as excessive weld defects.

Figure 5 shows an example of a misalignment between plates which is larger than the plate thickness, while the fabrication tolerances normally accounted for in the design and inspection planning normally is of the order of 30-50% of the plate thickness. This geometrical effect significantly reduces the fatigue life of the associated welded joint under transverse loading.

During fabrication detected cracks are repaired. Post welding treatment might also be applied. However, while the effect of weld toe grinding after fabrication corresponds to approximately a factor of 2 in terms of fatigue (design) life, the effect is more significant if it is done at a late stage during operation because the crack has grown to a larger size and is “removed”.

Even if the most fatigue-prone and critical areas of jackets and semi-submersibles are much more limited in extent than for ships, there might be several hundred hotspots to follow up.

It should be noted that limited experiences are available for novel concepts like Tension-leg and Spar platforms. The importance of updating the information of the geometry based on the as-built geometry is crucial as basis for the follow-up during operation.

3.4. Unknown phenomena
In some cases, accidents have been caused due to lack of knowledge in the engineering profession at large, i.e. unknown phenomena. Recently discovered new phenomena, such as ringing and springing of Tension-leg platforms, deterioration failure mechanism of flexible risers, and vortex induced motions of floating platforms, were observed in time before any catastrophic accident occurred, and the necessary precautions could be made. However, sometimes the accident cause can be attributed to design codes not being up to actual knowledge in the profession.
4. Safety management

4.1. General

Basically the integrity of structures is ensured by
- designing them to withstand environmental and intended operational loading throughout their life cycles according to limit state criteria listed in Table 1 – for a service life of 20 years or more.
- providing measures to detect through inspection or monitoring, hazards or damage and mitigate them at an early time to avoid accident escalation.

Relevant criteria for ULS, FLS and ALS (Table 1) are reviewed in [49], with emphasis on steel structures. It is emphasized that there is no criteria that account for the interaction between fatigue (crack growth) and ultimate failure (rupture). For this reason it is important that the limit (failure mode) considered in FLS and ULS is properly defined.

The ULS check is commonly made by determining action effects, S due to G (gravity actions), P (payloads) and E (environmental actions) by a linear global structural analysis while the component resistances R are determined by laboratory experiments and nonlinear structural analysis and given by parametric formula in design standards. The ULS component design check is the made typically by:

\[
S_d \leq R_d; \text{ where } \quad S_d = \gamma_G S(G_c) + \gamma_P S(P_c) + \gamma_E S(E_c) \quad (1a-c)
\]

where the \( \gamma \)'s are action and material factors. The subindices \( c \) and \( d \) denote characteristic and design values, respectively. A system design check is also emerging [47]. (NORSOK N-003). The characteristic environmental action for ULS refers to an annual probability, of exceedance of \( 10^{-3} \)– considering the short- and long- term variability of the actions.

Table 1. Safety criteria for design of structures.

| Limit states | Description | Remarks |
|--------------|-------------|---------|
| Ultimate (ULS) | Overall “rigid body” instability | Different for bottom– supported, or buoyant structures. |
|              | Ultimate strength of structure, mooring or possible foundation | Component design check of strength |
| Fatigue (FLS) | Failure of welded joints | Component design check depending on residual system strength (see Table 4) |
| Accidental collapse (ALS) | Ultimate capacity of damaged structure with “credible” damage | System design check |

1) Capacity to resist “rigid body” instability or total structural failure

A simple expression for the cumulative fatigue damage can be obtained by assuming that the SN-curve is defined by \( NS^n = K \) and the number, \( n(s) \) of stress ranges is given by the Weibull distribution:

\[
F_s(s) = 1 - \exp \left[ -\left( \frac{s}{A} \right)^{\beta} \right] \text{ for } s > 0 \quad (2)
\]

where \( A \) and \( B \) are the scale and shape parameters of the distribution, respectively. The corresponding uncertainty is modelled by the parameters \( A \) and \( B \), which then depend upon uncertainties associated with environmental conditions, wave load model and structural modelling. These parameters might be expressed as: \( A = s_0/\ln N_0 \) \(^{1/\beta} \); with \( s_0 \) corresponding to \( P/ S \geq s_0 \) \( f = 1/N_0 \), where \( N_0 \) is the number of cycles in a reference period for \( s_0 \). The cumulative damage, \( D \) in a period, \( t \) with \( N_I \) cycles, is then
\[ D = \sum_{i} \sum_{j} \frac{n_{ij}}{N_{ij}} = \frac{N_{\Gamma}}{K} \left[ \frac{s_0}{(\ln N_0)^{\beta}} \right]^m \Gamma \left( \frac{m}{B + 1} \right) \]  

where \( \Gamma(\cdot) \) is the Gamma function. The assumption of Weibull distribution of stress ranges is relevant for platforms operating in extratropical regions. The expression in Equation (3) can be refined by considering other models for the load effects (stress ranges) and SN curves, e.g. [50-51].

4.2. Human and Organizational Factors

From a human and organizational error point of view, however, the causes of failures and mitigation measures can be categorized as shown in Table 2. In general, the measures include quality assurance and control (QA/QC) relating to the engineering process as well as the hardware and operational procedures as well as the Accidental Collapse Limit State criterion.

Gross errors and their effects should be avoided by adequate competence, skills, attitude and self-checking of those who do the design, fabrication or operation in the first place; and by exercising “self-checking” of their work. In addition, quality assurance and control (QA/QC) should be implemented in all stages of design, fabrication and operation.

The quality assurance and control of the engineering process have to address two different situations, which require different type of attention, namely:

- detect, control and mitigate errors and omissions made in connection with technology that is known in the engineering community as such. With the increasing use of computers in the design, construction, and operation of oil and gas structures, software errors are of particular concern
- identify possible unknown phenomena, e.g. associated with load, response and resistance, and clarify the basis for accounting for such phenomena in design

In the future the aging of existing offshore structures, especially due to crack growth, needs attention, see Section 4.3.

### Table 2. Causes of structural failures and risk reduction measures.

| Cause                                | Risk Reduction Measure                                |
|--------------------------------------|------------------------------------------------------|
| Less than adequate safety margin     | Increase safety factors or margins in ULS, FLS;      |
| to cover “normal” inherent uncertainties. | Improve inspection of the structure(FLS)\(^1\)             |
| Gross error or omission during:     | Improve skills, competence, self-checking (for d, f, o) |
| - design (d)                        | QA/QC of engineering process (for d)                  |
| - fabrication (f)                   | Direct design for damage tolerance (ALS) – and provide |
| - operation (o)                     | adequate damage condition (for f, o)                  |
| Unknown phenomena                   | Inspection/repair of the structure (for f, o)\(^2\)   |

\(^1\) Measure by Structural Reliability Analysis  
\(^2\) Measure by Risk Assessment

As mentioned above, operational errors typically result in fires or explosions or other accidental actions. Such events may also be controlled by appropriate measures such as detecting the gas/oil leakage and activating valve shut in; extinguishing of a fire by a deluge system activated automatically etc. These actions are often denoted “Event Control”.

In the treatment of the effect of the gross errors in design one might separate between identifiable/quantifiable versus unidentifiable/unquantifiable hazards. Thus errors resulting in accidental loads belong to the first category while design errors belong to the second category.

Depending upon the function (oil and gas platform, wind turbine, bridge) of the structure and regulatory regime, the acceptance criteria in terms of consequences, such as fatalities, environmental damage or property damage, are established. While fatalities caused by structural failures would be
related to global failure, i.e. capsizing or total failure of deck support, smaller damages may result in pollution; or property damage which is expensive to repair, especially for the underwater part of a permanent structure.

4.3. Design for Robustness: Accidental Collapse Limit State

Accidental Collapse Limit State (ALS) criteria are introduced to limit the corresponding residual risk i.e. to prevent progressive failure [28]. This goal could be achieved by designing the structure locally to sustain accidental actions and other relevant actions. Alternatively, local damage may be accepted and the ALS requirement should focus on survival of the damaged structure to relevant actions, to avoid escalation.

Accidental Collapse Limit State (ALS), initially called the Progressive Collapse Limit State, requirements, are motivated by the design philosophy that “small damages, which inevitably occur, e.g. due to ship impacts, fires and explosions, and other accidental loads, as well as environmental hazards, should not cause disproportionate consequences”. The ALS criterion was formally first introduced for all failure modes of offshore structures in Norway in 1984 [52]. The background and practicing of the ALS criterion is described in [28, 49].

The introduction of the quantitative robustness check in terms of ALS, was possible because FEMs had been developed for accomplishing the necessary nonlinear structural analysis to estimate the damage and the strength of the damaged structure. See current versions in [10-12].

ALS checks apply to all relevant failure modes, like, structural failure as well as instability/capsizing (in terms of intact and damage stability requirements for floating platforms).

The structural integrity criterion in [10] is a two-step procedure as illustrated in Figure 6. First, the initial damage due to accidental actions (fires, explosions, ship collisions, dropped objects as well as abnormal distribution of payload or ballast) with an annual exceedance probability of $10^{-4}$ is estimated by a nonlinear analysis. The initial damage in some cases need to be specified, based on consideration of the vulnerability of the structural components, difficulty of detecting the damage or other experiences, as failure of a slender member in the hull, a mooring line etc. Based on the experience that crack type defects which are larger than the normal initial defects could occur and escape detection at the fabrication stage, Moan [28] suggested to include a corresponding specified damage condition. Other barriers to deal with the occurrence of abnormal defects are presented in Table 5. Abnormal sea loads, at an annual probability level of $10^{-4}$ also need to be considered in the ALS check – in a single step.

The accidental loads are to be determined by risk analysis, see e.g. [44], accounting for relevant factors that affect the accidental loads. In particular, risk reduction can be assumed to take place by reducing the probability or consequences of hazards.

![Figure 6](image_url) Schematic illustration of the two-step ALS check: (Left) assessment of damage caused by an accidental action (A) ship impact –considering relevant permanent and functional (F) loads and possibly environmental loads, (Right) a check of the survival of the damaged platform under environmental load, E as well as F loads.
The second step in the NORSOK ALS procedure is to demonstrate that the damaged structure resists relevant functional and environmental loads an annual exceedance probability of $10^{-2}$ or a lower probability depending on the correlation between the accidental event and the environmental condition – without global failure.

More details about accidental loads, risk analysis to estimate their magnitude, and their effect on structures may be found in e.g. [11-12, 44, 53-54].

The ALS criterion is supposed to include “abnormal” wave loading as well. Obviously, this check will involve a survival check based on a load event corresponding to an exceedance probability of $10^{-4}$ only. In this connection the focus is on possible “abnormal” waves, with high crest or other unusual shape – which is not a simple “extrapolation” of the $10^{-2}$ event [55-56].

4.4. Inspection, Monitoring, Maintenance and Repair

Inspection, Monitoring, Maintenance and Repair (IMMR) should address all kinds of damages as well as conditions that could lead to damages. The occurrence of accidental damage due to fires/explosions and ship impacts should on one hand be controlled by surveillance of hydrocarbon leaks and ship traffic but on the other hand the damage once it has happened, easy to identify.

Corrosion and crack growth need continuous surveillance. Corrosion damage is indirectly monitored by the quality of the coating or cathodic protection system; and eventually by thickness reduction. Moreover, there is normally ample time for repair in case of corrosion damage.

The challenge is cracks. It is important that the IMMR reflects the fact that fabrication errors occur and cause abnormal initial cracks. In view of the fact that normal welding induced cracks are of the order of 0.1 mm, an abnormal crack is not that large. In general, therefore, it becomes important to ensure that there is ample time between visible (detectable) crack and fracture. A general remedy to ensure this feature is to limit the stress level by designing for fatigue by a large FDF or to ensure ultimate strength after member failure.

For a given inspection (with normal quality) with no crack detection in a joint with an abnormally large defect, the updating of $P_f$ will be conservative. However, the inspection itself can be subjected to gross errors. Thus, if abnormal defects are present in joints which are not inspected, the estimate of the failure probability will obviously be non-conservative. This fact should be accounted for in the estimate of the risk of system failure in view of the coverage of the inspection program.

5. Reliability and reliability based design and inspection approach

5.1. General

In principle risk based design could be carried out, by achieving a total system (structural layout, scantlings and equipment, procedures and personnel) that complies with a certain acceptable risk level. This is, however, not feasible in practice. In reality, different subsystems, like:

- loads-carrying structure & mooring system
- process equipment
- evacuation and escape system

are designed according to criteria given for the particular subsystems. Safety criteria for the structural design of offshore structures may be classified as shown in Table 1. While ULS and FLS criteria are generally applied, the introduction of a quantitative ALS criterion by NPD [52] was a significant step towards the generally agreed concept of making structures damage-tolerant (robust). Figure 7 illustrates the design check involving the different safety criteria.

The assessment of the structure during the initial design and operation are subjected to uncertainties, namely

- normal variability and uncertainty due to inherent variability or lack of data (also to establish analysis models)
- human errors

affecting both the actions and their effects as well as resistance. Design is based on generic measures about uncertainties while the inspection of the as-built structure and its behaviour during operation
provide improved information about abnormal geometry, including defects, and, hence, the component strength.

In-service condition monitoring by e.g. acceleration and stress measurements may be used for validation of the structural analysis and design assumptions and the occurrence of damages. Measurements of the change of vibration properties can be used to detect damage [57]. Normally in-service measurements of stresses focuses on nominal stresses, while laboratory studies would be needed to validate local (hot spot) stresses as well as both ultimate and fatigue strength. Fatigue strength in design is normally based on SN curves, but crack initiation and propagation features would be required in a high fidelity analysis e.g. for inspection planning.

![Figure 7](image_url) Analysis of action effects and resistances for design checks.

Structural reliability methods (SRMs) have been developed as a tool to assess failure probability. However, the SRM does not account for human errors. Hence, the probabilities should be considered notional and not “real” – relating to the generic uncertainties known at the design stage. However, the inspection of the as-built structure makes it possible to (partly) eliminate the effect of gross errors that caused deviations from the planned structure – relating to the occurrence of cracks. For use of SRM in inspection planning it is important to identify and “eliminate” as far as possible abnormal defects and modelling the geometry of the as-built structure. These features are further treated for jackets and semisubmersibles in [47]. They show how SRM analyses give measure of the capability of the analyses to describe the actual fatigue failure potential.

The fabrication quality is one of the main design assumptions. Deviations in the fabrication quality are one of the reasons for reduced correlation between observed failures and the probability for failure given by the analyses.

The planned use of information from the inspection, repair, operation and modification history will determine the requirement for the process securing the data for the inspection, repair and modification history. However, this report describes how the inspection and repair history is applied as part of the assessment of structural integrity and define requirement for the inspection and modifications scope. Bayesian updating plays and important role in the analysis of information and data from inspections carried out.

5.2. Ultimate Limit States

5.2.1 General: Ultimate Limit State (ULS) criteria for overall stability of bottom-supported and floating structures as well as strength formulations are given e.g. in [29] for relevant load conditions.

Extreme loads with an annual exceedance probability of $10^{-2}$ are normally required for ULS check, while for FLS check the local stress range history is needed for welded connections while the joint variation in stress range and mean stress is required e.g. for base material.
Load effects for ULS design checks are typically obtained by considering all or a carefully selected sea states and applying relevant wave kinematics, hydrodynamic load and structural models [11]. The challenges in predicting extreme wave load effects for ULS design of offshore structures relate to the modelling freak or rogue wave or crest and their occurrence rate as well as dealing with severe nonlinear hydrodynamic effects; e.g. involving phenomena indicated in Figure 8. The latter effects include wave-in-deck loading, slamming, column run-up, green water on deck and excitation by steep, high waves, e.g. causing dynamic ringing effects. Figure 3a illustrates a damaged platform due to wave loads on the deck structure. Methods for predicting the corresponding hydrodynamic loads are still quite uncertain, and experiments are necessary, see e.g. [11]. The structural analysis is normally hierarchical, starting with a global and obtaining the local stresses in principle by using substructures in the global analysis or zooming/sub-modelling techniques.

![Figure 8](image)

**Figure 8.** Wave action effects with significant uncertainty.

Figure 9 shows the uncertainty in the base shear according to the API/ISO jacket wave load recipe based on a regular wave obtained by Heideman and Weaver [58]. The mean and CoV of the model uncertainty, $X$, are 1.06 and 0.25, respectively. It is noted that the uncertainty can be significantly reduced if a random wave model is applied [59]. On the other hand the uncertainty increases if the behaviour of the jacket is dynamic.

Ultimate strength formulations used in design are traditionally based on strength of material formulations and substantiated by extensive test results. However, design based on direct ultimate strength analysis, by using finite element methods and by accounting for nonlinear geometric and material effects, is emerging.

A simplified model for the total uncertainty in the base shear can by estimated by modelling the base shear, $S$ as:

$$S = X h^a$$

(4a)
where $\alpha$ is 1-3 depending on the relative magnitude of drag and inertia wave actions; $h$ - wave height and $X$ - model uncertainty of action. It is seen that the CoV of $S$ is approximately:

$$V_s^2 \approx V_X^2 + \alpha^2 V_h^2$$

(4b)

showing that the uncertainty in the wave height can contribute significantly the that in the base shear.

5.2.2 Reliability measure: Structural reliability methods (SRMs) have been used to ensure that ULS requirements are consistent with the desired target safety level, especially by the efforts by Fjeld, Moses, Lloyd and Karsan, Moan and Jordan and Maes [60-64], to calibrate the safety in design codes to a certain reliability level. An evaluation of previous efforts on calibration of offshore codes was provided in [65] in conjunction with the ISO effort to harmonize codes for offshore structures. Assessment of uncertainties in load effects and resistances was a crucial issue in these studies.

SRM is applied to determine the failure probability considering fundamental variability, as well as uncertainties due to lack of knowledge in loads, load effects and resistance. The state of art methods for calculating the failure probability are numerical First Order and Second Order Reliability as well as Monte Carlo simulation methods, e.g. [66]. However, analytical solutions exist for a few cases, for instance, when failure is expressed by $g(\cdot) = R - S \leq 0$ and both the resistance $R$ and the load effect $S$ are normal or lognormal random variables.

The failure probability is in general expressed by:

$$P_f = P(g(\cdot) \leq 0) = \Phi(-\beta) \quad \text{or} \quad \beta = -\Phi^{-1}(P_f)$$

(5)

where $\Phi(-\beta)$ is the standard cumulative normal distribution and $\beta$ is the reliability index. Numerical values of this relationship are shown in Table 3. The reliability index $\beta = \beta_{LN}$ can be exactly written as follows when $R$ and $S$ have lognormal distributions, see e.g. [66-67]:

$$\beta_{LN} = \sqrt{\ln[(1+V_S^2)(1+V_R^2)]}$$

$$\ln[\frac{\mu_R}{\mu_S} \sqrt{\frac{1+V_S^2}{1+V_R^2}}] \approx \ln[\frac{\mu_R}{\mu_S}]$$

$$\approx \frac{V_S^2 + V_R^2}{2} = \beta_{LN}$$

(6)

This simple expression has turned out to be useful and was applied in the API reliability based code calibration [64]. However, using the lognormal format to estimate the failure probability for cases where e.g. the distribution of $S$ is not lognormal, may result in significant discrepancy in the $P_f$. This fact shows that the target reliability level needs to be intimately associated with the reliability model applied.

The reliability estimate critically depends on the assessment of uncertainties in structural loads and strength, as indicated above and exemplified subsequently. It is important that authoritative values of the uncertainties are applied in reliability analyses.

Structural reliability methods provide notional estimates of probabilities. These probabilities are small (current ULS requirements imply the order of $10^{-3} - 10^{-5}$) and are lower than the experienced $P_f$ for offshore structures, e.g. [65, 68].

Another matter is that gross errors that often cause failures (Table 2), is not recognized in the SRM. For this reason the structural reliability method (SRM) does not provide a measure of the actuarial total risk level associated with offshore facilities. Yet, SRM is useful in ensuring that the ultimate strength and fatigue design criteria are consistent by calibrating safety factors for ULS and FLS criteria (Section 5.3). However, to achieve a true measure of safety, a risk assessment methodology is needed. See also overviews in [69-70].
Table 3. Relation between $\beta$ and $P_f$

| $\beta$ | 1.0 | 1.4 | 1.8 | 2.2 | 2.6 |
|---------|-----|-----|-----|-----|-----|
| $P_f$  | 0.16| 0.081| 0.036| 0.014| 0.47-10^{-2} |
| $\beta$ | 3.0 | 3.4 | 3.8 | 4.2 | 4.6 |
| $P_f$  | 0.14-10^{-2} | 0.34-10^{-3} | 0.72-10^{-4} | 0.13-10^{-4} | 0.21-10^{-5} |

Since offshore structures are subjected to time variant loads, the failure probability should refer to a time interval, e.g. a year or the service life. This can be achieved by considering $S$ as a random variable, referring to an annual or service life time maximum value. However, this approach is not straightforward when the failure event is described by multiple load effect variables. Then more advanced methods are needed [67, 71]:

### 5.2.3 Relationship between failure probability and safety factors given the uncertainty in $R$ and $S$

By assuming the simple ULS design format (Equations 1a-c) and the following relations between characteristic and design values:

\[
R_d = \frac{R}{\gamma_R} = \gamma_S S_c = S_d
\]

Mean CoV
\[
\mu_S = B_R S_c, B_S \leq 1; \quad V_S = 0.15 - 0.3
\]
\[
\mu_R = B_{R1} R_c, B_R \geq 1; \quad V_R = 0.1
\]
\[
B_S = B_{S1} B_{S2} \quad B_{S2} - load \ model \ bias
\]

the following relationship results:

\[
\beta_{SN} = \frac{\ln \left( \frac{\mu_R}{\mu_S} \right)}{\sqrt{\frac{V_R^2}{V_S^2} + V_S^2}} = \frac{\ln \left( \frac{B_R \gamma_S S_c / B_S}{B_S} \right)}{\sqrt{V_R^2 + V_S^2}}
\]

With the relationship between $P_f$ and $\beta_{SN}$ given above, the desired relationship between the uncertainty measures and the safety factors, $\gamma$ are obtained. This expression also shows the relative importance of systematic (B) versus random (V) uncertainty.

### 5.3. Fatigue Limit State

#### 5.3.1 General

Fatigue is an important consideration for structures in areas with more or less continuous storm loading (such as the North Sea) and especially for dynamically sensitive structures. Even if fatigue was known since Wöhler’s “scientific” account of the fatigue phenomenon in the 1850s, it was not until the 1980s and 1990s the criterion was fully recognized for offshore (and ship) structures.

Fatigue crack growth is primarily a local phenomenon. Fatigue strength is commonly described by SN-curves, i.e. the number of cycles to failure as a function of the stress (range) level that have been obtained by laboratory experiments. Failure is often defined as through thickness crack, visible crack and total rupture of the test specimen. Fracture mechanics analysis of fatigue strength has been adopted to assess more accurately the different stages of crack growth including calculation of residual fatigue life beyond what is defined as fatigue failure in conjunction with SN-curves. Such detailed information about crack propagation is also required to plan inspections and repair, e.g. [50, 51]. However, it is important to ensure that the fracture mechanics model is consistent with the SN-approach with respect to fatigue failure. This is because the initial crack size needs to be modelled in the fracture mechanics while it is implicitly represented in the experimental data that serve as basis for the SN-approach, e.g. [72].
5.3.2 Reliability measure: The elementary reliability format (6) may also be used to obtain an estimate for the fatigue reliability based on the SN formulation. By expressing fatigue failure by

\[ g(D) = \Delta - D \]  

Equation (6) can be used with \( R = \Delta \) (cumulative damage at failure) and \( S = D \). Moreover, if only the dominant variables \( s_0 \) and \( K \) are taken as random variables with lognormal distribution as advocated by Wirsching [73] a lognormal reliability format can be formulated (see further discussion in [68]). For a fatigue design with allowable damage \( \Delta_{dl} = 1.0 \) and 0.1; the implied \( P_f \)'s are about 0.1 and \( 2 \cdot 10^{-3} - 3 \cdot 10^{-5} \), depending on uncertainty measures, respectively, in the service life.

With a notional probability of fatigue failure in the service life of the order of 0.1 when the fatigue design factor is taken to be 1.0, inspection and repair are clearly required to ensure adequate lifetime safety [26]. In addition, gross errors could occur.

5.3.3 Reliability estimates by account of inspection: The failure probability, \( P_f \), of a specific structural component can be updated through additional information obtained by response measurement or observed damages and a fracture mechanics model of the crack growth, such as the Paris-Erdogan formulation, namely

\[ \frac{da}{dN} = \begin{cases} C(\Delta K)^m & \text{for } \Delta K > \Delta K_{th} \\ 0 & \text{for } \Delta K \leq \Delta K_{th} \end{cases} \]  

(10)

where \( a \) is crack depth, \( N \) is number of cycles, \( C \) is crack growth parameter, \( m \) is the inverse slope of the SN curve, and \( \Delta K_{th} \) is a threshold of the stress intensity factor range \( \Delta K \) given as a function of \( a \).

For instance when inspections are made, say with no detection of cracks in joint \( i \) after a time, \( t \) in-service, the failure probability of joint \( j \) may be updated as follows

\[ P_{j,IE} = P\left( (g_j(\cdot) \leq 0) \big| IE_j \leq 0 \right) = P\left( (g_j(\cdot) \leq 0) \cap (IE_j \leq 0) \right) / P(IE_j \leq 0) \]

(11a)

where the failure event is

\[ g_j(\cdot) = a_{ij} - a_j(t) \]  

(11b)

and the inspection event is

\[ IE_j(\cdot) = a_{ij} - a_{ij} \]  

(11c)

for the \( j \)th joint. \( a_i \) and \( a_d \) are the critical and detectable crack size, respectively. See e.g. [21-22]. The updated \( P_j \) of joint \( i \) based on the inspection of joint \( j \) depends on the correlation between the \( g/(a) \) and \( IE_j \) events. Equations (11a-c) can be recasted in a convenient form for analysis as shown by Madsen et al. [21-22].

5.3.4 Inspection quality: The quality of non-destructive examination (NDE) methods for detection of cracks in metal structures is expressed by a probability of detection (POD) curve, which corresponds to the distribution function of detectable crack size \( ad \). Various sources of POD data are discussed in [26, 74]. In practice it is important to define the quality of NDE inspections in classes in the range of a mean POD from 0.4 to 1.6 mm [47], depending upon the competence of the inspection crew and environmental conditions; e.g. air versus underwater.

The reliability of assessing corrosion damage relates to the accuracy of estimating the change of thickness due to corrosion.
5.3.5 Uncertainties: The failure probability is crucially dependent upon the uncertainty measures of load and resistance parameters. It is important that authoritative values of the stochastic variables are used. Relevant uncertainty measures are given e.g. in [25, 74].

5.3.6 Calculation of reliability: It is noted that the FORM/SORM methodology is approximate and should be validated by using "converged" Monte Carlo simulation. This is particularly important for calculating the probability of intersections of events.

5.3.7 Guidelines on inspection planning with respect to fatigue cracks: Recently DNV GL [74] issued a comprehensive guidance for use of probabilistic methods for inspection planning with respect to fatigue cracks in jacket structures, semi-submersibles and floating production vessels. The approach is rather general may be used also for inspection planning of other structures subjected to significant dynamic loading such as jack-ups.

5.3.8 Validation – or rather estimate of uncertainty: The various models that constitute the reliability analysis method may be validated by: using model tests or full scale measurements to validate wave induced nominal stress; model tests to validate hot spot stress and fatigue strength and the reliability model at large by direct comparison of predicted and observed crack occurrences, see e.g. [26]. The comparison in [75] showed that the number of predicted propagating cracks identified in 3411 inspections of tubular joints in jackets, was typically 3 to 10 times larger than the number observed. This discrepancy can be traced back to uncertainties (conservativism) in the prediction of the (nominal) stress.

5.3.9 The effect of inspection on the fatigue reliability: The effect of inspection may be estimated in two different ways: a) at the design stage, before inspections are done or b) after the actual inspection has been made. If the effect of inspections is estimated at the design stage, the two possible outcomes: detection: D and no detection: ND need to be their probability of occurrence based on the reliability method. After conducting an inspection the outcome (D or ND) is known.

Moreover, during the service life, there may be several inspections. Equations (11a-c) can be generalised to cover cases with several inspections, with two alternative outcomes. Moan et al. [76] show how the allowable fatigue damage, $\Delta_{\text{all}}$, at the design stage can be relaxed when inspections and necessary repairs are carried out; i.e. as a basis for Table 4.

Figure 10 shows the reliability index $\beta$ as a function of time based on prediction of the effect of inspections every 5th year with no crack detection using an NDE inspection method with mean detectable crack size of 1.5 mm - at the design stage and based on the outcome of actual inspections. The latter obviously is more efficient in increasing the reliability index $\beta$.

The updating methodology is useful in connection with extension of service life for structures with joints governed by the fatigue criterion [77]. In such cases, the design fatigue life is in principle exhausted at the end of the planned service life. However, if no cracks have been detected during inspections, a remaining fatigue life can be demonstrated. But it is not possible to bring the structure back to its initial condition by inspection only. This is because the mean detectable crack depth typically is 1.0–2.0 mm, while the initial crack depth is 0.1–0.4 mm.

5.3.10 Inspection planning of wind turbines: While the support structure of wind turbines can be treated by the methods used for oil and gas platforms, the blades and drive train involve mechanical equipment and are difficult to access and condition monitoring is primarily used to follow up during operation. Damage is detected by using vibration analysis, Damage to the gears and bearings is identified by the metal particle content in the lubrication oil. See [57].
Figure 10. Reliability index as a function of time and inspection strategy. Inspection Event Tree analysis is based on prediction at the design stage. The other curves are based on inspections with known outcome during the service life.

5.4. Structural System Reliability

Systems reliability approaches are attractive because the most significant platform failure consequences, and especially fatalities, are associated with system failure and hence are useful for making decisions which affect safety and the significant costs of replacing or modifying the structure.

System failure can be expressed mathematically by load and resistance parameters relating to all failure modes for all structural components (members, joints, piles) and the probabilistic properties of these parameters. Broadly speaking, this may be achieved by a failure mode (or survival mode) analysis or direct-simulation methods, considering a sequence of fatigue and overload failures, see e.g. [78-80] and the overview in [23].

A significant challenge is to describe the failure modes, the probabilistic features of the random variables, and especially the correlation between them.

However, De [81] and Wu and Moan [82] demonstrated for jackets that accurate estimates of the systems failure probability under extreme sea loading can be achieved by considering a single system failure mode, i.e. by referring both the load (S) and resistance (R) to a given load pattern and using the (overall) base shear as variable.

A first approximation to the failure probability, $P_{SYS}$, of a jacket system consisting of discrete elements, considering both overload as well as fatigue failure followed by over-load failure modes, may be expressed as:

$$
P_{SYS} = P[SYS] \approx P[SYS(U)] + \sum_{j=1}^{N} P[F_j] P[SYS(U) | F_j] + ... \tag{12}$$

where $SYS(U)$ and $SYS(U) | F_j$ are treated as pure over-load system failures readily calculated by efficient methods for framed structures [83-84] and $F_j$ the fatigue failure of component $j$.

The approximations made and the use of Equation (12) is discussed in [26]. Despite the approximation made in connection with Equation (12), use of this system reliability measure can give reasonable decisions if the target reliabilities are determined consistently for the same expressions.
The formulation expressed by Equation (12) is particularly applicable for structures with clearly defined components such as members and joints on jackets, jack-ups, drilling semi-submersibles (with braces) [68] while cracks in monocoque structures like ship hulls are more challenging to deal with.

There is an important link between fatigue and ALS design criteria and inspection, by the fact that the acceptable fatigue failure probability should depend on the consequences – i.e. potential progressive failure, see Table 4.

5.5. Target reliability or risk level for design codes
The target safety level should depend upon the following factors, e.g. [85-86]:
- initiating events (hazards) such as environmental loads versus accidental loads (which are caused by human errors or omissions)
- method of SRM or structural risk analysis, especially which uncertainties are included
- failure cause and mode
- the possible consequences of failure in terms of risk to life, injury, economic losses and the level of social inconvenience.
- the expense and effort required to reduce the risk of failure.

A main issue is that target levels for notional failure probabilities relating to SRM should be clearly distinguished from the true failure probabilities relating to risk assessment considering human factor effects also. Hence, Jordaan and Maes [64]: argued that the target failure probability in the context of SRM should be a fraction of the true failure rate.

Moreover, rather that setting an overall target level it is more practical to establish target levels for each hazard separately, see e.g. [41]. Moreover, target reliability levels for ULS and FLS criteria should be based on SRM accounting for normal variability and uncertainties in load effects and resistances, while ALS criteria needs to be based on a broader risk assessment.

In general it is recommended to establish target levels in a consistent manner based on inferring the target level by using the same reliability or risk analysis method to estimate the inherent reliability level implied by a reference design code that is considered acceptable and the method used to demonstrate compliance with the target level [85]. Herein the focus is on fatigue target levels.

Table 5 shows semi-probabilistic fatigue acceptance criteria established by NPD/NORSOK in Norway and API [87] (- essentially for jackets), respectively. A reference target failure probability level was first established based on that inherent in semi-probabilistic fatigue criteria for the cases of two consequence cases; namely where fatigue implied total loss and the structure surviving a 100 years storm after fatigue failure. By accounting for the effect of inspection [41] and using a simplified system approach by considering each term in the sum in Equation (12) for jacket structures [48, 76, 85] fatigue design criteria considering the effect of inspection, have been derived and compared with codified criteria in Table 4.

6. Inspection, monitoring, maintenance and repair during fabrication, installation and operation
6.1. General
As indicated in Section 4.3 IMMR needs to address structural damage but also other operational and hardware aspects, especially event control relating to fires/explosions, ship impacts that can result in damages or failures. Herein the focus is on crack control.

The main life cycle efforts to prevent that cracks develop into failures, include:
- adequate design with respect to
- fatigue design (Fatigue Design Factor)
- residual fatigue life
- ultimate reserve strength (to overload)
- adequate inspection, or
- adequate monitoring of leak, when relevant
Table 5 shows qualitatively which role different safety measures play regarding crack control for different types of structures. During design structural scantlings and local geometry to achieve a desired fatigue life, inspection, maintenance and repair plan are decided.

Fatigue design requirements depend upon inspectability and failure consequences are considered, e.g. as shown in Table 4. It is noted that the costs of the underwater inspections on jackets and the number of possible crack sites on FPSOs make it necessary to prioritize inspections. For semi-submersibles some welded joints will have a high priority because of high likelihood of crack occurrence and failure consequences.

Whether the inspection should be chosen to aim at detecting barely visible cracks, through-thickness cracks (e.g. by leak detection) or member failures would depend on how much resources are spent to make the structure damage tolerant. This choice again would have implication on the inspection method; the main inspection methods being non-destructive examination (NDE) methods, detection of through-thickness crack by e.g. leak detection, or failed members by visual inspection. The quality of visual or NDE methods depends very much upon the conditions during inspection. Large volume offshore structures are normally accessible from the inside, while, e.g., small diameter tubular tethers in TLPs and maybe some joints in semi-submersibles, are not.

Permanent repairs are made by grinding to remove small cracks, cut out and butt welding a new section, re-welding, adding or removing scantlings, brackets, stiffeners, lugs or collar plates.

Table 4. Fatigue design factor, FDF to multiply with the planned service life to obtain the design fatigue life: NPD-NORSOK/API and (reliability analysis).

| Classification of structural components based on damage consequence¹ | Access for inspection and repair | FDF¹ | Residual fatigue life | Ultimate reserve strength | Inspection method |
|---|---|---|---|---|---|
| No access or in the splash zone | Below splash zone | Above splash zone or internal |
| Substantial consequences | 10/10 (10) | 3/5 (4) | 2/5 (3) |
| Without substantial consequences² (i.e. satisfaction of ALS req.) | 3/5 (4) | 2/2 (2) | 1/2 (1) |

¹ NPD(1984)-NORSOK N-001(2002) – general requirements while; API[87]; and reliability estimates [48, 76, 85]
² The consequences are substantial if the Accidental Collapse Limit State (ALS) criterion is not satisfied in case of a failure of the relevant welded joint considered in the fatigue check.

Table 5. Crack control measures.

| Type of structure | Type of joint | FDF¹ | Residual fatigue life | Ultimate reserve strength | Inspection method |
|---|---|---|---|---|---|
| Jacket | Tubular joint | 2-10 | Some - Sign. | Normally | NDE, U² |
| Semi-Submersible | Plated brace | 1-3 | Some | By ALS⁴ | LBB³, NDE |
| | Plated column-pontoon | 1-3 | Some | Limited | NDE |
| TLP | Tether Plating Column-pontoon plates. | 10 | Small | By ALS | IM⁵ |
| Ship | Longitud.comp. | 1-3 | Some | Limited | NDE |

¹ FDF - Fatigue Design Factor – by which the service life is to be multiplied with to achieve the design fatigue life
² NDE - Non Destructive Examination Method; U-underwater
³ LBB - Leak before break monitoring
⁴ ALS - Accidental Collapse Limit State
⁵ IM - Instrumental monitoring (by “an intelligent rat”)
The design criteria (Table 4) are based on criteria that account for normal variability and uncertainties. However, these measures are generic values; i.e. with the same criteria for all kinds of offshore structures. The initial inspection plan is also based on generic information available at the design stage. Besides differences between the features of different structures, the fabrication process might induce additional uncertainties, especially on features regarding local geometry that affect fatigue performance as described below. Hence, it is crucial to update the model used to predict crack growth based on the particular features of each structure.

During fabrication the QA/QC addresses control of material and geometry, especially tolerances relating to misalignment etc., possible damage that could occur etc. It is noted that defects in welds are primarily controlled indirectly by the specification of welding procedure, environment etc. This is because the normal defect depth, say of the order of 0.1 mm are not likely to be detected by NDE inspections with a mean detectable crack size which is significantly larger. However, gross errors, like cracks of a depth 2.0 mm or more might be detected by NDE.

The importance of updating the information of the geometry based on the as-built geometry is crucial as a basis for the follow-up during operation.

Finally, achieving robust offshore structures by applying ALS criteria is an important issue. In the present context a damage condition for an ALS check associated with abnormal cracks is envisaged, as commented upon in Section 4.3, see also [28].

During operation inspections are carried out to detect cracks and deterioration. An inspection plan involves:
- prioritizing which locations are to be inspected
- selecting inspection method (visual inspection, Magnet Particle Inspection, Eddy Current) depending upon the damage of concern
- scheduling inspections
- establishing a repair strategy (size of damage to be repaired, repair method and time aspects of repair)
- assessment methodology for crack detections

Typically major inspections of offshore structures (special surveys, renewal surveys) are carried out every 4 - 5th year, while intermediate and annual inspections normally are less extensive. Further refinement of the inspection planning has been made by introducing probabilistic methods as described below. As mentioned above it is important then to account for the findings regarding the geometry and cracks etc. during inspections after fabrication and during operation. Moreover, repairs might involve structural modifications that need to be considered. Besides making the necessary repairs of damages etc. it is important to make a record of the deviation of the as-built structure from the as-designed structure, cracks, corrosion, inspection history and repairs in order to obtain a more general assessment of the quality of the fabrication, for use in integrity management of other structures as well.

Cracks in Floating Production Storage and Offloading (FPSO) vessels may be repaired during operation, but operational procedures need to be changed to avoid hot work in tanks with combustible gases. However, more extensive repairs such as by introducing some thousands of additional brackets, grinding of cracks etc. need to be done in yards.

Semi-submersibles have to be dry-docked to carry out inspection and repair of the hull in North Sea operations. A major cost issue in connection with inspection of semi-submersibles, is the demobilization offshore, transport to yard, yard set-up, transport to offshore site and offshore mobilization. Production semis and TLPs, however, would normally have to be inspected and repaired on site.

Tethers are particularly critical components. Each tether is a series system with multiple potential crack sites. Inspection is carried by a remotely operated instrument and possibly detection of leak before break. Repair usually requires replacement of tether. For tether systems it is hence crucial to achieve safety by restrictive fatigue design criteria as well as an elaborate quality assurance at the fabrication stage.
The inspection strategy would normally be to inspect pre-selected potential crack sites. If the detected damage exceeds the acceptable level, the inspection would have to be extended to cover more possible crack sites, in the same or other “sister” platforms.

Inspection, monitoring and repair measures can contribute to the safety only when there is a certain damage tolerance. This implies that there is an interrelation between design criteria (fatigue life, damage tolerance) and the inspection and repair criteria, as shown in Table 4.

However, during operation the situation is different. Modification of the design and hence the scantlings is very expensive, and the most relevant measure to influence safety is the inspection and repair. The following section briefly describes how fatigue design and inspection plans (based on an assumed inspection method) can be established by reliability analysis to ensure an acceptable safety level.

![Figure 11. Scheduling of inspections to achieve a target safety level of $P_{fT}(i)$.](image)

6.2. Reliability (or risk) based inspection (RBI)

The first step from empirical to more rational procure to plan inspections, was to use fatigue analyses based on SN-data. Moreover, as mentioned above, design and inspection criteria (Table 6) relating to fatigue crack growth, are based on generic information. Inspections during operation of the specific structure yields more information – that can be used in planning future inspections. Reliability methods can serve as tools for the decision making under uncertainty relating to fatigue crack growth – to maintain an acceptable safety level. However, it is crucial that such analyses are based on information from inspections during fabrication and operation in order to refer to an as realistic model of the structure and its behaviour as possible. This includes information about crack type defects with excessive size.

Moreover, any information about the environmental conditions and the global nominal stress level based on monitoring, will be useful.

By assuming that the fatigue failure probability in Equation (12) is updated based on inspection of the relevant joint (member), - before its (rupture) failure. Moreover, the target reliability is assumed by allocating a certain target probability level, $P_{fSYS(T)}$, to each term in the sum of Equation (12), i.e.

$$P_{fSYS}(i) = P_{fSYS}(i) \cdot P[F_{SYS}(U)] \cdot F_{i} \leq P_{SYS(T)}$$  \hspace{1cm} (13)

where the system failure probability, $P_{SYS}(i)$ is associated with a fatigue failure of member (i) followed by an ultimate system failure. $P_{SYS(T)}$ is obtained by generalizing e.g. acceptance criteria implied by Table 4. $P_{fT}(i)$ the represents the target safety level for the fatigue failure of the individual joint.

This approach has been implemented for template, space frame structures [88, 48]. Given the target level for a given joint, inspections and repairs by grinding or other modifications are scheduled to maintain the reliability level at the target level as shown in Figure 11.
7. Requirements to computational tools for structural integrity management

Managing of the integrity of offshore structures require tools to cover the following items:

- Geometry representation, visualization of the relationship between the parts and the whole – while accounting for life cycle changes by means of CAD/CAM/CAE tools.
- Data about environmental conditions,
- Methods to determine overturning and stabilizing moment, calculate gravity and payloads, hydrodynamic, aerodynamic- and accidental actions and their effects, structural resistance,
- Approaches for carrying out code checks according to different limit states
- Reliability and risk analysis with respect to structural integrity in the life cycle in a wide sense to manage uncertainties due to normal variability and human errors

in view optimal Capex and Opex

Such data and methods are applied in the initial design and during operation in connection with reassessment. In the operational phase the initial design analyses and data gathered of the as-built structure and during operation need to be available in a data base. While obviously data for each structure is needed, use of data (especially relating to failure and damages) of other (especially related) structures, is also of interest. The challenges in striking a balance between sharing data between the stakeholders involved in the lifecycle and protecting the “IPR” of the data, and standardization of data bases, are important issues in this connection.

The hierarchy of methods at different fidelity levels and efficiency is needed for the different phases: conceptual via engineering to detailed design. It is therefore important to highlight the need to carry out R&D to develop methods at different level of refinement and computational efforts.

To illustrate the hierarchy of refinements consider for instance the determination of extreme wave-induced action effects at an annual exceedance probability level of $10^{-2}$ for ULS design: a) the wave condition may be described by a full long-term model of metocean data, selected sea states or even selected regular waves, clearly with different inherent uncertainties in representing the probability of the resulting action effect; b) Different wave theories may be applied; c) Hydrodynamic actions may be estimated by using a semi-empirical Morison formula, linear or nonlinear potential theory or full CFD methods; d) The determination of action effects can be done typically using Finite Element methods with different refinements, based on a static or dynamic frequency or time domain approach, considering linear or nonlinear behaviour. e) Uncertainties in the methods applied, beyond the fundamental variability of the wave condition, might be dealt with in design by introducing conservative simplifications, or a more formal semi-probabilistic approach with safety factors or a reliability analysis.

In general, high fidelity methods, validated against model tests or in-service measurement might be applied to calibrate simplified methods. An important aspect of choosing methods is the fact that high fidelity methods require “high fidelity data” to perform better than simplified methods and hence require expert users to avoid a false impression of accuracy or even human errors.

Similar features apply for analyses relating to other environmental actions, and for FLS and ALS design checks. Moreover, design is an iterative process – in the first place to satisfy all design criteria and also account for the balance between the design and inspection/monitoring, maintenance and repair plans. An additional challenging iterative approach is to satisfy all design targets in an optimal manner according to a certain measure, such as life cycle costs. To obtain a realistic optimum, it is important that all serviceability and safety constraints, objectives together with realistic cost data are explicitly accounted for. If the design is based on direct analysis of action effects, resistance and use of a goal-based setting with safety in terms of reliability or risk acceptance, the computational effort becomes excessive. Hence, there needs to be a balance of the refinement in the methods/tools applied in view of the uncertainties in the end solution. It might also be convenient to apply a sequential approach for the design, starting with a global design and gradually including detailed design relating to fatigue.

For the above reasons it is crucial that information about the uncertainty and efficiency of the hierarchy of mechanics and probabilistic methods for different purposes, is available, also as a basis for reliability based design. While apparently the same methods are used by different organizations, there are differences that need to be identified by benchmarking. The increasing complexity of the tools also
increases the chance of errors in the software or by the users; i.e. use of simplified methods might also reduce the risk of gross errors. Besides providing information from research in terms of research papers, research results might be disseminated in a more easily accessible way for users, in the form of standards and guidelines for data bases and methods.

8. Concluding remarks
The main life cycle efforts to prevent that cracks develop into failures, include: adequate design with respect to fatigue life (Fatigue Design Factor), residual fatigue life and ultimate reserve strength (to overload); adequate inspection, or adequate monitoring of leak, when relevant. This structural integrity management approach especially depends a follow-up during operation based on continuously establishing an inspection, modification and repair history. This is important because the initial structural design and inspection and repair planning is based on generic information for a class of structures and don’t reflect the particular features of a given structure with regard to design, fabrication and operational features. Some of the features are result of gross errors.

The importance of properly accounting for uncertainties in the integrity management is crucial. Structural reliability methods can provide an improved basis for ULS and FLS design and inspection and repair planning by accounting for the normal uncertainties in actions and resistances and inspection quality, to ensure that these criteria comply with an intended target failure probability. However, observations made during inspections might identify deviations between geometry, including fabrication defects that need to be considered in the structural integrity management during operation. The advantage of reliability approaches can only be realized if the modelling is updated based on data gathered in connection with fabrication and operation.

However, it is recognized that the main cause of damages and accidents is human and organizational errors and omissions. To achieve an acceptable safety level, therefore, requires quality in all phases of carrying out engineering, fabrication and operation, as well as QA and QC of the engineering process; inspection, monitoring and repair of the structure; and design for structural robustness; e.g. through an ALS criterion. In connection with crack control for aging structures, robustness is required to rely on a favorable effect of inspection and repair on the safety.

The development of high fidelity tools to aid the integrity management is clearly welcome. On the other hand, design requires repetitive analyses, especially in connection with optimal and reliability-based design. Moreover, the increasing refinement and automatization of analyses, increases the chance of errors in the software and its users. Development of efficient, robust and simplified methods is therefore also important. Besides providing information from research in terms of research papers, research results might be disseminated in a more easily accessible way for users, in the form of standards and guidelines for data bases and methods.

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