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INTEGRITY MANAGEMENT OF MARINE STRUCTURES; WITH EMPHASIS ON DESIGN FOR STRUCTURAL ROBUSTNESS

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ABSTRACT

Based on relevant accident experiences with oil and gas platforms, a brief overview of structural integrity management of offshore structures is given; including an account of adequate design criteria, inspection, repair and maintenance as well as quality assurance and control of the engineering processes. The focus is on developing research based design standards for Accidental Collapse Limit States to ensure robustness or damage tolerance in view damage caused by accidental loads due to operational errors and to some extent abnormal structural damage due to fabrication errors. Moreover, it is suggested to provide robustness in cases where the structural performance is sensitive to uncertain parameters. The use of risk assessment to aid decisions in lieu of uncertainties affecting the performance of novel and existing offshore structures, is briefly addressed.

Keywords: Safety management, Accidental Collapse Limit State, Robustness, Risk Assessment

INTRODUCTION

The continuous innovation in the oil and gas industry to deal with new serviceability requirements and the demanding environment as well the inherent potential of risk of fires and explosions, have led to an industry which has been in forefront of development of design and analysis methodology for structural integrity assessment.

The focus in this paper is design for robustness to ensure structural integrity during, installation and operation (Figure 1). In this paper robustness is defined as “the ability of a structure to limit the escalation of accident scenarios (caused by accidental actions and abnormal strength due to fabrication or deterioration phenomena) - into accidental conditions with a magnitude disproportionate to the original cause”. Robustness requirements apply to the different failure modes which ultimately can lead to fatalities, pollution or property loss. Structures supported on the seafloor can experience failure of the structure, foundation or soil, while buoyant structures can experience capsizing or sinking, hull or mooring system failure.

Current industry practice for structural integrity management is inspired by motherhood codes [1-2], and is implemented in offshore codes, e.g. [3-5] as well as in standards and guidelines by classification societies, and the most advanced codes are characterized by:

- design criteria formulated in terms of serviceability and safety limit states, considering payloads, environmental and accidental loads,
- semi-probabilistic methods for ultimate strength design which have been calibrated by reliability methodology,
- fatigue design checks depending upon consequences of failure (damage-tolerance) and the planned inspection, monitoring, maintenance and repair.
- explicit accidental collapse design criteria to achieve damage-tolerance for the system,
- local and global Finite Element Analysis, considering nonlinear features when relevant, e.g. in connection with demonstrating damage tolerance in view of inspection planning and progressive failure due to accidental damage.

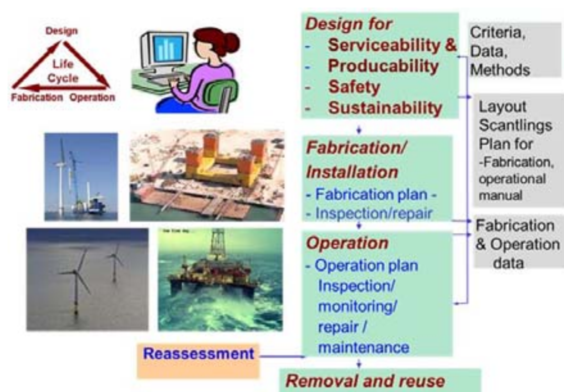


FIGURE 1. LIFE CYCLE PHASES OF OFFSHORE STRUCTURES.

The traditional design criteria deal with serviceability and safety. The latter criteria commonly include ultimate and fatigue limit states. However, service experiences show that accidental loads and abnormal strength due to gross errors or omissions made during design, fabrication or operation, contribute significantly to the risk of failure. Such features are not covered by the ULS and FLS criteria. The control of the risk associated with those kinds of events needs a broad safety management approach during the life cycle, including design for damage tolerance. e. g. in [6]. Motherhood design codes [1-2, 7-8] have for decades included a statement such as "structures should be designed to be robust". However, many codes do not specify how such a requirement should be implemented, others mention that robustness should be achieved by:

- designing against accidental actions – through a ultimate strength
- designing for alternate load paths
- providing ductility

Such formulations, however, are not sufficiently operationalized for the designer to use. Moreover, the criteria commonly refer to civil engineering structures supported on the ground or seabed, and hence do not cover all failure modes of floating structures. The Norwegian Petroleum Directorate introduced the so-called Progressive Limit State (later denoted: Accidental Collapse Limit State) Criteria in 1984 [9]; with the background explained in [10]. Another issue is that the structural integrity management takes place under uncertainties. This fact was early recognized by the offshore oil and gas industry by adopting risk and reliability methods to aid decision-making. In addition to the uncertainties affecting the predicted behaviour under extreme and cyclic load conditions, the inspection is subjected to uncertainty. Structural reliability methods (SRMs) 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 1980's, as outlined e.g. in [11-14]. However, SRMs do not include the effect of human errors on structural loads and resistance. Hence, risk assessment methods are needed to deal with failure probabilities and consequences in general [15].

In the following sections characteristic safety features based on service experiences of offshore oil and gas structures are briefly described, as a background for formulating the structural integrity management approach involving QA/QC of the engineering process, fabrication and operation. In particular a quantitative limit state for design to ensure structural robustness and hence reduce the likelihood of progressive failure is outlined. It is based on consideration of all system failure modes, use of mechanical systems models and a probabilistic approach to account for inherent uncertainties; indirectly including the effect of human errors.

CHARACTERISTIC FEATURES OF OFFSHORE STRUCTURES

The principal features of offshore structures, such as size and layout, are primarily determined by their intended function and safety in their natural and industrial environment – including met-ocean and hydrocarbon fire and explosion hazards. An overview of design and engineering analyses of different offshore structures, such as jackets, semi-submersibles, tension-leg and spar platforms may be found in [16].

Safety requirements are specified to avoid fatalities, environmental as well as property damage, and are related to the following failure modes:

- overall, rigid body instability (capsizing) under permanent and variable functional loads as well as environmental and accidental loads,
- failure of (parts of) the structure, foundation or mooring systems, considering external hazards due to permanent, variable, and environmental as well as accidental loads; and internal hazards due to design and fabrication errors causing abnormal strength.

The location far offshore 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 often do.

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.

Depending upon the regulatory regime, separate acceptance criteria for consequences such as fatalities, environmental damage or property damage are established.

IN-SERVICE FAILURE EXPERIENCES

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 [6, 10, 15, 17, 18] for offshore structures. In addition, statistics about offshore accidents, regularly compiled in WOAD[19], provide an overview of offshore "accident rates". Detailed investigations have been carried out for accidents with significant consequences; e.g. [20-25].

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.

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 materialize as a deficient (or excessive) resistance, which cannot be derived from the parameters affecting the "normal" variability of resistance.

The significant damage to the jacket in Figure 2a was caused during the hurricane Lilli in the Gulf of Mexico by waves hitting platform deck due to apparently too small deck clearance (deficient design requirements/standards).

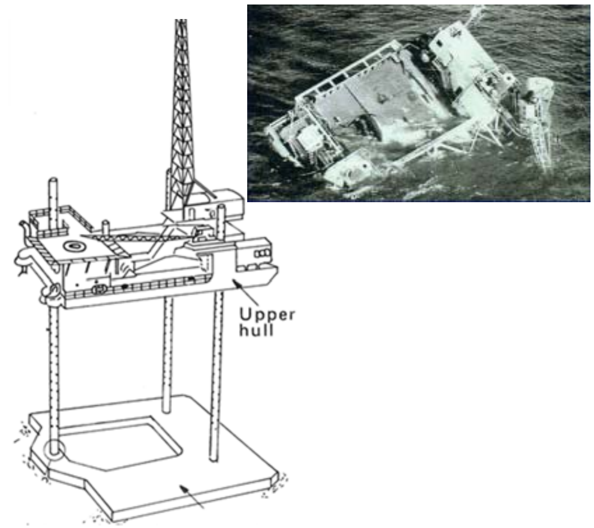
(a) (b)

FIGURE 2. (A) JACKET IN THE GULF OF MEXICO AFTER THE LILLI HURRICANE AND (B) PIPER ALPHA AFTER THE EXPLOSION/FIRE [23].

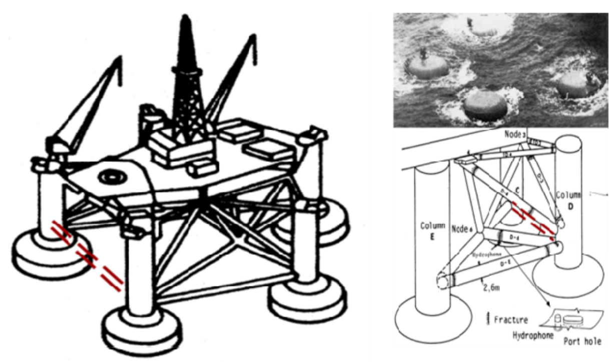
Fabrication imperfections (such as cracks, plate misalignment, etc.), which also affect the resistance, are influenced by human actions. The "normal" variability of welders performance, environmental conditions, etc. lead to a "normal" variability in the imperfection size, characterized by a smooth variation 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, fabrication defects as well as inadequate inspection [26]. 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 1970's had joints with design fatigue lives as low as 2-5 years when operating in extratropical regions. Fatigue failure has been rediscovered many times, even in marine technology, since Wöhler's initial discovery more than 150 years ago.

Man-made live loads have a "normal" and an abnormal component, while some loads, notably fires and explosions, do not have a normal counterpart. They are simply caused by operational errors or technical faults. Ship impacts might be undesirable accidental collisions or intended contacts during supply vessel approach. Well documented accidents due to accidental or abnormal loads, are that of Ocean Ranger, Piper Alpha (Fig. 2b) and P-36 [22-24]. Other accidents and structural failures are discussed e.g. in [15].

There are limited overload failures due to abnormal resistance.



a) Ranger I, Gulf of Mexico, 1979 [20].



b) Alexander L. Kielland, NCS, 1980 [21]. Dashed red lines indicate members that were not included in the design.

FIGURE 3. FATIGUE INDUCED TOTAL LOSSES

Degradation due to corrosion would normally develop slowly to failure. However, fatigue cracks can result catastrophic fractures if the fatigue life is not sufficient to make IMMR effective or if there is lack of robustness, as for the Ranger I [20] and Alexander Kielland [21] platforms. 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 like ships, the situation is different in that cracks in the main hull girder can grow continuously until global rupture of the hull [27]. Accidents associated with cracks appear to have been caused by e.g. [17]

- not carrying out proper fatigue design checks and inspections and possible repairs, e.g. [21]
- error in load (stress) analysis (environmental conditions, method, stress concentration factor) and particular phenomena like VIV,
- abnormal initial defect size, e.g. due to wet electrodes or improper pre-heating and post weld cooling/heating,
- abnormal local geometry due to deviation between as-built structure deviating and design or bad design. Hence, the assessment of existing structures should always refer to the as-built condition.
- abnormal crack propagation e.g. due to corrosion fatigue effects due to (increased crack propagation rate and plate thinning),
- fatigue caused by cathodic overprotection or loss of protection relating to corrosion effects,

Extensive experiences regarding cracks in North Sea jacket platforms and semi-submersible drilling platforms have been analyzed in [17, 28-29].

The most important lesson learnt about cracks in tubular joints in jackets is that 2-3 % of the 600 cracks detected in about 3300 inspections were not predicted [29]. The latter fact indicates that gross fabrication defects do occur. Similar observations have been made for semisubmersibles. It should be noted that limited experiences are available for novel concepts like TLPs and Spar platforms.

Deviations from the normal local geometry and defect sizes, which in an absolute sense are small, can clearly have a significant effect on the fatigue life due to the very local character of the fatigue phenomenon [29].

In some cases, lack of knowledge in the engineering profession at large, have caused accidents. Such phenomena have then been unknown to the profession and have not been accounted for in regulations and standards. They often occur in times with novel technology, significant activity and pressure on time, e.g. [30, 31]. A particularly representative example of this kind of accident is the brittle fractures of several Liberty ships, e.g. [32]. They occurred in World War II, using new welding techniques to produce a large number of ships in great haste. The steel that had worked well in riveted construction exhibited a brittle behavior when welded. In particular crack nucleated at the square corner of a hatch which coincided with a welded seam, fractured. It is noted that these fractures occurred about 20 years after the launching of the Griffith theory to deal with brittle fracture.

In the history of fatigue performance there are related examples. Wöhler discovered the fatigue of railway axles in 1860-70, and others also contributed to the development of the understanding of fatigue phenomenon. The engineering community "rediscovered" the phenomenon in connection with Comet aircrafts around 1950, see e.g. [30, 31], welded bridges [33] and offshore platforms in the 1960-70, e.g. [34, 35].

The remedy to deal with unknown phenomena is R&D and implement the results in regulations and standards..

STRUCTURAL INTEGRITY MANAGEMENT IN GENERAL

In Table 1 the causes of failures are categorized and the corresponding measures to control the accident potential are listed. In general, the measures include design criteria, quality assurance and control (QA/QC) relating to the engineering process as well as the hardware and operational procedures. Hence, different safety measures are required to control error-induced risks of overloading due to accidental events, as indicated in Figure 4.

TABLE 1. CAUSES OF STRUCTURAL FAILURES AND RISK REDUCTION MEASURES.

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

1) Measure by Structural Reliability Analysis
2) Measure by Risk Assessment

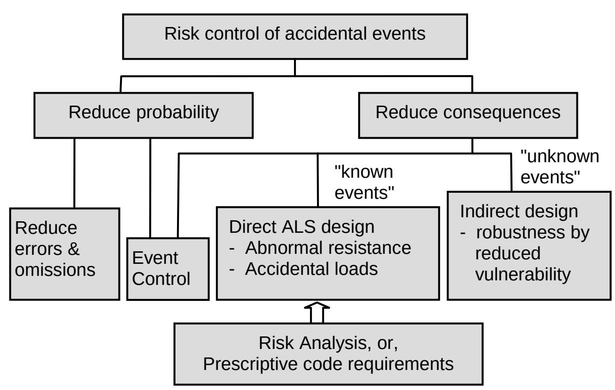


FIGURE 4. RISK CONTROL OF ACCIDENTAL OVERLOAD EVENTS - AND THE ROLE OF THE ALS.

Safety criteria for the design of offshore structures include ultimate and fatigue limit states (ULS and FLS), which are well developed and the inherent normal uncertainties and variability are accounted for by partial safety factors or by direct Structural Reliability Analysis (SRA). In practice SRA has been applied in calibrating ULS design requirements based on partial safety factors, e.g. [36-37] to a certain reliability level. An evaluation of previous efforts on calibration of offshore codes was provided in [38] 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. By combining simplified systems SRA with Bayesian reliability methods it has been possible to establish fatigue design criteria as a function of the planned inspection and failure consequences.

Moreover, SRA has been used in RBI (reliability based inspection planning), e.g. [14, 39].

However, the SRA does not account for human errors, and hence provides failure probabilities that are notional and not "real". To limit this deficiency it is important that RBI analyses are based on information from inspections during fabrication and operation in order to refer to an as realistic (as-is) model of the structure as possible [29]. This includes information about crack type defects with excessive size; yet small in an absolute sense. Therefore, abnormal strength associated with crack type defects need to be considered in the context of robustness or ALS criteria.

The introduction of a quantitative ALS criterion by NPD [9] was a significant step towards the generally agreed concept of making structures damage-tolerant (robust).

Primarily, 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. Such structural integrity features have been documented in aeronautical engineering [30, 31], in civil engineering [40, 41] and for offshore structures [6, 10, 18, 42].

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 loads, response and resistance, and clarify the basis for accounting for such phenomena in design.

As mentioned above, operational errors typically result in fires or explosions or other accidental loads. 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".

Table 2 shows qualitatively which role different safety measures play regarding crack control for different types of structures. Fatigue design requirements, that is especially the Fatigue Design Factor (FDF), are made dependent upon the effect of inspection and failure consequences. The residual fatigue life is the difference between "fatigue failure" (actually a visible crack or a crack through the plate thickness) and final member or joint rupture. The ultimate reserve capacity is the reserve against system failure given a component failure. This reserve is provided by ALS criteria.

Table 2. CRACK CONTROL MEASURES.

Type of structure	Type of joint	FDF[1)]	Residual fatigue life	Ultimate reserve strength	Inspection method
Jacket	Tubular joint	2-10	Some-Sign.	Normally	NDE,U[2]
Semi-Subm.	Plated brace Plated col.-pont.	1-3 1-3	Some Some	By ALS[4)] Limited	LBB[3)] NDE LBB NDE
TLP	Tether Plated col.-pont.	10 1-3	Small Some	By ALS Limited	IM[5)] LBB NDE
Ship	Plated longitud.	1-3	Sign.	None	Close Visual

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")

In the treatment of the effect of gross errors in design one might separate between identifiable/quantifiable versus unidentifiable/unquantifiable hazards. Thus errors resulting in accidental loads and to some extent fabrication errors causing an abnormal strength belong to the first category while design errors, belong to the second category. The first category can somehow be assessed and design mitigation measures introduced while both categories can be counteracted by competent execution of the work and QA/QC. However, in addition to providing robustness in relation to such hazards it might be argued that robustness in terms of reduced vulnerability should be provided when the behavior is sensitive to uncertain parameters, exemplified with resonant dynamic response which is sensitive to damping and fatigue strength which is sensitive to the local geometry.

DEVELOPMENT OF STRUCTURAL ROBUSTNESS CRITERIA

Despite the efforts that are made to avoid error-induced accidental actions or abnormal resistance, they cannot be completely eliminated. For this reason the trend is to base regulations on the following general safety principles [1-3, 5, 43].

- Structural integrity to withstand environmental and operational loading,

- Prevent occurrence of and protect against accidental events (loads and abnormal strength),
- Tolerate damage without resulting in a major hazard or damage to structure,
- Provide measures to detect, control and mitigate hazards at an early time to avoid accident escalation.

It is interesting in this connection to note that damage stability criteria, which are ALS-type criteria, were discussed in decades based on lessons learned through accident such as the Titanic accident on 20. January 1914, and were introduced first qualitatively, later quantitatively for sinking/ instability of ships in the 1948 SOLAS Convention [44]. A reason for the late acceptance of damage stability criteria was the complexity of the analysis to demonstrate compliance. Damage stability criteria were introduced in the early mobile platform rules (e.g., [45, 46]). The damage stability check has typically been specified with a deterministic damage in terms of one or two compartments flooded – relating to ship impacts.

Motivated by the design philosophy that "small damages, which inevitably occur, should not cause disproportionate consequences" the ALS criterion, initially called the Progressive Collapse Limit State, was formally introduced for all failure modes of offshore structures in Norway in 1984 [9, 10]. The background and practicing of the ALS criteria are described in [6]. While previous accident experiences showed the need for this approach, it was the Alexander Kielland accident made it possible to introduce it [10, 21]. Moreover, the introduction of the quantitative ALS criteria was made possible also because nonlinear FEMs had become available to estimate the damage and the strength of the damaged structure to demonstrate compliance with the requirements.

Contrary to the UK building codes and damage stability requirements, the NPD requirements were more functional based on damage scenarios that had to be assessed by risk analysis. For instance, such analyses were applied to demonstrate that the conventional compartmentation of floating steel structures was not necessary for the Heidrun TLP concrete hull - in view of the resistance of the reinforced concrete structure against ship impacts and dropped objects and how ballast faults could be controlled [47].

When the ALS criteria were introduced by referring to accidental loads/damage with an annual probability of 10^{-4} in [9, 10]., it was also found relevant to include consideration of damage due to abnormal environmental loads, i. e. corresponding to an annual probability of exceedance of 10^{-4}, to achieve a consistent safety level. This criterion can be governing over ULS criteria e.g. for jackets with predominant hydrodynamic drag loads.

It is noted that an inspection and repair measure can contribute to the safety only when there is a certain structural damage tolerance. This implies that there is an interrelation between design criteria (fatigue life, damage tolerance) and the inspection and repair criteria, see e.g. the comparison of the API and NORSOK fatigue design criteria for jackets with reliability based criteria in [34].

THE ACCIDENTAL COLLAPSE LIMIT STATE

Robustness or damage tolerance criteria need to cover different scenarios such as:

- Structural hull failure initiated by damage due to accidental loads or abnormal strength due to fabrication errors, etc
- Overturning of a structure due to accidental loads or abnormal foundation strength due to fabrication/ installation errors, etc
- Capzing/sinking of a floating structure due to abnormal environmental or accidental loads; especially due to flooding or technical or operational faults in the ballast system
- Failure of mooring system or other station keeping system due to technical faults in structural components or possibly the power supply and thruster system as well as operational errors need to be considered

The relevant damage needs to be assessed by risk assessment.

Accidental Collapse Limit State (ALS) criteria are introduced to prevent progressive failure. The basic principle relates to the fact that accidents develop in a fault sequence of events and it becomes important to establish a barrier to stop the escalation of the accident. This goal could be achieved by (e.g. [1]) by either of the following approaches

- designing the structure locally to sustain accidental loads and other relevant simultaneously occurring loads. (key element design); i.e. a quantitative "ULS" approach for designing elements, the removal of which would lead to a collapse defined as disproportionate, for an accidental load case. This is a component design check.

  Notes: This approach might also be applied in the case of fatigue criteria. By applying a large FDF the robustness regarding fatigue failure is increased since e.g. there is more time to identify and possibly repair cracks.
- designing the structure by accepting local damage but require the damaged structure to survive relevant actions (alternate path design). The relevant damage may be obtained as the effect of accidental actions. Systematic experiences from such analyses may serve as basis for specified damage conditions, representative for a certain industrial environment. In addition, "damages" implied by fabrication errors need to be considered. Such damages normally need to be specified by judgement. This will be a system design check.
- designing the structure to meet robustness requirements through (prescribed) minimum levels of ductility and continuity

In practice the first two methods are implemented for failure modes associated with structural strength. The third method relating to ductility and continuity is also crucial in making the second method work.

The first method is only applicable for structural strength in relation to accidental loads and does not apply for station-keeping systems nor for damage tolerance checks relating to (rigid body) instability.

It is noted that the Eurocodes [2] refer to this method as a ULS check in a similar manner as for other loads; i.e. with a set of load combination scenarios involving accidental events. This method will normally imply higher structural costs than the systems approach outlined below since all parts of the structure that can be subjected to accidental actions, need to be designed for such actions.

The second method was initially made a regulatory requirement in [9] and is currently specified in NORSOK N-001 [5]. It is applied to ensure damage tolerance in view of global structural, mooring a foundation failure as well as instability see Figure 5. The damage is to be determined by a risk assessment.

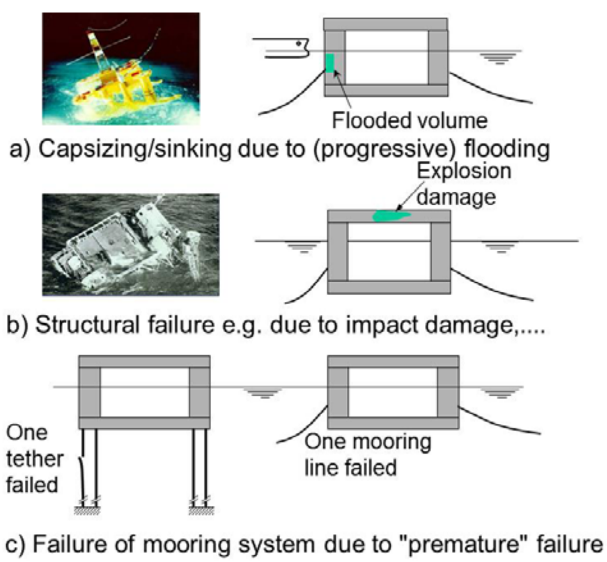


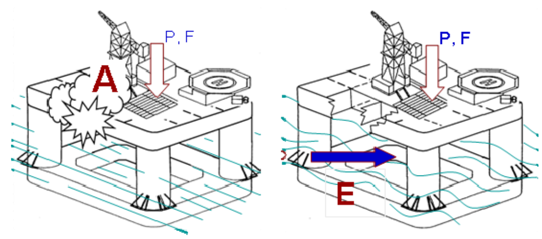
FIGURE 5. ALS DESIGN CHECK FOR DIFFERENT FAILURE MODES.

THE NORSOK N-001 ALS APPROACH

The current ALS criterion in NORSOK N-001 [5] is expressed by a two-step procedure as illustrated in Figure 6, based on characteristic actions and resistances. The first step is to estimate the initial damage due to accidental actions or other damage conditions (caused by "error-induced" abnormal strength) with an annual exceedance probability of 10^{-4}. This exceedance probability refers to accidental events on the whole platform and needs interpretation [6]. The second step is to demonstrate that the damaged structure resists relevant functional and environmental loads with an annual exceedance probability of 10^{-2} or 10^{-1} if the correlation between the accidental event and the environmental condition, is large – without global failure. The characteristic resistance value used for steel is defined as a value exceeded with a probability of 95%. Load and resistance factors for steel structures are taken to be 1.0 in these design checks.

The NPD/NORSOK approach is applicable to the other failure modes, like rigid body instability (damage stability) or station-keeping system failure.

The ALS procedure described above, is that in NORSOK N-001. When it is used in other regulatory regimes the same principles can be applied while other characteristic values of accidental and environmental events could be applied, e.g. [3].



(a) *b)*

FIGURE 6. THE TWO-STEP NORSOK ALS CHECK:
a) ASSESSMENT OF DAMAGE CAUSED BY AN ACCIDENTAL LOAD (A): EXPLOSION IN THE DECK – AND RELEVANT PERMANENT (P) AND FUNCTIONAL (F) LOADS AND POSSIBLY ENVIRONMENTAL LOADS,
b) A CHECK OF THE SURVIVAL OF THE DAMAGED PLATFORM UNDER ENVIRONMENTAL LOAD, E AS WELL AS P AND F LOADS

Damage conditions of hull structures

Damage conditions for the hull depends on the accidental loads and possible conditions relating to deterioration phenomena. Accidental loads include the effects of fires, explosions, ship collisions, dropped objects as well as abnormal distribution of payload or ballast. The accidental loads corresponding to an annual probability of 10^{-4} are to be determined by risk analysis, see e.g. [15], accounting for relevant factors that affect the accidental loads. In particular, risk mitigation can be assumed to take place by reducing the probability or consequences of the hazards. However, it should be noted that extensive experiences with accidental loads for typical platforms have led to the use of specific loads for well-defined conditions [6].

In connection with the limit state relating to ship impact, both strength and puncturing of components which is important for maintaining buoyancy, should be considered. One (conservative) approach could be to use a strength design philosophy for ship impacts (i.e. with energy absorption in the ship), see Figure 7, respectively.

In general, a risk assessment is needed to estimate the characteristic accidental loads or abnormal damage. At the same time, it is reasonable to specify minimum values, e.g. relating to frequent impacts of supply vessels on offshore structures [48]. The assessment should account for relevant factors of influence. Hence, when determining accidental loads possible risk reduction measures should be accounted for. Regarding fires and explosion events detection and control of hydrocarbon leaks and ignition would have a significant effect on the corresponding accidental loads. Moreover, fires are also normally controlled by sprinkler/inert gas system or by fire walls. Ship impacts will be affects by operational control of ship traffic and by use of fenders to reduce the damage due to collisions. For each physical phenomenon (fire, explosions, collisions, etc.) a continuous spectrum of accidental events is envisaged. The corresponding fire load (heat flux) is then determined. Next, the design load is determined by sorting the relevant accidental events in order of decreasing overpressure and by determining their cumulative probability. Since the 10^{-4} annual exceedance probability refers to accidental load on the whole platform, the exceedance probability level to use to determine the characteristic actions at the different locations needs to be modified. In view of Eq. (3), the characteristic accidental action (of a given type, e.g. explosion pressure) on different components of a given installation, could be determined as indicated in [6].

More details about accidental loads, risk analysis to estimate their magnitude, and their effect on structures may be found in e.g. [49-51].

As mentioned above, the ALS criterion was initially supposed to include "abnormal" wave and other environmental loads as well. Rather than a two-step approach described above, this check is a survival check based on an load corresponding to an exceedance probability of 10^{-4}. In this connection the focus is on possible "abnormal" waves, with high crest or other unusual shape – which are not a simple "extrapolation" of the 10^{-2} event [52]. Since the relevant wave load in this criterion should refer to a 10^{-4} sea state, and not least crest height, it will especially affect air gap criteria or wave in deck loads.

It is noted that the documentation of survival is made by use of nonlinear finite element methods, by accounting for large deflections and elasto-plastic behavior. In view of the fact that the sea loading is cyclic it is also necessary to demonstrate that low cycle fatigue does not occur.

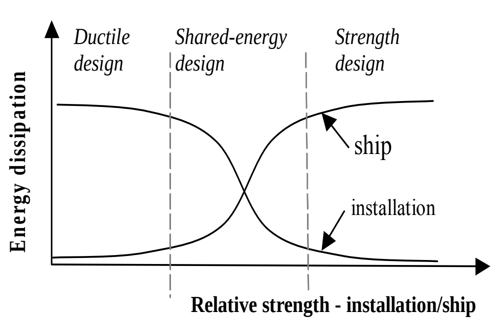


FIGURE 7. SHIP IMPACT DESIGN PRINCIPLE BASED ON RELATIVE ENERGY SHARING BETWEEN SHIP AND INSTALLATION

While there seems to be international agreement to consider accidental loads caused by operational errors, abnormal resistance due to fabrication errors might be considered unidentifiable and hence not considered in the ALS check. However, such damage (abnormal resistance) has been explicitly specified by generic values for specific types of structures based on some consideration of their occurrence rate and the vulnerability of the system to component failure. For instance failure of slender braces in mobile drilling platforms (semi-submersibles) and tethers in tension leg platforms has been considered to be a relevant damage condition due to the vulnerability of these components. Moan [6] suggests that abnormal strength due to cracks is considered. The basis for this suggestion is the fact that crack type defects which are larger than the normal initial defects (which are of the order of 0.1–0.5 mm) could occur and escape detection at the fabrication stage. To illustrate this point consider that: Inspections in air can reliably detect cracks which are about 1–2 mm and 15–20 mm deep, by NDE and close visual inspections, respectively. With a fatigue design factor (FDF) of 1 and by assuming an (abnormal) initial defect size of 2.0 mm, the failure probability over a 5 year period (i.e. before the first inspection) will be of the order of 10% in a butt-welded plate. The occurrence of abnormal defects which are not detected at the fabrication stage, suggests that various barriers indicated in Table 7 should be considered to control them before they result in fracture. Reliance on sufficient residual fatigue life/fracture strength associated with "long" through thickness cracks (TTCs) is often difficult to document. Since the residual life with a TTC is small, the LBB approach is not applicable either and failure of a brace may be considered as a damage condition in the two-step ALS check under such circumstances.

However, in addition to providing robustness by the conventional ALS, robustness against fatigue failure, a large FDF will be an efficient risk control measure since it will reduce the stress level and hence crack growth rate and give more time for detecting and repairing cracks.

Prediction of damage and survival of hull structures

To demonstrate compliance with ALS requirements calculation of the damage due to accidental loads as well as the ultimate capacity of a damaged structural system is needed. To estimate damage, i.e. permanent deformation, rupture etc. of parts of the structure, nonlinear material and geometrical structural behavior need to be accounted for. Dynamic effects may be of importance for explosions and ship impacts. Recent advances in computer hardware and software have made nonlinear finite element analysis (NLFEM) a viable tool for assessing damage and system resistance for steel structures. Examples of general purpose computer codes, which have been used widely are ABAQUS, ANSYS and LS_DYNA. Compliance with the global strength requirement of the damaged structure can in some cases be demonstrated by removing the damaged parts, and then accomplishing a conventional ULS design check, based on a global linear structural analysis and ultimate strength checks of components. Such methods may be very conservative. Software dedicated to progressive collapse analysis of frame offshore structures have also been developed, e.g. USFOS and SACS. Simplified methods based on plastic analysis often provide fast and accurate estimates of the damages caused by accidental actions on steel structures. The DNVGL guidelines [49] and are especially useful in early design for screening purposes. A major challenge in NLFEM analysis is prediction of ductile crack initiation and propagation. Hence, it is also important not only to check the capacity in a pushover mode but also carry out analysis with a representative cyclic storm loading. Even if general purpose nonlinear FE methods might be used to deal with the ultimate structural behavior of platforms with large diameter columns and pontoons and ships, limited efforts have been devoted to such analyses, partly because global strength is not as critical as local damage causing flooding and instability of such structures.

Damage conditions for the stability limit state of floating structures

The damage for floating structures would have to refer to its effect on structural integrity as well as floating ability/stability. In connection with stability a risk assessment to determine relevant damage conditions represents an extension of the conventional method based on prescribed flooding of 1 or 2 compartments since the damage will depend on the structural design and also all hazards causing flooding, including technical faults in the ballast system and its operation, abnormal deck loads that affect the vertical center of gravity. The Ocean Ranger accident [22] directed the attention to buoyancy loss, e.g., due to ballast error, which in principle could occur in any compartment with variable ballast. This would imply consideration of flooding of any compartment.

Some of the current damage stability criteria for mobile drilling platforms refer to damage of one compartment everywhere, some refer to one adjacent to the sea etc. Some codes recognize two-compartment damage in the still-water zone. For instance, such analyses were applied to demonstrate that the conventional compartmentation of floating steel structures was not necessary for the Heidrun TLP concrete hull - in view of ship impacts, dropped objects and ballast faults [47]. Moreover, it is noted that damage to the “submerged” parts of a floating structure, leads to a change of the floating position which hence will influence the wave and current actions on the structure. See also [53, 54].

The Alexander Kielland platform capsized in 1980 [21] after losing one of its 5 columns due to a structural failure. This accident made the Norwegian Maritime Directorate (now: Norwegian Maritime Authority) proposed that semi-submersible platforms should survive this kind of severe structural damage. However, by applying proper structural design criteria, including ALS, the probability of such damage will be limited and should be considered in the risk analyses to determine damage conditions for stability check. Later this criterion has been modified for mobile units [55].

It should be noted that the regulatory regimes for mobile units differ from that of floating production platforms. For instance, on the Norwegian continental shelf functional risk-based criteria are practiced for floating production systems while the criteria for mobile units are more prescriptive.

Prediction of the damage stability of floating structures

Current stability criteria for catenary moored floating platforms primarily refer to the initial metacentric height, GM_O and the overturning moment due to wind and the stabilizing moment due to hydrostatics. The effect of wave and current forces are not explicitly taken into account [54]. The stability criteria essentially refer to heeling which may cause flooding and eventually capsizing. The relevant parameters are then the wind-induced moment, M_H, acting on the floating structure and the corresponding angle of heel. The stabilizing (righting) moment, $M_R = \Delta \cdot GZ$, where Δ and GZ are the displacement and "righting arm", respectively. Simplified dynamic stability considerations are used by considering the energy associated with M_H and M_R. Reference is made to heeling angles that define “instability”(capsizing) as well as down-flooding. The fact that the stability criteria refer to quasi-static models and still-water conditions, have initiated actions with the aim to improve the criteria, e.g. by allowing dynamic analysis to be applied in the intact stability check[54], but such approaches are not widely used yet.

Damage condition for mooring and other station keeping systems

The experienced failure rate of mooring lines is of the order of 10^{-2} per line-year [56]. Line failures are often caused by "abnormal strength" - such as local bending at fairleads, which is not accounted for in design; fabrication defects, wear etc. - and inaccurate modelling of hydrodynamic loads, while failures of load-bearing hull structures are often caused by accidental loads due to operational errors. The experienced failure rate implies that the damage event corresponding to 10^{-4} is failure of one or two mooring lines. However, it is noted that the failure rate was reduced from the early operation in the 1980s towards 1990s – due to improved technology and design approaches [15, 57]. Unless it can be shown by risk assessment that the failure rate should be reduced beyond the values given above, the damage in mooring systems should be specified in terms of failure of one or two lines. Experiences with DP systems are discussed in [15, 57].

Comments on damage tolerance and robustness

It is often suggested to ensure robustness by providing redundancy. However, requiring survival after removal of an individual component does not necessarily give a precise robustness measure. This is because the vulnerability of components such as a thick-walled concrete cylinder, a thin-walled steel cylinders, to e.g. a ship impact, differ. Actually some impacts might cause partial damage or damage to more than one component. Moreover, the implied robustness varies with the location of the component relative to the spatial variation of the hazards. These facts suggest use of a rational approach based on risk assessment considering various hazards, their probability in time and space varies.

Figure 3a shows the Ranger I jack-up in the Gulf of Mexico. One leg failed due to fatigue and the deck collapsed. A second example is shown in Figure 3b. This is the Alexander Kielland platform. The brace D-6 failed due to fatigue and the other 5 braces connecting the column D to the platform, failed in a condition with 6 – 10 m high waves. In these two accidents a failure of a member leads to catastrophic events. While Alexander Kielland could have been made more robust if some additional braces had been introduced, Ranger I could in principle have been a four-legged structure. But the robustness with respect to failure of a leg would not be much omproved. For such a system the overall reliability would have to be ensured by adequate reliability of each leg. As a third example consider the single column platform in Figure 8, which have a reinforced, large diameter, thick-walled column. Clearly this structure does not score highly in terms of simple redundancy consideration. However, it is robust for damage scenarios like ship impacts and dropped objects, because it possesses reserve capacity after damage. This fact then shows that robustness is not necessarily synonymous with "redundancy".

The ALS check is directed towards avoiding global collapse, but also failure of safety systems like evacuation and escape-ways, which are crucial in order to limit the failure consequences in terms of fatalities.

FIGURE 8. THE DRAUGEN PLATFORM: A ROBUST STATICALLY DETERMINATE (NON-REDUNDANT) REINFORCED CONCRETE STRUCTURE IN VIEW OF SHIP IMPACTS AND DROPPED OBJECTS. COURTESY: NORWEGIAN CONTRACTORS

WIDER ASPECT OF STRUCTURAL ROBUSTNESS

An important feature of the ALS robustness criterion is that it provides an approach that the designer can apply it to achieve the goal in the case of identifiable/quantifiable hazards. This is a step forward compared to the initial statements that were made in codes, namely that: "the structures should be designed to be robust". However, in addition to the ALS criterion which aims at damage tolerance relating to conditions caused due to human errors during operation and fabrication. However, in addition it is important in design standards to encourage designers to provide robustness in cases where the structural performance is sensitive to uncertain parameters. This is because the normal characteristic values and partial safety factors in ULS requirements do not properly account for such situations. Examples of such cases are resonant dynamic response which is sensitive to damping; the ultimate strength of cylindrical shells under axial compression, which is sensitive to imperfections and fatigue life estimates that is very sensitive to the local geometry and defects.

For instance, in addition to provide robustness against fatigue failure by the conventional two-step ALS approach, use of a large FDF will also provide robustness since implied lower stress level will lead to more time to identify and possibly repair cracks.

SIMPLIFIED PROBABILITY OF SYSTEM FAILURE IMPLIED BY THE ACCIDENTAL COLLAPSE LIMIT STATE

Figure 4 illustrates how accidental loads can cause local damage that escalates into system loss. This escalation from local damage into total loss would normally take place progressively. A truly risk based design should account for the various sequences of progressive development of accidents into total losses. However, in a design context simplifications are necessary. One such approach is to prevent escalation of damage induced by accidental loads or abnormal strength, by requiring the structural system to resist relevant actions after it has been damaged.

The probability of system loss, relating to different accidental actions and "accidental damages" identified as abnormal resistance, may be written in a simplified manner, as [6].

$$P_{FSYS} = \sum_{jk} P\left[FSYS \mid D \cap A_{jk}^{(i)} \cap PE\right] \cdot P\left[D \mid A_{jk}^{(i)}\right] \cdot P\left[A_{jk}^{(i)}\right] + \sum_{lm} P\left[FSYS \mid D_{lm}\right] \cdot P\left[D_{lm}\right] \tag{3}$$

where $A_{jk(i)}$ are – mutually exclusive - accidental loads (i) at location (j) and intensity (k) and D_{lm} are damage at location (k) with a magnitude (l). PE represents the payloads and environmental loads to consider for the damaged structure. The locations (j) need to be discretized partly to represent the spatial variability of the accidental load and partly to accommodate the behavior of the structure after damage. A minimum model of spatial variability is to consider the following three locations: deck, zone between deck and sea surface, and submerged parts. The loads $A_{jk(i)}$ might have to be described by more than one variable, such as pressure and impulse for explosions, heat radiation and duration for fires etc. D is assumed to be "uniquely" given by $A_{jk(i)}$, and the indices on D are omitted. In general the damage, D corresponds to a permanent deformation, fracture of a certain cross-section area. In particular situations it would correspond to failure of a member or joint. $P(A_{jk(i)})$ is the probability of $A_{jk(i)}$ and is determined by risk analysis while the other probabilities are determined by structural reliability analysis. Event-Fault Tree techniques in most cases serve as basis for determining $P(A_{jk(i)})$. The events are not uniquely defined in a single sequence but appear in many combinations, making the event sequences correlated, especially at the same location. Operational errors that result in accidental loads are implicitly dealt with by using observed releases of hydrocarbons, probability of ignition etc. While explicit prediction of design and fabrication errors and omissions that result in D_{lm} for a given structure may be impossible, a rating of the likelihood, based on indicators for gross errors could be possible [18, 41].

A crucial issue in determining $P[FSYS|D \cap A_{jk(i)} \cap PE]$ is which associated payloads (P) and environmental loads (E) to consider. The main issue is then the correlation between the accidental event and the loads that occur in the time that elapses before the damage can be remedied or - if consequences in terms of fatalities are of concern - the time to evacuation of personnel. The time to repair is in principle a random variable. In extratropical regions, like the North Sea, it may be reasonable to assume a (maximum) time to repair be a year, since remedial actions may be difficult to carry out during the winter season. Fire and explosion events are obviously not correlated to sea actions.

When the formulation was introduced in NPD [9] (now NORSOK N-001 [5]) with accidental loads referring to an annual exceedance probability of 10^{-4}, an implied annual probability of total loss of 10^{-5} associated with each hazard, was intended. However, the question might be raised about the consequences of an accidental load or (local) damage with probability slightly less than $\alpha \cdot 10^{-5}$, with an α between 0.1 and 1.0, will cause. If a total loss will result, the actual implied target level will correspond to $\alpha \cdot 10^{-5}$.

Another related issue is the fact that the impact load by supply vessels at the 10^{-2} and the 10^{-4} probability level does not differ much. Hence, the ULS with the 10^{-2} event and the use of ULS partial safety factors is governing to achieve a consistent safety level.

TARGET RELIABILITY OR RISK LEVEL FOR DESIGN CODES IN GENERAL

The risk acceptance level serves as a basis for defining safety factors/margins used in ULS/FLS criteria and whether ALS criteria are applied or not, and the extent and quality of QA/QC.

The ultimate risk relates to consequences such as: fatalities; environmental damage and economic loss. 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.

Rather that setting a target level for the total risk level, it is more practical to establish target levels for each hazard separately, see e.g. [10]. This may be reasonable since all hazard scenarios and failure modes rarely contribute equally to the total failure probability for a given structure, e.g. [58, 59].

Risk acceptance criteria depend on the nature of hazards (e.g. man– made accidental and abnormal resistance due to human errors or omissions versus environmental loads), failure modes (e.g. system versus components), method of risk estimate (SRM or risk analysis), failure consequences and the expense and effort required to reduce the risk of failure [58,59].

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.

Current ULS requirements for offshore structures imply notional annual component failure probabilities of the order of 10^{-3}-10^{-5} [38], depending on the type of structure, consequences and partly the regulatory regime. A main issue is that target levels for notional failure probabilities relating to SRM should be clearly distinguished from the true failure probabilities estimated by risk assessment considering human factor effects also. Hence, it was argued in [60].that the target failure probability in the context of SRM should be a fraction of the true failure rate. Similar or even lower values are targeted for civil engineering structures e.g. [2]. These values are so low that accidents due to too low partial safety factors do not materialise for offshore structures. The corresponding systems failure probability varies significantly depending on the system layout and governing load conditions. This is because there are no explicit ULS system requirements. However, the special global (ALS) design check in NORSOK N-001 considering environmental loads with an annual probability of 10^{-4} is noted in this connection. By using the corresponding environmental event rather than scaling 10^{-2} load by load factor, a consistent target reliability level can be achieved.

Current FLS requirements, based on an FDF (ratio of characteristic fatigue life and service life) varying between 1 and 10, implies "fatigue failure" (visible or through thickness cracks) probabilities of the order 10^{-1} to 10^{-4} probabilities in the service life for structures in extratropical climates, see e.g. [17,34]. By neglecting the conditional probability of member fracture given fatigue "failure" and combining the fatigue failure probability with the conditional probability of system failure (fracture) given fatigue failure (according to the fatigue design criteria), the implied target probability of total loss is of the order of 10^{-4} [34, 58, 59].

The target level for ALS criteria should in principle be inferred from

- acceptable fatality rates
- environmental damage limit
- cost benefit analysis

and the most critical value of the relevant criteria, should be adopted.

The main consideration used in establishing the ALS criteria in NORSOK N-001 [5] is the experienced failure rates, and especially the fatality rate. Often the consequences, e.g. fatalities are plotted as a function of frequency – in so-called frequency - fatality rate diagram. The experienced failure rates, e.g. shown in [58] show that the annual frequency of 50–100 fatalities – which could be considered as total losses – is of the order of $6 \cdot 10^{-5}$ for fixed (production) platforms and 10^{-3} for mobile units. Based on these data, the annual target failure probability of structural system collapse of production platforms due to each accidental action was chosen to be 10^{-5}. It was then assumed, as mentioned earlier, that the contributions from different hazards rarely add up. Moreover, the survivability of the damaged structure referred to a period of a year after the occurrence of the damage. While a period of a year might be relevant for the survival of the structure (i.e. survival of a winter season), survival of personnel depends on the correlation between the hazardous event causing damage and the environmental condition in the period after the damaging event and when evacuation can be carried out.

However, they might also be compared with targets for ULS and FLS criteria, especially the latter since they are linked to ALS criteria. However, it should be noted that the probability of total loss aims at referring to actuarial values while the target component failure probabilities relating to ULS and FLS criteria refer to notional values obtained by SRA, however, with some contribution to real probability from that on environmental phenomena.

APPLICABILITY OF ALS REQUIREMENTS

It is noted that ALS criteria are normally not enforced if there is no risk of fatalities, severe environmental damage or significant economic loss potential [9]. This fact implies that the use of ALS criteria for oil and gas platforms that are unmanned and with safety valves for oil flow; as well as for wind turbines and fish-farms should be discussed. The decision will also vary in different regulatory regimes. Moreover, different stakeholders, like the society, owners of structures, and insurance companies, will use the ALS criteria in different ways.

ALS criteria for oil and gas platforms were first introduced in Norway [9]. They are now adapted in international offshore standards [3] and are increasingly introduced for other types of structures.

CONCLUSIONS

Based on in-service experiences for oil and gas platforms a framework for safety management of offshore structures is briefly outlined in terms of design criteria and QA/QC in all life cycle phases and especially inspection and monitoring during fabrication and operation. This structural integrity management approach especially depends on a follow-up during fabrication and 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 actual features are results of gross errors.

The focus herein is on formulation of a limit state to achieve damage tolerance or robustness of the structural system with respect to different failure modes such as overall instability and global hull and a possible station-keeping system failure. These Accidental Collapse Limit States or (ALS) criteria implicitly account for the effect of human errors on structural loads and resistances. In particular the background for robustness or damage tolerance requirements is highlighted and it is shown how limit states can be formulated in terms of ALS criteria. Criteria applied for the Norwegian Continental Shelf are used as examples in this paper. The basic principle is that the ALS robustness check is a two-step procedure:

- estimation of the damage corresponding to accidental events with an annual probability of exceedance of 10^{-4}
- demonstration of the “survival” of the damaged structure, under specified permanent and environmental loads (10^{-2} or 10^{-1} depending upon correlation between the damage scenario and environmental conditions

These principles for ALS are also applicable in other regulatory regimes, however, different characteristic values may be adopted.

The ALS criteria are formulated to formally comply with a certain risk acceptance level, based on actuarial probabilities while ULS and FLS criteria are primarily based on notional probabilities estimated by structural reliability methods (SRMs) and accounting for the normal uncertainties in loads and resistances and inspection quality.

It is believed that the risk based ALS approach yields a consistent robustness measure, by expressing the probability of total loss by a sum of products of the probability of the hazard and the corresponding damage and the conditional probability of overall failure. The conditional probability of global failure under payloads and environmental loads for a damage with a given magnitude and location, represents a vulnerability measure relating to the relevant damage (hazard).

It is noted that the ALS criteria naturally do not account for design errors. However, it is suggested that standards "encourage" designers to reduce risk associated with behaviour which is very sensitive to uncertain parameters, such as resonant dynamic response which is sensitive to damping and fatigue life which is sensitive to the local geometry, since such features are not directly covered by the characteristic values and partial safety factors used in the limit states.

Finally it is noted that robustness regarding fatigue failure can be provided by the conventional ALS approach as well as by using a high fatigue design factor (FDF).

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