Special Workshop on Risk Acceptance and Risk Communication
March 26-27, 2007, Stanford University

Development of Accidental Collapse Limit State Criteria for Offshore Structures

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Abstract

Accident experiences for offshore structures are briefly described. It is argued that Accidental Collapse Limit State (ALS) checks are necessary to complement other safety measures to achieve an acceptable risk level. The ALS procedure for offshore structures in Norway is outlined, with a focus on risk acceptance criteria. This approach is quantitative, i.e. the ALS check is specified as a survival check of a damaged structural system. The damage may be due to accidental actions or fabrication defects corresponding to an annual exceedance probability of 10^{-4}. Survival of the damaged structure under relevant actions with an annual exceedance probability of 10^{-2}, should be demonstrated. Risk analysis methodology to establish relevant damages is discussed. In these analyses possible risk reduction actions should be accounted for. Methods for predicting accidental damage and survival of the damaged structure is highlighted. Finally, the trend towards establishing more prescriptive ALS requirements is also observed.

1. Introduction

Oil and gas are dominant sources of energy, which are partly produced in a demanding ocean and industrial environment with significant fire and explosion hazards. Safety of men, environment and assets is therefore of main concern. Hence, especially overall failure of the structure, foundation or soil should be avoided for structures supported on the seafloor, while capsizing or sinking, hull or mooring system failure should be avoided for buoyant structures. The regulations for offshore structures are primarily issued by authorities in the continental shelf states. They include MMS/API in USA, HSE in UK and PSA (NPD) in Norway. Since early 1990's ISO has been developing codes for world-wide operation. Current practice is implemented in new offshore codes issued e.g. by ISO 19900 (1994-) and NORSOK (1998-2002) as well as by many classification societies.

Operational experiences (e.g. WOAD, 1996) show that accidental actions or abnormal resistance contribute significantly to failures of offshore structures. Such events can commonly be traced back to errors in design, fabrication or operation. To limit the risk of undesirable events it is therefore primarily important to avoid errors by those who do the work in the first place. Secondly, it is crucial to carry out quality assurance and control in all life cycle phases. An additional safety measure is to design the structural system to sustain the accidental actions. In principle, the structure can be designed to resist the accidental action locally (without damage) or by alternate paths. In the latter case local damage is allowed and the design criterion ensures robustness or damage tolerance, i.e. to ensure that a small damage does not escalate into disproportionate consequences through a progressive failure that leads to loss of stability/capsizing or global structural failure.

Attention to progressive structural collapse especially evolved in the 1960's, and achieved world prominence by the Ronan point accident when a corner of an apartment block collapsed (Griffiths et al., 1968). In the 1970s requirements dealing with progressive collapse emerged (e.g. NBC, 1970; Allen and Schriever, 1972, Allen, 1975, Taylor, 1975, Ellingwood and Leydendecker, 1978). The attention in the first code requirements was directed towards buildings made of large concrete panels as well as masonry structure. Even if the first codes for offshore steel and concrete structures in Norway incorporated qualitative robustness requirements, it was not until 1984 that quantitative ALS criteria first appeared.

In this paper lessons learnt from accidents are first described, followed by a brief outline of general principles for safety management in view of the experiences. The emphasis is placed upon Accidental Collapse Limit State criteria. The background of the quantitative ALS criteria used for offshore structures in Norway- and increasingly in other geographical regions, is presented, and the current procedure is briefly explained.

2. In-service experiences

2.1. Accidental experience at large

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, such as that of the platforms Ranger I in 1979, Alexander Kielland in 1980 (ALK, 1981), Ocean Ranger in 1982 (OR, 1984), Piper Alpha in 1988 (PA, 1990), and P-36 in 2001 (P-36, 2003), see Fig. 1a-d. In addition, statistics about offshore accidents, as given biannually in WOAD, provides an overview of offshore accident rates. Capsizing/sinking and global structural failure normally develops 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.

The three-legged jack-up platform Ranger I collapsed when one of its legs failed due to fatigue. The technical-physical sequence of events for the Alexander Kielland platform was: fatigue failure of one brace, overload failure of 5 other braces, loss of column, flooding into deck, and capsizing. For Ocean Ranger it was: flooding through broken window in ballast control room, closed electrical circuit, disabled ballast pumps, erroneous ballast operation, flooding through chain lockers and capsizing. Piper Alpha suffered total loss after a sequence: of accidental release of hydrocarbons, explosion and fire events which escalated. P-36 was lost after an accidental release of explosive gas, burst of emergency tank, accidental explosion in a column, progressive flooding, capsizing and sinking after 6 days.

Fig. 2 shows accident rates for mobile (drilling) and fixed (production) platforms according to the initiating event of the accident (WOAD, 1996). This figure is primarily based upon technical-physical causes. Most notable in this connection is of course accidental actions such as ship impacts, fires and explosions which should not occur, but do so because of operational errors and omissions. Accidents which are characterized as structural damage or capsizing/foundering, are often influenced by some kind of human error or omission in design and fabrication.

2.2 Human and organizational factors

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 ULS and FLS criteria. But the main causes of structural failures are abnormal resistance or accidental actions 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 affect the resistance, are influenced by human factors which partly cause "normal" variability but sometimes an abnormal deviation from this behaviour occurs, e.g., caused by using a wet electrode, etc. Thus, the initial fatigue failure of a brace in the Alexander L. Kielland platform was due to an abnormal fabrication defect, lack of fatigue design checks as well as inadequate inspection (ALK, 1981; Moan, 2007).

Man-made live loads also have a "normal" and an abnormal component, while some actions, notably fires and explosions, ship collisions, etc. do not have a normal counterpart. They are simply caused by operational errors or technical faults. The capsizing of the mobile platform Ocean Ranger offshore New-foundland in 1982 was initiated by control room window breaking due to wave slamming. The water entering the control room leads 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 (OR, 1984). The catastrophic explosion and fire on the Piper Alpha platform in 1988 was initiated by a gas leak from a blind flange of a condensate pump that was under maintenance and not adequately shut (PA, 1990). The gas ignited and the initial explosion leads 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 (P-36, 2001).

It is a well known fact that gross errors dominate as the cause of accidents, and appropriate control measures should be implemented. It is found that gross errors cause 80-90% of the failure of buildings and bridges and other civil engineering structures (Matousek and Schneider, 1976). A similar tendency is found for offshore structures.

In some cases, accidents have been caused by lack of knowledge in the engineering profession at large, i.e. an unknown phenomenon. Recently discovered new phenomena, such as ringing and springing of TLPs, deterioration failure mechanism of flexible risers, were observed in time before any catastrophic accident could occur (Moan, 2004).

3. Safety management

3.1 General

Offshore oil and gas facilities are complex systems consisting of structures, equipment and other hardware. Ideally such systems should be designed and operated to comply with a certain acceptable risk level with respect to fatalities, pollution and loss of assets. 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.

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 the acceptable risk level. This is, however, not feasible in practice. In reality, the design is handled separately for different hardware subsystems (structure, foundations, mooring..) by considering different failure modes and hazards.

The hazards associated with normal variability and uncertainty inherent in prescribed payloads and environmental loads and resistance, are handled by ULS and FLS design criteria. Such criteria do not reflect human errors. The notional annual failure probability of components implied by current ULS requirements for offshore structures, is of the order 10^{-3} – 10^{-5} (Moan, 2004). Fatigue and fracture are controlled by a combination of design for adequate fatigue life and robustness (ALS criterion) as well as by inspection and repair. If the fatigue design factor is taken to be 1.0, the fatigue failure probability in the service life, is 0.1. This value can be reduced significantly by more restrictive design criteria or inspection (Moan, 2005).

Various safety measures are required to control error-induced risks. Primarily, gross errors 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. It is not possible to quantify the effect of QA/QC relating to gross errors, on the risk level. However, structural reliability theory can be applied to quantify the effect of QC (inspection) of the structure on the partial risk associated with normal variability and uncertainty.

As mentioned above, operational errors typically result in fires or explosions or other accidental actions. Such events may be controlled by detecting the gas/oil leak and activating valve shut in; extinguishing of a fire by a deluge system activated automatically etc. - often denoted "Event Control". The conditional probability of detecting a leak, fire, and activating the deluge system etc can normally be estimated quite well.

Despite the efforts made to avoid error-induced accidental actions or resistance, they cannot be completely eliminated. For this reason Accidental Collapse Limit State (ALS) criteria are introduced to prevent progressive failure. The ALS is therefore also denoted Progressive Failure Limit State. Progressive failure could be avoided 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 (alternate path design). The relevant damage may be obtained as the effect of accidental actions. In addition, "damages" implied by fabrication errors need to be considered. Such damages normally need to be specified by judgement.

While there seems to be international agreement to consider accidental actions caused by operational errors for offshore structures, abnormal resistance due to fabrication errors is not generally recognized. Moreover, to account for design errors by an ALS criterion is paradoxical and is not considered in any code.

Adequate evacuation and escape systems and associated procedures are crucial for limiting fatalities caused by accidents.

3.2 Accidental actions and damage

In a rational ALS criterion the accidental action and thus the damage, should correspond to a defined characteristic value preferably defined in probabilistic terms. Allen (1975) indicates values of the same order of magnitude as the estimated failure probability, i.e., 10^{-4} to 10^{-6} per year. The characteristic accidental action for offshore structures in Norway was specified by an exceedance probability of 10^{-4} in order to achieve a probability of total loss associated with each hazard, of 10^{-5}. In general, a risk assessment is needed to estimate the accidental action. At the same time it is reasonable to specify minimum values, e. g. relating to frequent impacts of supply vessels on offshore structures.

While ship impacts on fixed platforms reduce the structural strength and possibly cause progressive structural failure; impact damage on buoyant structures can lead to flooding and, hence, loss of buoyancy. The measure of damage in this connection is the maximum indentation, which is taken as the indentation depth at which water tightness is lost. Moreover, large damage can cause reduction of structural strength of floating structures.

Accidental actions

The dominant *fire and explosion* events are associated with hydrocarbon leaks from flanges, valves, equipment seals, nozzles etc. As indicated in Fig. 3 fire and explosion events are strongly correlated. Commonly the effect of 40 – 80 scenarios needs to be analyzed. This means that location and magnitude e.g. of relevant hydrocarbon leaks, likelihood of ignition, as well as combustion and temperature development (in a fire) and pressure-time development (for an explosion) needs to be estimated, followed by a structural assessment of the potential damage.

The thermal flux in fires may be calculated on the basis of the type of hydrocarbons, release rate, combustion, time and location of ignition, ventilation and structural geometry, using simplified conservative semi-empirical formulae or analytical/numerical models of the combustion process. The heat flux may be determined by empirical or numerical methods (BEFETS, 1998). Typical thermal loading in hydrocarbon fires may be 200- 300 kW/m^2 for a 15 min – 2 hours period.

The analysis of explosion scenarios includes assessment of leaks, gas dispersion and possible formation of gas clouds, ignition, combustion and development of overpressure. Tools such as FLACS, PROEXP, or AutoReGas are available for this effort (e.g. Moan, 2000b; Czujko, 2001, Walker et al., 2003). Typical overpressures for topsides of North Sea plat-forms are in the range 0.2-0.6 barg, with a duration of 0.1-0.5s., while open air explosions typically imply 0.1 barg with a duration of 0.2s. The corresponding impulse varies between 1.2 and 2.5 kPas. The explosion pressure in a totally enclosed compartment might be 4 barg.

Impact actions are described by the kinetic energy and the impact geometry. Collision scenarios should be based upon all current (and future) ship traffic in the relevant area of the offshore installation, see e.g. NORSOK N-003 and -004 as well as Amdahl (1999). Ship traffic may for this purpose be divided into categories: trading vessels and other ships external to the offshore activity, offshore tankers; and supply or other service vessels. Merchant vessels are often found to represent the greatest platform collision hazard, which would depend upon the location of the structure relative to shipping lanes. While historical data provide information about supply vessel impacts, risk analysis models are necessary to predict other types of impacts, involving e.g. trading vessels, see e.g. NORSOK N-003(1999), Safetec (1998/99) and Moan (2000b). Impact scenarios should include bow, stern and side impacts on the structure. For offshore structures in the North Sea a minimum accidental load corresponding to 14 MJ and 11 MJ sideways and head-on impact, respectively, is to be considered.

The impact damage can normally be determined by splitting the problem into two uncoupled analyses, namely, the external collision mechanics applying the principle of conservation of momentum and energy, and internal mechanics dealing with the energy dissipation and distribution of damage in the two structures (NORSOK, N-004). The impact damage is estimated by using simplified load-intendation curves or direct finite element analysis (Amdahl, 1999; NORSOK N-004; 1998).

Other accidental actions that for instance need to be considered include: dropped objects and uneven ballast distribution in floating platforms. The ALS criterion also includes *"abnormal" natural hazards* such as wave action. Obviously, this check will involve a survival check based on an action event corresponding to an annual exceedance probability of 10^{-4}. 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. While the 10^{-2} wave might not reach the platform deck, the 10^{-4} crest could hit the deck and cause a significant increase in wave loading (e.g. Moan, 2000a). Abnormal wave loading is also relevant for structures with restricted operations. Failure to comply with operational restrictions with respect to wave condition could represent an accidental wave condition.

Abnormal resistance

Risk analyses to determine abnormal resistance, e.g. due to fabrication defects, is not feasible. Such damages (abnormal resistance) are normally specified by generic values for specific types of structures, taking the vulnerability of the structure into account. For instance individual failure of slender braces in mobile drilling platforms (semi-submersibles) is considered to be a relevant damage condition due to the vulnerability of braces to ship impacts and fatigue. Fatigue is of concern for slender members due to limited likelihood of detecting an abnormal crack, say with a depth of 2 mm before it is grown to a critical size in cases where the fatigue design factor (FDF) is 1.0 (Moan, 2007). The tether system in tension leg platforms is also required to fulfil a similar ALS criterion, even though the FDF is taken to be 10.

3.3 Risk assessment

Quantitative Risk Assessment (QRA) is a tool to support decisions regarding systems' safety. The application of risk assessment in the offshore industry has evolved since about 1980 (Moan and Holand, 1981, NPD, 1984). The Piper Alpha Disaster (PA, 1990), was the direct reason for introducing QRA in the UK (HSE, 1992). Risk analysis methodology is currently applied to validate offshore facilities at large, as outlined by Vinnem (1999). The focus herein is on the risk associated with total system loss induced by accidental actions on offshore structures.

3.4 Probability of system failure induced by accidental actions

Fig. 4 indicates how accidental actions 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 actions, by requiring the structure to resist relevant actions after it has been damaged, as sketched in Fig. 4.

The probability of system loss, relating to an accidental action (i), may be written as:

$$P_{FSYS}(i) = \sum_{jk} P\left[FSYS|\,D\right] \cdot P\left[D\,|\,A_{jk}^{(i)}\right] \cdot P\left[A_{jk}^{(i)}\right] \tag{1}$$

where $A_{jk}^{(i)}$ are – mutully exclusive - accidental action (i) at location (j) and intensity (k). The actions $A_{jk}^{(i)}$ might have to be described by a set of variables, such as (maximum) pressure and impulse for explosions, heat radiation and duration for fires etc. D is assumed to be "uniquely" given by $A_{jk}^{(i)}$. $P[A_{jk}^{(i)}]$ 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 $P[A_{jk}^{(i)}]$. One challenge in this connection is to determine the dominant among the (infinitely) many sequences. Events are not uniquely defined in a single sequence but appear in many combinations, making the events correlated, especially at the same location. Operational errors that result in accidental actions are implicitly dealt with by using observed releases of hydrocarbons, probability of ignition etc. While explicit prediction of design and fabrication errors and omissions for a given structure may be impossible, a rating of the likelihood, based on indicators for gross errors could be possible (Bea, 2000).

A crucial issue in determining $P[FSYS|D\ ]$ is which payloads and environmental actions to consider. The main issue is then the correlation between t the accidental event and the actions 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. 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. It also turns out that collisions by supply vessels are not correlated to severe environmental actions because supply vessels are not operating under such conditions. This, however, might not be the case for trading vessels.

4. Accidental Collapse Limit State

4.1 Introduction

Model codes have since long contained statement on robustness. The British requirements introduced after the Ronan Point progressive failure in 1968, were the first explicit robustness requirements. However, robustness criteria in most codes do not refer to any specific hazard but rather requires resistance to progressive failure with one element removed at a time and therefore does not create a performance objective for a “real “threat. The weakness with such a criterion is that it does not distinguish between the difference in vulnerability. The NORSOK N-001 code (2002) specifies quantitative ALS criteria.

4.2 The NORSOK criteria

ALS checks apply to all relevant failure modes. See Fig. 5. In addition to these failure modes of the structural system, possible escalation of damage to safety systems (e.g. fire detections and sprinkler equipment), piping/tanks carrying hydrocarbons, escape and evacuation system should be prevented. It is interesting in this connection to note that ALS-type criteria were introduced for sinking/ instability of ships and mobile platform, long before robustness criteria were introduced for all failure modes of offshore structures in 1984 (NPD, 1984).

The structural integrity criterion in NORSOK is a two-step procedure as illustrated in Fig. 6. First, the initial damage due to accidental actions with an annual exceedance probability of 10^{-4} is estimated. The second step is to demonstrate that the damaged structure resist relevant functional and environmental actions an annual exceedance probability of 10^{-2} – without global failure. The load and resistance factors for steel structures are taken to be 1.0 in these design checks.

The target safety level for $P_{FSYS}\,(i)$ should in principle depend upon e.g. the possible consequences of failure in terms of risk to life, injury, economic losses and the level of social inconvenience as well as the expense and effort required to reduce the risk of failure. In practice it is convenient to treat different hazards, failure modes, and life cycle phases separately. This may be reasonable because rarely do all hazard scenarios and failure modes contribute equally to the total failure probability for a given structure, see e.g. Moan (1998).

4.3 Design accidental actions

The accidental actions are supposed to be determined by risk analysis, see e.g. Vinnem (1999) and Moan (2000b), by accounting for relevant factors of influence. This includes risk reduction that is achieved by reducing the probability of initiating event; leak and ignition (that can cause fire or explosion), ship impact, etc. or by reducing the consequences of hazards. Passive or active measures can be used to control the magnitude of the accidental event and, thereby, its consequences. For instance, the fire action is limited by sprinkler/inert gas system or by fire walls. Fenders can be used to reduce the damage due to collisions. The (local) damage, or permanent deformations or rupture of components need to be estimated by accounting for nonlinear structural behaviour. For each physical phenomenon (fire, explosions, collisions, ..) there is normally a continuous spectrum of accidental events. A finite number of events has to be selected by judgement (Vinnem, 1999; Moan, 2000a). For instance, various fire and explosion scenarios are envisioned based on different leak rates at different locations, gas filling ratios and composition, as well as ignition conditions. The corresponding fire action (heat flux) and explosion action (pressure-time history) are first determined. Next, the design action, e.g. for explosions is determined by sorting the relevant accidental events in order of decreasing overpressure and determining their cumulative probability.

Since the 10^{-4} exceedance probability refers to accidental action 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.(1) the probability level is taken to be a portion of 10^{-4} for each location. Hence, the characteristic accidental action (e.g. explosion over-pressure) at different locations of a given platform can be determined by establishing the exceedance diagram for the action at each location, allocating a certain portion of the reference exceedance probability (10^{-4}) to each location and determining the characteristic action at each place from the relevant action exceedance diagram and reference probability (Moan, 200b).

If the accidental action is described by several parameters (e.g. heat flux and duration for a fire; pressure peak and duration for an explosion) design values may be obtained from the joint probability distribution by contour curves (Winterstein et al, 1993; NORSOK N-003, 1999). However, in view of the uncertainties associated with the probabilistic analysis, a more pragmatic approach would normally suffice. Yet, significant analysis efforts are involved in identifying the relevant design scenarios for the different types of accidental actions.

Risk analysis, especially hazard identification, of novel structures and systems has turned out to be useful, i.e. resulted in systems that have significant increase in safety at the same expense. This applies in particular to the topside system. However, for mature systems the tendency is that the risk analysis confirm previous results. This fact suggests using specific, generic values for such cases. Examples of typical values for some accidental actions loads are given in Section 3.2. Obviously such an approach simplifies the design considerations.

4.4 Analysis methods for verification

To demonstrate compliance with ALS requirements calculation of the damage due to accidental actions as well as the ultimate capacity of the structural system is needed. To estimate damage, i.e. permanent deformation, rupture etc of parts of the structure, nonlinear material and geometrical structural behaviour need to be accounted for. Simplified methods based on plastic analysis often provide fast and amazingly accurate estimates of the damages caused by accidental actions (Amdahl, 1999; Czujko, 2001). Such methods have been implemented in standards and guidelines (NORSOK N-004, 2004) or are underway (UKOOA Fire and Explosion Guidance, 2003) and are especially useful in early design for screening purposes.

Compliance with the 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. The advances of nonlinear finite element techniques over the past decades allow modelling of nonlinear geometrical and material behaviour of members. This, in turn, makes it possible to account for redistribution of forces and subsequent component failures until system's collapse, even for very large and complex systems. Example of general purpose computer codes, which have been used widely are LS_DYNA, ABAQUS and ANSYS. Software dedicated for progressive collapse analysis of frame offshore structures have also been developed, e.g.USFOS and SACS (Skallerud and Amdahl, 2002).

4.5 Implied risk level

The survival check of the ALS criterion is based on a characteristic value of the resistance corresponding to a 95% or 5% fractile; implying 10 % bias to the mean value. The characteristic action effect due to functional and sea actions are 1.0-1.2 and 1.2-1.3 of the respective mean annual values, respectively. The safety factors are generally taken to be 1.0. The conditional annual probability of failure in a year, for the damaged structure, will hence, be of the order of 0.1. The intended probability of total loss implied by the ALS criterion for each category of abnormal strength and accidental action would then be of the order of 10^{-5}.

4.6 Implications on design

As indicated above, ALS checks apply to global failure modes such as capsizing, overturning as well as progressive failure of the structure and station-keeping system. Fires and explosions are of particular concern for the topside structure (petroleum production plant). Ship impacts could affect the structure and risers in the waterline area. Dropped objects (from cranes) are relevant for the topside and underwater structure. Account of accidental actions on safety systems is a crucial safety measure, to prevent accidents to escalate.

Conclusions

The risk implied by current ultimate and fatigue limit state criteria for offshore structures is small and does not show up in accident statistics. The main cause of accidents is human and organizational errors and omissions. To achieve an acceptable safety level, therefore, requires QA and QC of the engineering process; inspection, monitoring and repair of the structure; as well as design for structural robustness. QA and QC tasks are particularly challenging in connection with novel concepts for new environmental conditions or new functions, to possibly identify new phenomena, especially associated with the loading and dynamic response. In this paper, particular emphasis is placed on the accidental collapse limit state design check related to accidental actions and abnormal strength. The philosophy behind this robustness criterion is described, and it is shown how information has been established for a proper implementation of the criterion.

Acknowledgements

The work reported herein has been carried out over many years in the development codes for the Norwegian Petroleum Authority (now: Petroleum Safety Authority), NORSOK and ISO (offshore structures), as well as in many R & D projects for the oil and gas industry. I would acknowledge the fruitful cooperation with many members of code committees and colleague researchers; especially J. Amdahl, S. Fjeld, A. Kvitrud, I. Holand (deceased), D. Karsan, J. Lloyd and J. E. Vinnem.

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WOAD: “Worldwide Offshore Accident Databank”, Det Norske Veritas, Oslo, 1996.

Figure 1: Examples of accidents which resulted in a total loss.

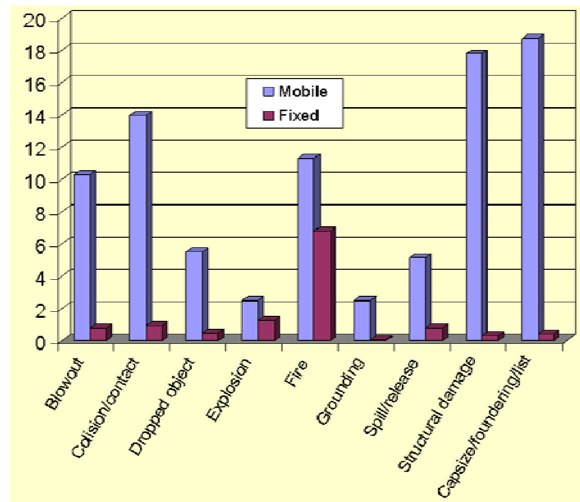


Figure 2: Number of accidents per 1000 platform-years. Adapted after WOAD (1996).

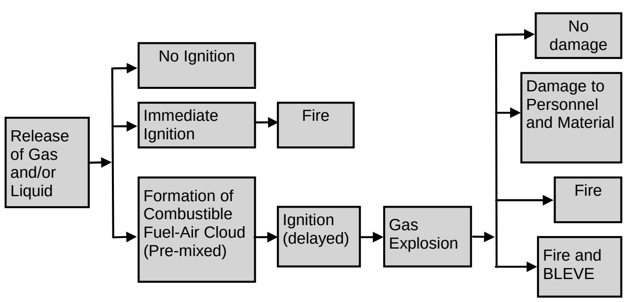


Figure 3: Fire and explosion scenarios.

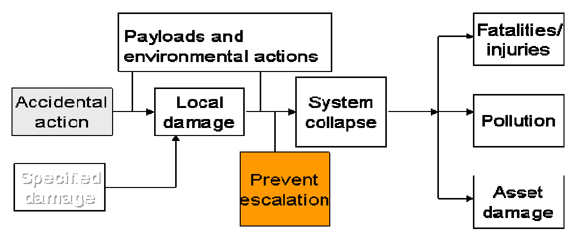
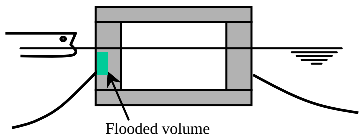
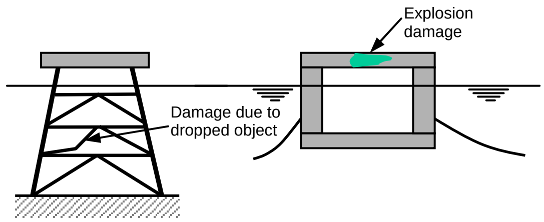


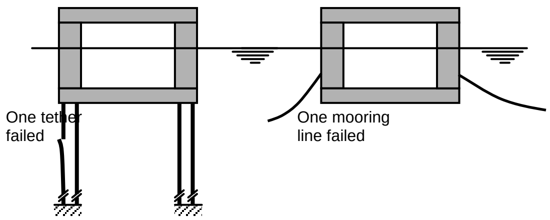
Figure 4: Accident induced system collapse



a) Capsizing/sinking due to (progressive) flooding



b) Structural failure e.g. due to impact damage,....



c) Failure of mooring system due to "premature" failure

Figure 5: ALS criteria for different system failure modes

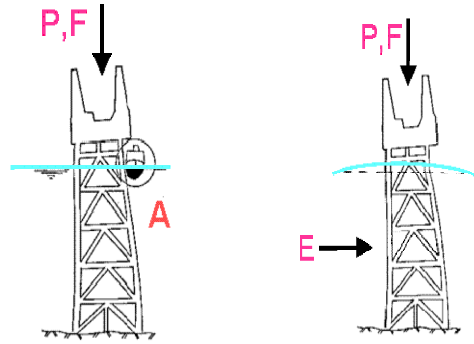


Figure 6: Accidental Collapse Limit States for different global failure modes.

Table 1: Causes of structural failures and risk reduction measures

Cause	Risk Reduction Measure	Quantitative method
Less than adequate safety margin to cover "normal" inherent uncertainties.	- Increase safety factors or margins in ULS, FLS; - Improve inspection of the structure (FLS)	Structural reliability analysis
Gross error or omission during life cycle phase: - design (d) - fabrication (f) - operation (o)	- Improve skills, competence, self-checking (for life cycle phase: d, f, o) - QA/QC of engineering process (for d) - Direct ALS design – with adequate damage condition (for f, o) - Inspection/repair of the structure (for f, o)	Quantitative risk analysis
Unknown phenomena	- Research & Development	None