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Development of accidental collapse limit state criteria for offshore structures

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ABSTRACT

Experiences with offshore and other structures show that catastrophic accidents often are initiated by human errors that cause accidental actions or abnormal resistance which escalate progressively into undesirable consequences. It is therefore argued that damage tolerance or robustness is a desirable feature of structures to complement other safety measures to achieve an acceptable risk level. Robustness may be achieved by specific Accidental Collapse Limit State (ALS) criteria. A quantitative, semi-probabilistic ALS procedure has been introduced for offshore structures in Norway in terms of a survival check of damaged structural systems. The initial damage is considered to be due to accidental actions corresponding to an annual exceedance probability of 10^{-4} or abnormal resistance, e.g. due to fabrication defects. Survival of the damaged structure under relevant actions with environmental actions at an annual exceedance probability of 10^{-2} should be demonstrated. The basis for an implementation of this approach is outlined, with a focus on risk acceptance criteria. The risk analysis methodology on which this procedure rests, is described with an emphasis on determining the characteristic accidental actions with due account of possible risk reduction actions. Since the ALS procedure is based on an alternate path approach, methods for predicting the initial accidental damage and the survival of the damaged structure need to account for nonlinear structural behaviour. It is described how the recent development of computational tools facilitates a realistic ALS approach for steel structures.

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 are therefore of main concern. Hence, especially overall failure of the structure, foundation or soil should be avoided for structures supported on the seafloor. For buoyant structures, capsizing or sinking, hull or mooring system failure should also be avoided. The regulations for offshore structures are primarily issued by authorities in the continental shelf states. They include for instance Mineral Management Services (MMS) in the USA, Health and Safety Executive (HSE) in the UK and Petroleum Safety Authority (PSA, formerly NPD) in Norway. Since the early 1990s, ISO has also been developing codes for world-wide operation. The current practice is implemented in new offshore codes issued, e.g. by ISO [18] and NORSOK [34–36], as well as by many other classification societies.

Operational experiences (e.g. [52]) show that accidental actions or abnormal resistance significantly contribute 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 of primary importance 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 avoid global (system) failure due to accidental damage. 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. ensures that a small damage does not escalate into disproportionate consequences through a progressive failure that could lead to a loss of stability/capsizing or a global structural failure. The global failure modes are crucial since fatalities caused by structural failure primarily result from such failure modes.

The focus on progressive structural collapse especially started evolving in the 1960s to achieve world prominence by the Ronan point accident when a corner of an apartment block collapsed [16]. In the 1970s, requirements dealing with progressive collapse of buildings emerged (e.g. [2,3,13,33,45]). The attention in the first code requirements was directed towards buildings made of large concrete panels as well as masonry structures. In the 1980–90s, the interest in such criteria decreased to then raise anew in the late 1990s due to sabotage bombings of buildings, and not least, with the attack on the WTC in 2001 [22]. However, the focus often seems to be on damage tolerance requirements relating to the survival of the structure after removal of individual members, without reflecting the relevant hazards (actions) for each location. Even if

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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 [28].

Nevertheless, the implementation of such criteria is not straight forward, partly due to the difficulty of establishing the relevant spectrum of possible threats, or else due to the lack of structural analysis methodology. For offshore structures, it is possible to rely upon the occurrence rate of relevant hazards with due account of possible changes in the technology and operational procedures which may imply changes in the hazard rates. The structural analysis methodology for offshore structures is especially well developed for jackets and similar structures for which beam elements for members and semi-empirical models for the joints are suitable. Quantitative approaches for building structures with widely varying layout and hazard spectra are very challenging to establish.

The lessons learnt from accidents with offshore structures are first described in this paper, followed by a brief outline of general principles for safety management in view of the experiences. The emphasis is here placed on the Accidental Collapse Limit State criteria. The background and implementation of the risk-based ALS criteria used for offshore structures in Norway – and increasingly in other geographical regions – are presented. Moreover, the necessary computational tools for their implementation are briefly outlined.

2. Accident experiences

2.1. Technical and physical features

Safety may be defined as the absence of accidents or failures. Hence, a useful insight about the safety or risk features can be gained from the detailed investigations of catastrophic accidents, such as those of the platforms Ranger I in 1979, Alexander Kielland in 1980 [1], Ocean Ranger in 1982 [38], Piper Alpha in 1988 [41], and P-36 in 2001 [40], see Fig. 1a–d. In addition, statistics about offshore accidents, as given biannually in the World Offshore Data Bank (WOAD), provide an overview of offshore accident rates. Capsizing/sinking and global structural failure normally develop in a sequence of technical and physical events. Structural damage can cause progressive structural failure or flooding which may result in the 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 five other braces, loss of column, flooding into deck and capsizing. As for Ocean Ranger, it was: flooding through broken window in a 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 the accident rates for mobile (drilling) and fixed (production) platforms according to the initiating event of the accident [52]. 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 capsiz-

Fig. 1. Examples of accidents which resulted in a total loss.

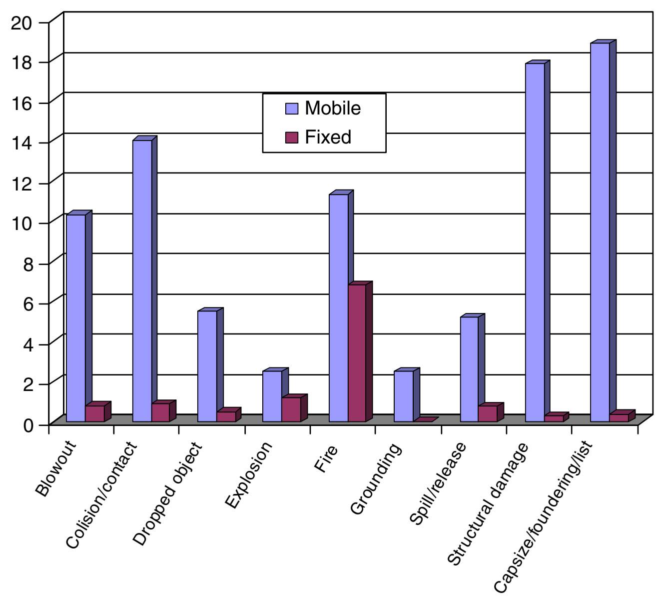

Fig. 2. Number of accidents per 1000 platform-years according to technical–physical causes. The seven causes to the left are typically due to operational errors and the other two are most often due to design and fabrication errors. Adapted after WOAD [52].

ing/foundering in WOAD are often influenced by some kind of human error or omission in design and fabrication.

2.2. Human and organizational factors

Structural failure basically occurs when the resistance R is less than a corresponding load effect S. From an HOF point of view, this can occur due to too small safety factors to account for the normal uncertainty and variability in R and S relating to the 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. The fabrication imperfections affecting the resistance (cracks, plate misalignment, etc.) are influenced by human factors which partly cause "normal" variability, though sometimes an abnormal deviation from the normal behaviour occurs, e.g., caused by using a wet electrode in the fabrication of metal structures, etc. Thus, the initial fatigue failure of a brace in the Alexander L. Kielland platform was due to an abnormal fabrication defect, a lack of fatigue design checks as well as an inadequate inspection [1,29].

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 Newfoundland in 1982 was initiated by the breaking of a control room window due to wave slamming. The water entering the control room caused a 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 the lack of crew training, and partly because of inadequate ballast pumps and open chain lockers [38]. 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 which was under maintenance and not adequately shut [41]. The gas ignited and the initial explosion caused damage on an oil pipe, leading subsequently to an escalating 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 of the sinking [40].

It is a well-known fact that gross errors dominate as the cause of accidents. It is found that gross errors cause 80–90% of the failure of buildings and bridges and other civil engineering structures [21]. A similar tendency is found for offshore structures.

In some cases, accidents have been caused by the lack of knowledge in the engineering profession at large, i.e. an unknown phenomenon rather than the lack or erroneous use of existing knowledge. Recently, discovered new phenomena relating to offshore structures include dynamic response such as ringing of monotowers and TLPs, springing of TLPs, as well as deterioration failure mechanism of flexible risers. The dynamic ringing and springing response was typically due to a nonlinear mechanism of wave action that caused excitation at natural periods of vibration of the structures. However, all the mentioned new phenomena were observed in time before any catastrophic accident could occur [26].

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 given acceptable risk level with respect to the ultimate failure consequences in terms of fatalities, pollution and loss of assets. The focus here is on consequences which result from structural failure while fatalities that are directly caused by toxic and thermal effects in fires or explosion blasts are, for instance, not considered. Table 1 shows how the causes of failures may be categorized in view of the corresponding measures to control the accident potential. In general, the measures include design criteria, "self-checking", quality assurance and control (QA/QC) related to the engineering process, fabrication and operational procedures, QA/QC of the structure, as well as Event Control of accidental events.

In principle, the design could be carried out by achieving a total system (structural layout, scantlings and equipment, procedures and personnel) which complies with the acceptable risk level. Such a direct risk-based design is, however, not feasible in practice. In reality, the design is handled separately for different hardware subsystems (structure, foundations and mooring) by considering different failure modes and hazards, typically by semi-probabilistic approaches which are then calibrated by more refined approaches.

The probability of ultimate and fatigue failure of components (and systems), associated with normal variability and uncertainty inherent in prescribed payloads and environmental loads and resistance, is estimated by Structural Reliability Methods, without accounting for human errors. The corresponding semi-probabilistic ULS design criteria for offshore structures typically imply a notional annual failure probability of components of the order 10^{-3}–10^{-5} [26]. Fatigue and fracture failures are controlled by a combination of design for adequate fatigue life and robustness (ALS criterion), as well as by inspection and repair criteria. The fatigue design factor, that is the ratio of the fatigue and service life, is assumed between 1 and 10. If it is 1.0, the notional failure probability in the service life is about 0.1. This value can be reduced significantly by more restrictive design criteria or by inspection [27].

Various safety measures are required to control error-induced risks and to reduce the probability or consequences of undesirable events. Primarily, gross errors should be avoided by adequate competence, skills, attitude and self-checking of those who do the de-

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 and development	None

sign, fabrication or operation in the first place, as well as by exercising "self-checking" of their work. In addition, quality assurance and control (QA/QC) should be implemented at all stages of design, fabrication and operation. It is impossible to quantify the effect of QA/QC relating to gross design errors on the risk level. The structural reliability theory can be applied to quantify the effect of QC (inspection) of the structure on the risk level associated with normal variability and uncertainty in the structural behaviour and inspection method.

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 as "Event Control". The conditional probability of detecting a leak, fire or 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 commonly denoted as 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 experiences described previously suggest that the damage caused by accidental actions should be taken into account in the design. As explained later in Section 4.2, the accidental actions are considered with an annual probability of 10^{-4} in the ALS design check, while the characteristic action value for ULS design refers to an exceedance probability of 10^{-2}. Since a "10^{-4}" wave (action) phenomenon could have a spatial variation quite different from the "10^{-2}" phenomenon, involving e.g. wave hitting the deck of a platform or causing water on deck of a ship, it is important to consider this kind of events in an ALS context. In addition, "damage" in terms of abnormal resistance due to fabrication errors needs to be considered. The aim of the ALS procedure is schematically illustrated in Fig. 3.

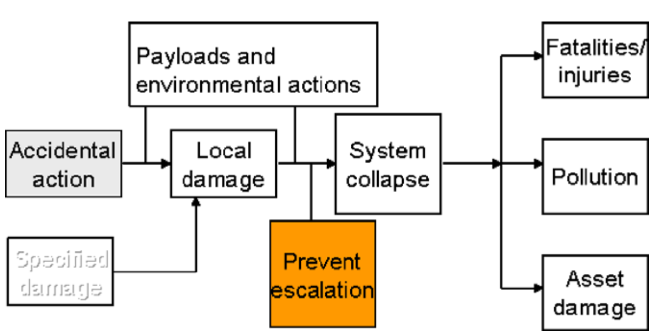

Fig. 3. Accident induced system collapse.

There seems to be an international agreement to design offshore structures to resist "reasonable" accidental actions caused by operational errors. NORSOK N-001 [34] also requires consideration of abnormal resistance due to fabrication errors while other codes do not recognise such damage conditions. Moreover, no design code naturally seems to account for design errors by an ALS criterion. Design errors are assumed to be eliminated by Quality Assurance and Control of the design.

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

3.2. Accidental actions and damage

Initial accidental conditions may be categorised as

- damage caused by accidental actions (fires, explosions, ship impacts, dropped objects, abnormal sea loads, abnormal payload or ballast condition);
- abnormal resistance (due to fabrication defects, abnormal degradation).

Accidental actions such as ship impacts and explosions may cause structural damage relevant for progressive structural failure or capsizing. The latter failure may be initiated by damage on buoyant structures that causes flooding, hence, loss of buoyancy. The measure of damage in this connection is the indentation depth at which water tightness is lost.

The spatial and temporal variation of the accidental actions needs to be assessed. Regarding variation in space, the cause of different accidental actions indicates their typical locations. Hence, fires and explosions occur in the process plants in the platform decks, ship impacts affect the structure in the water surface area, and dropped object fall on (top of) the deck or hit the submerged parts.

The accidental actions in general need to be determined by risk assessment methods, considering the chain of events which is involved [47].

3.2.1. Fires and explosions

Fires and explosions are continuous threats on offshore oil and gas installations. The dominant *fire and explosion* events are associated with hydrocarbon leaks from flanges, valves, equipment seals, nozzles, etc. Since the main fire and explosion events both result from combustion processes which are associated with hydrocarbon gas leaks, such events are strongly correlated (Fig. 4). Commonly, the effect of 40–80 scenarios needs to be analysed. 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) need to be estimated, followed by a structural assessment of the potential damage.

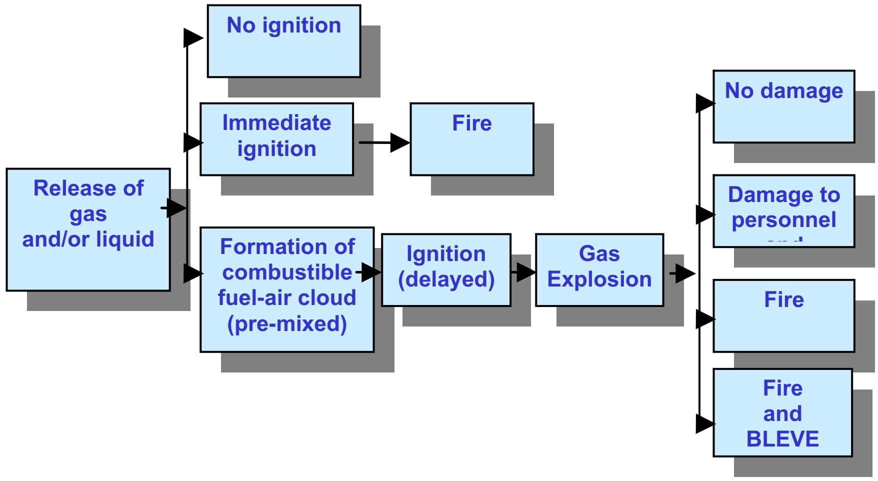

Fig. 4. Fire and explosion scenarios resulting from gas releases.

Explosion actions expressed by pressure–time histories are determined by assessment of leaks, gas dispersion and possible formation of gas clouds, ignition, combustion and development of overpressure (Fig. 5). Tools such as FLACS, PROEXP or AutoReGas are available for this effort (e.g. [12,25,49]). In the calculation of the probability of the resulting actions, the critical issue is the estimate of the probability of leaks as a function of leak magnitude and location. The conditional probability of gas dispersion, ignition, etc. can be estimated in a relatively accurate manner. Data from the relevant industrial activities are necessary to obtain a reasonable estimate of probabilities (e.g. [39]). Resulting characteristic overpressures for topsides of North Sea platforms are typically in the range of 0.2–0.6 barg, with a duration of 0.1–0.5 s, while open air explosions typically imply 0.1 barg with a duration of 0.2 s. The corresponding impulse varies between 1.2 and 2.5 kPa s. The explosion pressure in a totally enclosed compartment might be 4 barg.

Fires cause structural failure mainly by reduced strength due to heating, but to some extent, also due to thermal stresses. Differences in fire characteristics and consequences make the design strategies different for different types of structures. For instance, the costs and consequences of a complete collapse of one or more floors of high-rise buildings are enormous. The amount of flammable materials within buildings is limited whereas the fire temperatures caused by combustion of building materials, furniture, paper, etc. normally do not exceed 800 °C. Strict acceptance criteria are therefore applied to building structures. For offshore oil installations, the situation is different. The amount of fuel can be "unlimited": the fire temperatures are generally higher (1000–1300 °C) and the cost of the structure itself is limited compared to the equipment and process units inside the platform. A major accidental fire will most likely result in the renewal of some platform modules or the entire platform. The main concern for offshore structures is that they are able to withstand the actual fires for a certain time, for example the time needed to evacuate personnel safely (typically 1–2 h) and to avoid failure of pressurised hydrocarbon pipes and vessels which could lead to escalation of the fire.

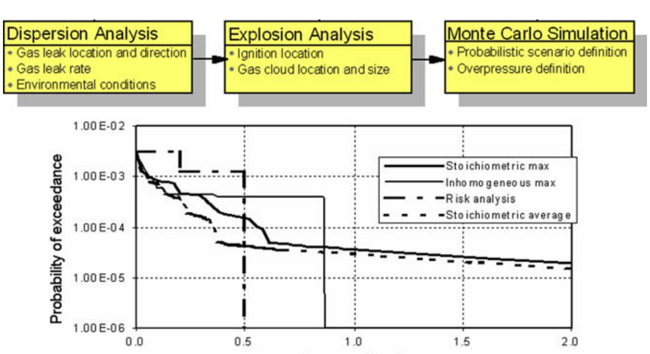

Fig. 5. Analysis procedure for explosion actions.

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 [9]. Typical thermal loading in hydrocarbon fires may be 200–300 kW/m^2 for a 15-min to 2-h period. Both the spatial extend and time duration of the fire are crucial parameters. The various means to limit the consequences of an accidental leak and fire are mostly: gas detectors, deluge, Emergency Shutdown Valves (ESV), de-pressurisation systems, etc. They all should be accounted for in the analysis. However, some codes require that the structural integrity should be maintained without the deluge system (which could be "knocked out" due to explosion, etc). In this case, the accidental actions should be determined without account of the deluge system.

3.2.2. Ship impacts

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 standards [35,36] as well as Amdahl [4]. For this purpose, ship traffic may 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 depends upon the location of the structure related 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 [35], Safetec [43] and Moan [25]. 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–indentation curves or nonlinear finite element analysis [4,36].

3.2.3. Other accidental actions

Other *accidental actions* which need to be considered include for instance: dropped objects and uneven ballast distribution in floating platforms. Moreover, *"abnormal" natural hazards*, for instance related to wave actions with an annual exceedance probability of 10^{-4}, should also be considered. This ALS check will simply 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. It is also noted that extreme waves are skewed, with larger crests than troughs, as illustrated in Fig. 6. While the 10^{-2} wave crest might not reach the platform deck, the 10^{-4} crest could hit the deck and cause a significant increase in wave loading, e.g. [24].

Consideration of abnormal wave loading is also relevant for structures with restricted operations since failure to comply with operational restrictions with respect to wave conditions could imply that the waves encountered are more severe than those based upon for the ULS design criteria.

3.2.4. Abnormal resistance

As mentioned above, the ALS check should include possible damage conditions due to abnormal resistance. In the following, some considerations of possible abnormal resistance associated with fatigue failure or fracture are made in view of abnormal cracks initiated during the fabrication. The design and inspection practices applied are also indicated. The basis for this consideration is the fact that crack type defects which are larger than the normal initial defects (which are of the order of 0.1 mm) could occur and escape detection at the fabrication stage. A theoretical prediction of such defects is not possible. However, experiences [31,48] give some indication of crack type defects. The mean value of the initial depth of 144 propagating cracks detected on North Sea jackets was estimated to be 1.0 mm while their mean depth was 4.9 mm when they were first detected. Moreover, these data indicate that an initial defect greater than 2.0 mm occurs once per 20 joints. The mean detectable crack size in the underwater non-destructive examination (NDE) was found to be 1.95 mm. 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 (e.g. [27]). The occurrence of abnormal defects and the probability that they are not detected at the fabrication stage, suggest that various barriers should be considered to control them before they result in fracture.

The crack growth in steel structures can conveniently be separated into two phases: (a) growth from initiation to a through thickness crack (TTC) and; (b) from TTC to fracture. The TTC condition commonly defines the failure criterion implied by SN-data and, hence, the common fatigue design criterion. The second phase differs very much for cracks in simple plane plates with membrane stress, tubular joints and monocoque stiffened panel ship structures (e.g. [27]). The following barriers are envisaged to control that abnormal fabrication cracks do not cause fracture and a subsequent system failure:

(a) Fatigue Design Factor (FDF) between 1 and 10 with respect to through thickness crack (TTC).
(b) Residual fatigue life (i.e. between a TTC and final fracture).
(c) In-service inspection by close visual inspection or NDE.
(d) Detection of TTC by Leak Before Break (LBB).
(e) Accidental Collapse Limit State (ALS) criterion for the system.

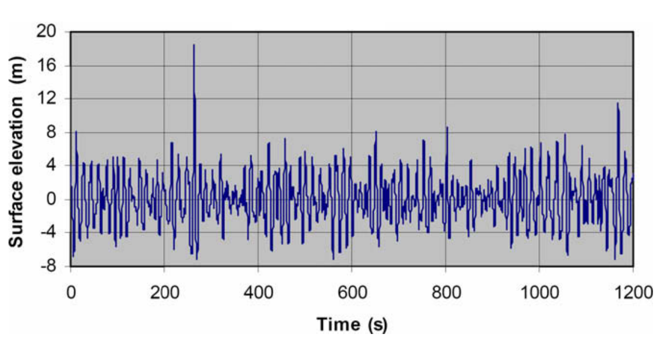

Fig. 6. The Draupner wave observed on January 1, 1995 showing the wave skewness.

As mentioned above, the barrier (a) is linked to (c) and (e) [34]. NDE inspections on offshore platforms are typically carried out every 4th or 5th year while ships are analogously examined by close visual inspection. However, as pointed below, in-service inspections sometimes are not or cannot be carried out. Reliance on (d) depends on (b): i.e. sufficient fatigue life and hence, fracture strength associated with "long" TTCs as discussed, e.g. by Bin and Moan [7]. However, it is often difficult to document the necessary residual fatigue life of TTCs, partly because current methods for fracture assessment are conservative. Alternatively to relying on a residual fatigue life(b), use of TTC detection, i.e. item(d), may be based on system residual strength after member failure, according to item(e).

The effect of abnormal defects on the failure probability of a steel joint is illustrated in Table 2. It shows the conditional probability of the occurrence of a TTC during a time *T* in a welded plated T-joint and tubular joint, assuming a typical defect and abnormal initial defect depth. No in-service inspections are assumed. This probability is calculated by an approach established by Ayala-Uraga and Moan [5]. The fracture mechanics model is based on the BS 7910 [10] single-slope model in air and calibrated according the (laboratory) SN-data. The fatigue loading is modelled by a Weibull distribution of stress ranges, relevant for an extra-tropical climate. While the probability of a typical initial crack depth of 0.1 is about 1.0, the probability, *p*, of the abnormal initial crack can only be subjectively judged. It is seen that for a probability *p* greater than 0.01 (per joint), the occurrence of abnormal cracks would increase the failure probability as compared to the normal conditions for the case with FDF = 10 over a period of 20 years. The possible implications of abnormal fatigue cracks will be exemplified by two cases.

First, consider slender braces in, e.g. semi-submersible platforms. With an FDF = 1 and an initial defect size of 2.0 mm, it is seen from Table 2 that the failure probability over a 5 year period (i.e. before the first inspection) is of the order of 10%. Since the residual life after TTC is small, the LBB approach is not applicable either and failure of a brace is considered as a damage condition for ALS check under such circumstances. Actually, such a consideration of fatigue failure together with the possible damage due to

Table 2
Conditional failure probability of a welded plated T-joint, $P_{fT|a0,nd}$ based on a model specified by Ayala and Moan [29] except that the initial crack size is varied

Design fatigue life (years)	Initial crack size (mm) (Distr. means: Exponential distribution)	Failure probability in a period of	
		5 years	20 years
20	0.1(distr.)	3.5×10^{-3}	0.15
	2.0 (fixed)	0.074	0.62
200	0.1 (distr.)	1.4×10^{-8}	6×10^{-5}
	2.0 (fixed)	8.5×10^{-6}	6×10^{-3}

ship impacts was the reason for introducing an ALS requirement for semi-submersibles to survive failure of individual (slender) braces. An interesting issue in this connection is the relevant environmental action to consider in the survival design check. Since fatigue failure occurs when the ultimate resistance is degraded, this failure is not strongly correlated to extreme sea loads. For drilling platforms, an annual action is used while for production platforms, a 100 year action is applied according the Norwegian offshore standards in order to check the survivability of the damaged structure.

Consider for the second case a pile for jacket structures. The transverse butt welds in piles cannot be inspected after installation. Moreover, the residual life after TTC is limited and LBB is not applicable. Whether adequate safety can be based on an FDF (say of 10) or an ALS requirement is needed, depends on the actual assessment of the potential abnormal defect and its likelihood. If the probability of an abnormal defect of depth 2 mm is of the order 0.015 or more, the probability of TTC (and "failure of the pile"), is of the order 10^{-4}, i.e. a damage condition for the ALS check. In this connection it is noted that tethers in tension-leg platforms are required to fulfil an ALS criterion, even though the FDF = 10 and in-service inspections are supposed to be carried out.

3.3. Risk and reliability assessment

Quantitative Risk Assessment (QRA) is a tool to support decisions regarding the systems' safety. The application of risk assessment in the offshore industry has evolved since approximately 1980 [30,37]. The Piper Alpha Disaster [41] was the direct reason for introducing QRA in the UK [17]. Risk analysis methodology is currently applied to validate offshore facilities at large, as outlined by Vinnem [47]. Typically, Fault and Event Trees are applied in the analysis of the development of accident scenarios, by account of various barriers to control the risk, see Fig. 7. The focus herein is on the risk associated with total loss of offshore structures induced by accidental actions and abnormal resistance.

3.4. Simplified probability of system failure induced by accidental actions

Fig. 3 illustrates how accidental actions can cause local damage which escalates into system loss. This escalation from local damage into total loss would normally take place progressively. Faber et al. [15] addressed the problem of quantification of robustness taking basis in a generic framework for risk assessment. 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.

The probability of system loss, relating to different accidental actions and "accidental damages" identified as abnormal resistance, may be written as:

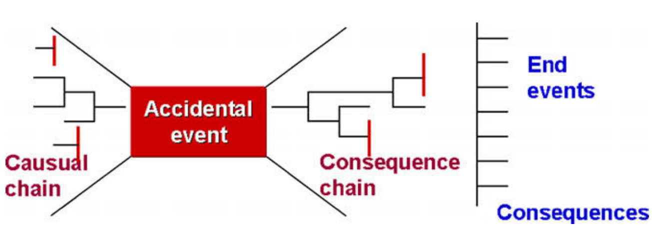

Fig. 7. Development of accident scenarios, modelled by fault and event trees.

$$P_{\mathrm{FSYS}} = \sum_{jk} P[\mathrm{FSYS}|D \cap A_{jk}^{(i)} \cap PE] \cdot P[D|A_{jk}^{(i)}] \cdot P[A_{jk}^{(i)}] + \sum_{lm} P[\mathrm{FSYS}|D_{lm}] \cdot P[D_{lm}], \quad (1)$$

where $A_{jk}^{(i)}$ are – mutually exclusive – accidental actions (i) at location (j) and intensity (k) and D_{lm} is damage at location (m) with a magnitude (l). PE represents the payloads and environmental actions to consider for the damaged structure. The locations (j) need to be discretised partly to represent the spatial variability of the accidental action, and partly to accommodate the behaviour 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 actions $A_{jk}^{(i)}$ 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 corresponds to failure of a member or a 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 $P[A_{jk}^{(i)}]$. One challenge in this regard is to determine the dominant among the (infinitely) many potential sequences of events. Moreover, 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 which 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 [6].

A crucial issue in determining $P[\mathrm{FSYS}|D \cap A_{jk}^{(i)} \cap PE]$ is the definition of which payloads (P) and environmental actions (E) to consider. The main challenge is then the correlation between the accidental event and the actions that occur in the time which elapses before the damage can be remedied or – if consequences in terms of fatalities are of concern – the time which elapses before personnel can be safely evacuated. The time to repair is basically a random variable. In extra-tropical regions, like the North Sea, it may be reasonable to assume that the (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.

3.5. Target safety level

The target safety level should depend upon the following factors (see e.g. [14,23]:

- method of reliability or risk analysis, especially which uncertainties are included;
- failure cause and mode;
- the possible ultimate consequences of failure in terms of risk to life, injury, economic losses and the level of social inconvenience;
- the expense and effort required to reduce the risk of failure.

As to the first issue, target levels for structural reliability analyses (SRA) concerned with notional failure probabilities and quantitative risk assessments (QRA) dealing with actuarial values of risk, should obviously differ.

The most important distinction of different failure causes is whether they are instantaneous or progressive – i.e. appearing over time. The most relevant practical examples would be an instantaneous overload failure versus a gradually developing fatigue failure or other deterioration, respectively. The failure development over time may influence the failure consequences since a warning may initiate escape and evacuation of personnel. The most important distinction of structural failure modes is between component and system modes.

Ultimate failure consequences include fatalities, environmental damage and loss of assets. While these consequences could all be expressed in monetary terms, the acceptance criteria in some regulatory regimes, e.g. Norway, express them separately. Fatalities induced by structural failure of offshore platforms occur primarily when the support of the deck fails or the platform capsizes, that is when system failure occurs. The failure of individual components (members, joints) commonly does not lead to fatalities. Moreover, the risk of fatalities would depend upon whether platforms can be evacuated before or during the accidental scenario or not. For instance, the likelihood of fatalities caused by storm overload in the Gulf of Mexico (GOM) may be less than in the North Sea (NS) because most platforms in the GOM can be evacuated in face of a storm (hurricane) while this is not the case in the NS. Environmental damage may occur due to direct damage to risers/conductors, piping or process equipment, or structural failure that leads to oil leaks. Potential environmental damage depends upon the safety systems (subsea safety valves, etc.) available. An important aspect of the economic consequences of failures and accidents is their possible impact on the reputation, both towards the public and the government. Loss of reputation may affect the business of the oil industry at large.

Fundamentally, a target level which reflects all hazards (e.g. loads) and failure modes (collapse, fatigue, etc.) as well as the different phases (in-place operation and temporary phases associated with fabrication, installation and repair) could be defined for each of the three ultimate consequences and the most severe of them would then govern the decisions to be made. If all consequences were measured in economic terms, a single target safety level could be established. However, in practice, it is convenient to treat different hazards, failure modes and phases separately. A certain portion of the total (target) failure probability may then be allocated to each condition, assuming e.g. that the total failure probability is just equal to the sum of the individual probabilities. This simplification is often made to treat the different hazards, failure modes and phases separately. 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. [23]).

The target failure probability should be referred to a given time period, i.e. a year or the service life. If the consequence is fatalities, annual failure probabilities are favoured to ensure the same fatality risk of individuals at any time.

Various methods may be applied to establish the target level for SRA and QRA, see e.g. CIRIA [11], Jordaan and Maes [20], ISSC [19] and Pate-Cornell [42]. They include:

(a) the safety or risk level implied by existing codes, or in actual structures which are considered acceptable;
(b) the experienced likelihood of fatalities, environmental damage or property loss associated with operations which are considered acceptable;
(c) the cost-benefit criteria.

The main consideration used in establishing the ALS criteria in NORSOK N-001 [34] is the experienced failure rates, and especially the fatality rate. Fig. 8 shows the frequency-fatality rate diagram of some ship and platform types. In this diagram, the horizontal axis represents the consequences in terms of fatalities while the vertical axis represents the annual occurrence rate of N or more fatalities. It should be noted that such a FN-diagram was presented by Whiteman [50] and based on early accident data for offshore structures and ships. However, these data differ significantly from the more recent data shown in Fig. 8. This diagram shows that the annual frequency of losses with 50–100 fatalities – which could be considered as total losses – is of the order of 6×10^{-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 added up.

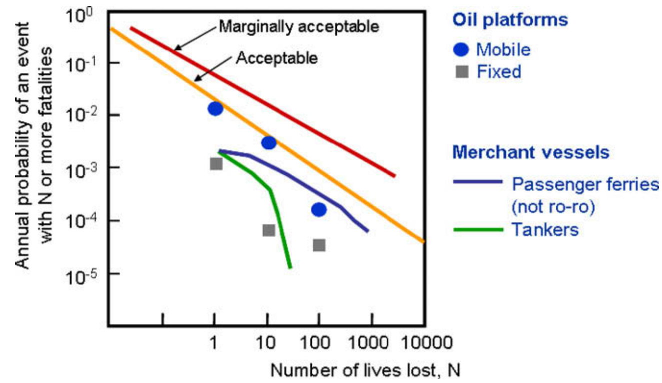

Fig. 8. Frequency-fatality diagram based on data for ships and offshore platforms compiled by the author [23].

4. Accidental collapse limit state

4.1. Introduction

The main safety criterion is to ensure that the system failure probability complies with the target level. Based on Eq. (1), a sufficiently low system failure probability can be achieved by making $P[A_{jk}^{(i)}]$, $P[D|A_{jk}^{(i)}]$ or $P[\mathrm{FSYS}|D \cap A_{jk}^{(i)} \cap PE]$ small. The former measure involves various tasks in connection with, for instance, fire and explosion hazards, such as gas detection, use of sprinkler system, etc. to reduce the occurrence rate of an explosion. The latter two measures involve direct local (ULS) and global (ALS) design checks, respectively, to resist accidental actions.

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 in terms of resistance against accidental actions. Also, ALS criteria based on alternate path emerged. Such criteria in most codes do not refer to any specific hazard but rather require resistance to progressive failure with one element removed at a time and therefore, they do not create a performance objective for a "real threat". The weakness of such an approach is that it does not distinguish between the differences in vulnerability. The NORSOK N-001 code [34] specifies quantitative ALS criteria, as subsequently explained. The basic procedure is first described. Then, the implied probability of system failure is estimated.

4.2. The NORSOK criteria

ALS checks apply to all relevant failure modes. Fig. 9 shows various system failure modes. In addition to these structural failure modes, possible escalation of damage to safety systems (e.g. fire detections and sprinkler equipment), piping/tanks carrying hydro-

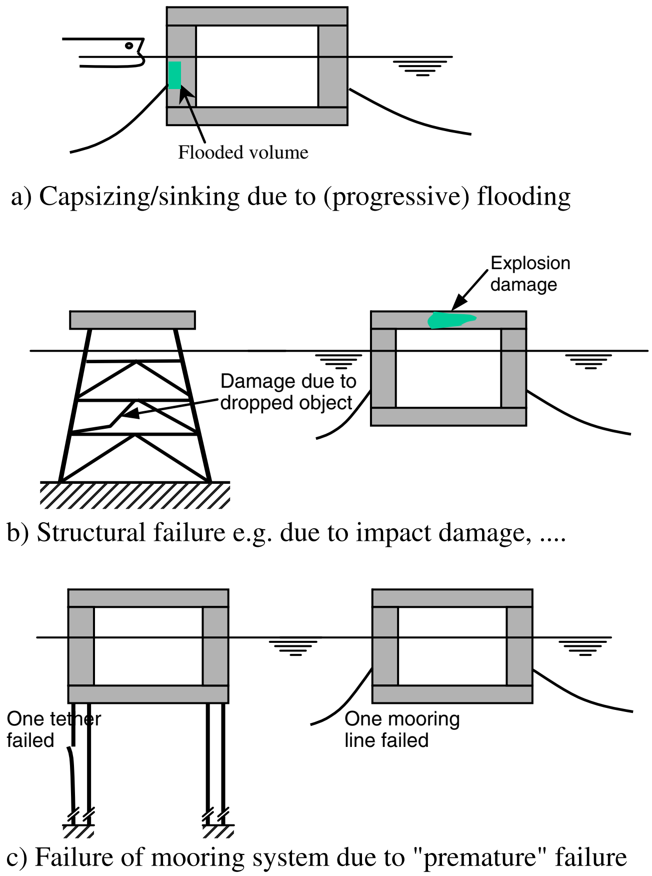

Fig. 9. ALS criteria for different system failure modes.

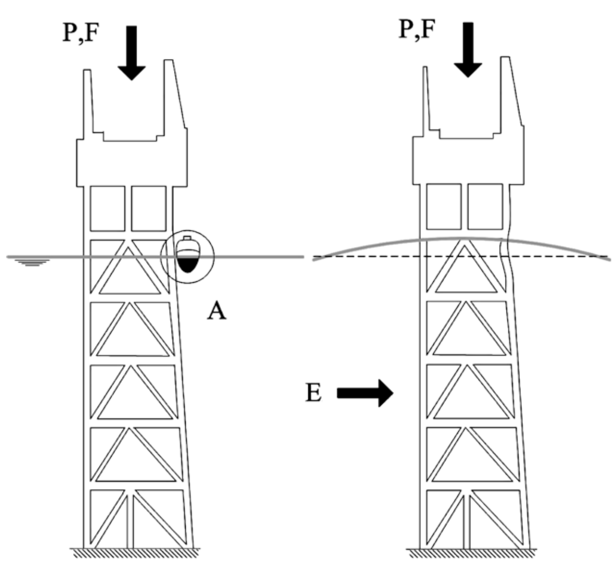

Fig. 10. Accidental Collapse Limit States for different global failure modes.

carbons, escape and evacuation system should be prevented. It is interesting in this connection to note that some ALS-type criteria were introduced for sinking/instability of ships and mobile platforms (e.g. [8]), long before robustness criteria were introduced for all failure modes of offshore structures in 1984 [37].

The target safety level for P_{FSYS} in the NORSOK ALS procedure is established separately for each hazard, failure modes and life cycle phase.

The structural integrity criterion in NORSOK is expressed by a two-step procedure as illustrated in Fig. 10. The first step is to estimate the initial damage due to accidental actions (illustrated by a ship impact in Fig. 10) with an annual exceedance probability of 10^{-4}. This exceedance probability refers to accidental events on the whole platform and needs interpretation, as discussed subsequently. The second step is to demonstrate that the damaged structure resists relevant functional and environmental actions with an annual exceedance probability of 10^{-2} without global failure. The characteristic resistance value used for steel is defined as the 95% quantile. Load and resistance factors for steel structures are taken to be 1.0 in these design checks. In this approach, the safety level is primarily determined by the characteristic values chosen for the action effects and partly by that of the resistance. The reason for this approach is the significant uncertainty, especially in the accidental action effects. This procedure was chosen to achieve a probability of total loss associated with each hazard of 10^{-5}, as detailed subsequently.

4.3. Design accidental actions

In general, a risk assessment is needed to estimate the characteristic accidental actions. At the same time, it is reasonable to specify minimum values, e.g. relating to frequent impacts of supply vessels on offshore structures.

The accidental actions are primarily supposed to be determined by risk analysis, see e.g. Vinnem [47] and Moan [25], by accounting for relevant factors of influence. This includes risk reduction which is achieved by reducing the probability of initiating event, leak and ignition (potentially causing 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, permanent deformations or rupture of components need to be estimated by accounting for nonlinear structural behaviour.

For each physical phenomenon (fire, explosions, collisions, etc.), a continuous spectrum of accidental events is envisaged. A finite number of events have to be selected by judgment [24,47]. For example, various fire and explosion scenarios are envisioned based on different leak rates at different locations, gas filling ratios and composition, gas dispersion 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 by determining their cumulative probability.

Since the 10^{-4} annual 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 characteristic accidental action (of a given type, e.g. explosion pressure) on different components of a given installation, could be determined as follows [25]:

– establish an exceedance diagram for the action on each component.
– allocate a certain portion (α_i) of the reference exceedance probability (10^{-4}) to each component so that the sum of the α_i-values is equal to 10^{-4}.
– determine the characteristic action for each component from the relevant action exceedance diagram and reference probability.

Alternatively, the following more refined consideration of risk may be used to determine the characteristic accidental action (of a given type on different structural components):

– component (i) is assumed to be designed for an accidental action with an exceedance probability of p_i for that component;
– estimate the probability of total loss due to failure of component (i) – implied by the residual risk associated with the accidental action;
– estimate the total probability of failure (P_f) associated with the given accidental action on all components;
– compare P_f with the target level;
– reallocate p_i's in order to get a more optimal design while complying with the target level.

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 [35,51] even though 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 with a significantly increased safety at the same expense. This applies particularly to the topside system. However, the tendency for mature systems is that the risk analysis confirms the previous results. This fact suggests using specific, generic values for such cases. Examples of typical values for some accidental actions are given in Section 3.2. Obviously, such an approach simplifies the design procedure.

4.4. Analysis methods for determining the accidental damage and residual strength of the damaged system

To demonstrate compliance with ALS requirements, both the damage due to accidental actions and the ultimate capacity of the structural system need to be calculated. To estimate damage (permanent deformation, rupture, etc.) of parts of the structure, nonlinear material and geometrical structural behaviour 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. Dedicated software is available for particular tasks.

Simplified methods based on plastic analysis often provide fast and amazingly accurate estimates of the damages caused by accidental actions on steel structures [4,12]. Such methods have been implemented in standards and guidelines [36,46] and are especially useful in early design for screening purposes. In particular cases for which simplified methods have not been validated, nonlinear time domain analyses based on numerical methods like the finite element method should be applied.

Determining the damage due to ship collisions is particularly challenging. Collision analyses are often carried out by splitting the problem into two uncoupled analyses: (a) the external collision mechanics dealing with global inertia forces and hydrodynamic effects, and (b) the internal mechanics dealing with the energy dissipation and distribution of damage in the two structures (NORSOK, N-004, [36]). The analysis (b) can be based on simplified approaches using load–indentation relationships obtained for each of the two structures by laboratory tests or refined analyses of a rigid body impacting the relevant deforming body. This simplified approach may imply uncertainties. Care should therefore be exercised in ensuring that the load–deformation curves used are representative for the true interactive nature of the contact between the two structures.

In finite element analyses of collisions, a careful choice of mesh is required in order to obtain accurate results, especially for components deforming by axial crushing. A major challenge in NLFEM analysis is the prediction of ductile crack initiation and propagation. This problem is not yet solved. Crack initiation and propagation should be based on fracture mechanics analysis, using the *J*-integral or Crack Tip Opening Displacement method rather than simple strain considerations. The simplest approach to the problem is to remove elements once the critical strain is attained. This is fairly easily done in an explicit computer codes to treat the transient dynamic problem because there is no need to assemble and invert the effective system stiffness matrix. However, deleting elements disregards the fact the large stresses can be maintained parallel to the cracks. An improved modelling is to introduce a double set of nodes so that the elements are allowed to separate once the critical stress is attained. A drawback with a double set of nodes is that the potential location of cracks needs to be defined prior to analysis.

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, especially for damaged structures. NLFEM makes it possible to account for redistribution of forces and subsequent component failures until system's collapse, even for very large and complex systems. The ultimate behaviour of fixed platforms is sensitive to the structure–soil interaction which needs to be accounted for by appropriately using the material properties in the different soil layers. Soils exhibit nonlinear behaviour, even at low load levels, which needs to be considered. Some softwares dedicated for progressive collapse analysis of frame offshore structures have also been developed, e.g. USFOS and SACS [44].

As mentioned above, the analysis of systems is particularly of interest to demonstrate robustness in connection with structures which are damaged due to accidental actions or fatigue fracture. To illustrate the effect of damage on the residual global strength of fixed platforms, the jacket in Fig. 11a is considered [32]. This is an 8-legged North Sea jacket in 109 m water depth. The overall dimensions at the mudline are 56 by 70 m. Leg diameters range from 1.6 m at deck level to 3.0 m while braces have a diameter ranging from 0.8 to 1.6 m. The ultimate capacity in terms of base shear force, is normalized with respect to the wave action force with an annual exceedance probability of 10^{-2}, F_{100}. The damage is considered in terms of removal of individual braces as indicated in Fig. 11b. Table 3 shows that the failure of the braces 261 and 463 for broad side loading does not reduce the ultimate strength, and, most importantly, for all cases with a single brace failure, the reserve capacity is at least $0.76 \times 2.73 = 2.08$ times the 100 year characteristic action while the normal total safety factor for design checks of components of offshore structures is about 1.5.

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 a 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 for the damaged structure will hence be of the order of 0.1. The

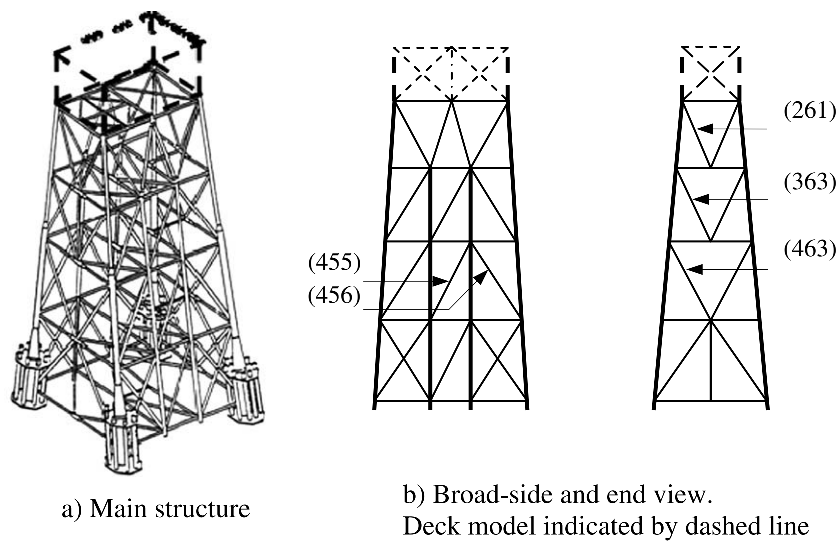

Fig. 11. Damage sensitivity of a North Sea jacket.

Table 3
Residual strength of damaged North Sea jacket expressed as the base shear force; using a linear pile-soil model

	Loading and damage condition				
	Broad side loading			End-on loading	
	Brace 261	Brace 363	Brace 463	Brace 455	Brace 456
Ultimate strength F_{ult}/F_{100}	2.73	2.73	2.73	2.89	2.89
Residual strength $F_{ult(d)}/F_{ult}$	1.0	0.76	1.0	0.91	0.85

F_{100} – wave load exceeded annually by a probability of 10^{-2}.
Note: F_{ult} – ultimate strength, $F_{ult(d)}$ – ultimate strength of damaged platform.

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 $10^{-1} \cdot 10^{-4} = 10^{-5}$.

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. The account of accidental actions on safety systems is a crucial safety measure in preventing the accidents to escalate.

5. Conclusions

The risk implied by current ultimate and fatigue limit state criteria for offshore structures is small and does not appear in accident statistics. The main causes of accidents are human and organizational errors and omissions. An acceptable safety level is therefore achieved by 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 this limit state criterion. This includes not least the recent developments of efficient and accurate finite element methods for nonlinear structural analysis.

Acknowledgements

The work reported herein has been carried out over many years in the development of codes for the Norwegian Petroleum Authority (renamed the Petroleum Safety Authority), NORSOK and ISO as well as in many R&D projects for the oil and gas industry. I would like to acknowledge the fruitful cooperation with many colleagues working in code committees and the research community.

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