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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-

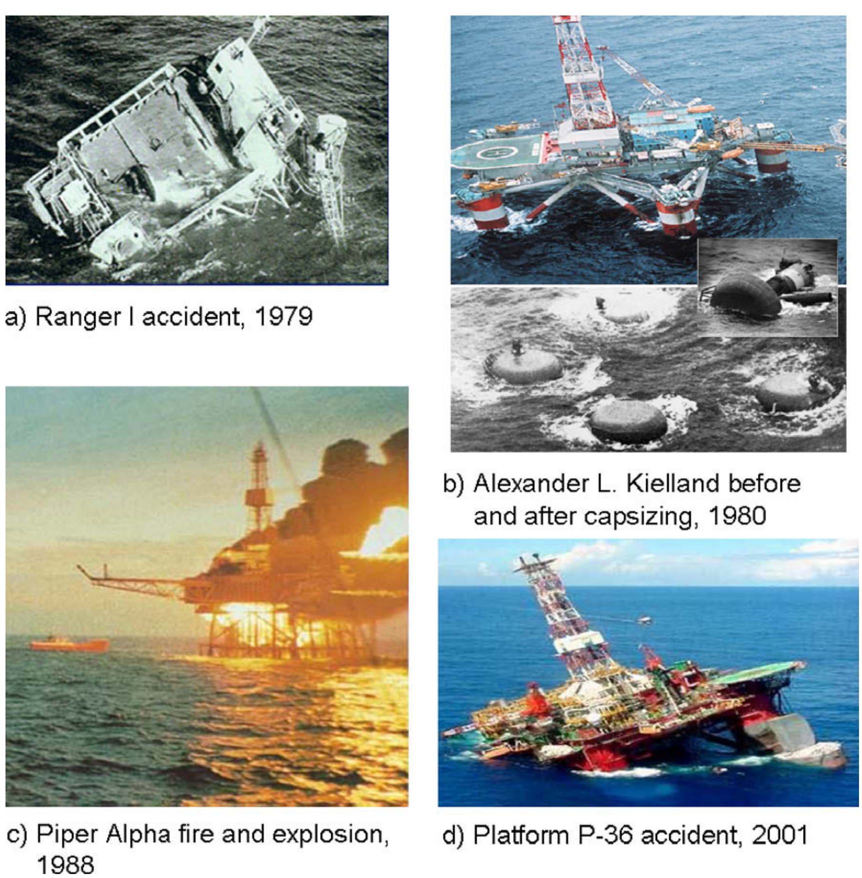

Fig. 1. Examples of accidents which resulted in a total loss.