Challenges in the Application of System Reliability Principles to Floating Structures[1]

Roger I. Basu[2]
Baidurya Bhattacharya[3]

Abstract

Over the last several years risk and reliability principles have been increasingly applied in assessing the safety of offshore installations. In part, this has been in response to some spectacular accidents. While the focus of this paper is on the structural systems in floating installations, the paper opens with a broad overview of the development of risk-based methods used in the design and assessment of offshore installations in general. This includes a description of techniques used, and also describes some recent developments and difficulties.

Structural reliability methods are well established in the design and assessment of many classes of large engineered structures, particularly at the component level. But their application to floating offshore installations, especially at the system level, has been limited. This is partly due to some difficulties unique to floating structures including (i) the existence of multiple system failure modes some of which are non-structural in nature, and (ii) the existence of strong interaction between structural and non-structural component failures leading to global failure. Drawing on work performed by ABS in the development of a classification guide for the Mobile Offshore Base, and other subsequent work the challenges faced by designers and assessors of such systems are described. The semisubmersible form is used to illustrate the issues and possible solutions.

INTRODUCTION

Engineering technology associated with marine structures, at least away from coastal areas, has been driven primarily by the transport and petroleum industries, and to some extent by the military. While engineering structures associated with oil exploration and production are most relevant to the subject of this paper, aspects of the paper are pertinent to all large floating structures. The engineering requirements for most offshore installations are demanding, particularly designs that rely on buoyancy for support. Such installations generally have to be self-propelled, have the ability to maintain position, have good motion characteristics, and support processing plant appropriate to its function. Often these installations are located in severe environments away from the kind of infrastructure that land-based installations enjoy. Many of these facilities process crude oil, the byproducts of which can be dangerous.

In the history of the offshore industry, which is barely half-a-century old, there have been a number of spectacular accidents (major ones are listed later in the paper). Some of these accidents have been as result of the process plant these installations support, and in this regard their land-based counterparts have also suffered similar catastrophic accidents. Other accidents are related to the fact that these installations are floating and supported by buoyancy. A general loss of buoyancy, of course, results in ultimate failure for the installation. The initiating event that ultimately leads to a general loss of buoyancy may be structural or non-structural in origin.

The accidents referred to above led the engineering community to develop new rational methodologies to systematically investigate the hazards that onshore and offshore installations were exposed to, and to minimize

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[2] American Bureau of Shipping, Houston, TX 77060. Email: rbasu@eagle.org

[3] Department of Civil and Environmental Engineering, University of Delaware, Newark, DE 19716. Email: baidurya@udel.edu

the consequences of hazards in the event they occurred. Accidents at land-based process plants in the mid-seventies (e.g., Flixborough, U.K. in 1974 and Seveso, Italy in 1976) were mostly responsible for the development of quantitative risk assessment (QRA) methodologies (Spouge 1999). Soon after, similar techniques were applied to offshore installations, particular to examine risks to living quarters. In this regard the Norwegian Petroleum Directorate were among the first such agencies to require the use of QRA methodologies.

Quite independently risk principles were being applied in the assessment of structural safety, particularly for buildings, but also for fixed offshore platforms. The discipline is commonly known as structural reliability. While the broad goals of QRA and structural reliability are the same, the evolution has been quite different, and there do not appear to have been any significant attempts to treat structural reliability in a QRA framework. There are, in any case, many impediments to any such attempt.

Structural reliability analysis (SRA), as usually applied, treats the loads on the structure and the resistance of the structure within a probabilistic framework. In this sense, and in comparison to QRA, structural reliability as applied in practice is rather narrow in scope. Typically the interaction between structural and non-structural component failures is not considered in SRA. Furthermore, some ultimate failures are the result of multiple component failures, some of which are structural in origin while others are not.

Even though this paper does not attempt to provide answers to all the issues raised above, it does identify the challenges, and poses the most relevant questions. Some limited progress has been made to addressing the issues, and these are described. The issues that remain are outlined and tentative proposals are made on how these challenges may be met.

The paper opens with an overview of QRA in order to provide a context for the remaining elements of the paper. Structural reliability analysis methodologies are reviewed, and their limitations described in regard to floating structures and their treatment of system failures, particularly those involving a mix of structural and non-structural failure modes. Suggestions are then made on how a systems reliability methodology may be developed.

Work has been performed that addresses some of the issues raised above and these are summarized. In particular the American Bureau of Shipping was responsible for developing a Classification Guide for the Mobile Offshore Base, conceptually a system comprising a number of linked floating structures. The most common form envisaged for the structures is the semisubmersible, which has a long history of successful use in the offshore industry. The Guide treats some of the system aspects mentioned above. In addition, other work is relevant – the use of structural reliability principles to consider the problem of rupture of the outer shell of submerged structure and the resulting demands on bulkheads. Failure of bulkheads, of course, can lead to overall loss of buoyancy and capsizing and sinking.

The semisubmersible form of offshore installation is used as a vehicle for describing the issues of interest to this study, and also for illustrating the application of a methodology to assess risk that accounts for the interaction between structural and non-structural failure modes. This form is used almost exclusively for oil exploration and production in the offshore industry. Considerable data on failures has been gathered and this is used in this study to develop the aforementioned methodology.

While the discussion is centered on semisubmersibles in the oil industries, in principle much of the development of the approach presented below can be applied to the semisubmersible form used for other applications. In this regard the Mobile Offshore Base concept is a good example. While they will not be concerned with the kinds of activities associated with the oil industry, they have the potential to be exposed to even greater hazards. Such facilities will be exposed to, for example, military attack and will also carry hazardous cargo such as explosives and fuels.

SAFETY AND THE ORIGINS OF RISK METHODOLOGIES IN THE OFFSHORE INDUSTRY

As noted above risk methodologies were developed in response, at least in part, to several accidents in onshore process plants and in their offshore counterparts. In the offshore industry the Norwegian Petroleum Directorate was probably the first such national agency to require a risk evaluation to be performed as part of the design process. The application of risk methodologies evolved gradually over time, as did their influence on design of offshore installations.

The *Piper Alpha* accident in 1988 in the UK sector of the North Sea was pivotal in the UK authorities, under the aegis of the Health and Safety Executive (HSE), in requiring, at least implicitly, the application of risk methodologies. The guiding principle is that the regulations should be “goal setting” rather than prescriptive. The implementation of this in practice is through the use of the “safety case”. A guiding principle in the application of this methodology was the concept of ALARP, or As Low As Reasonably Practicable. ALARP represents a recognition that very

high standards of safety are extremely costly and that, in any case, absolute safety cannot be achieved. Clearly it is not possible to define ALARP in objective and absolute terms, and hence there is an implicit acceptance of a subjective element in any risk assessment.

The "safety case" as practiced in the offshore industry, and indeed other industries, is an integrated risk management system (Industry Science Resources (undated), Spouge 1999). According to the first of these references the safety case serves two purposes:

- To give the "regulator" (assessor) confidence that the "operator" has the ability, commitment and resources to properly assess and effectively control risks to the health and safety of staff and the general public; and
- To provide a comprehensive working document against which the "operator" and the "regulator" can check that the accepted risk control measures and safety management systems have been properly put into place and continue to operate in the way in which they are intended.

The same reference identifies three broad categories of information required in a safety case:

- A complete description of the subject facility, its activities and operations and its interaction with other facilities. (Facility Management)
- The system, which will be used in the design, construction and operation of the facility that will ensure requisite level of safety and corporate responsibility for safety. (Safety Management System)
- The methodology that will be used to characterize the nature, likelihood and impact of potential major hazards which may impact the facility and the means to prevent the hazards being realized, but if they are, the means to minimize the consequences. (Formal Safety Assessment)

QRA is the generally applied methodology to investigate the nature, likelihood and impact of potential major hazards.

QRA as a quantitative, analytical methodology is regarded as objective when compared other more qualitative approaches. Nevertheless, several limitations have been identified. Among these are inadequate historical data and difficulties in statistically characterizing human error. This is, of course, critical in view of the fact that a general rule-of-thumb is that some 80% of accidents are caused by human error.

There are several types of QRA that are applied in assessing the safety of offshore installations varying in objectives and scope. The scope of QRA studies can be very wide, and this is due to the wide range of hazards offshore oil and gas exploration and production installations are exposed to. Spouge (1999) categorizes these hazards as follows:

- Blowouts
- Riser/pipeline leaks
- Process leaks
- Non-process fires
- Non-process spills
- Marine collisions
- Structural events
- Marine events
- Dropped objects
- Transport accidents
- Personal (or occupational) accidents
- Construction accidents
- Attendant vessel accidents
- Diving accidents

"Structural events", the focus of this paper, are further broken down into the following types of hazard:

- Structural failure due to fatigue, design error, scour, subsidence, etc.
- Extreme weather
- Earthquakes
- Foundation failure (including punch-through)
- Bridge collapse
- Derrick collapse
- Crane collapse
- Mast collapse
- Disintegration of rotating equipment

Some kinds of structural failures are local in scope while others have global implications. Figure 1 shows an informal fault tree diagram describing how several types of hazard can lead to one category of failure, compartment flooding in this case. The elements shown shaded in the fault tree diagram are ones that can be treated using traditional structural reliability methods. These methods are very well developed, and as noted earlier, have evolved independently of QRA.

The potential for using the results of structural reliability analysis in QRA has been recognized for some time (see, for example, Frieze 1992). However, there are significant difficulties in integrating the results of structural reliability analysis into a QRA (Spouge 1999). Firstly, traditional SRA does not include all types of uncertainties, most notably those arising from human error. Secondly, QRA generally uses probabilities obtained from actuarial or field data; such data are usually not available and difficult to obtain for structural failures. Finally, SRA generally does not account for non-structural initiation events or interaction with non-structural failures.

Key aspects of the development of structural reliability analysis and its application are described in greater detail in the next section.

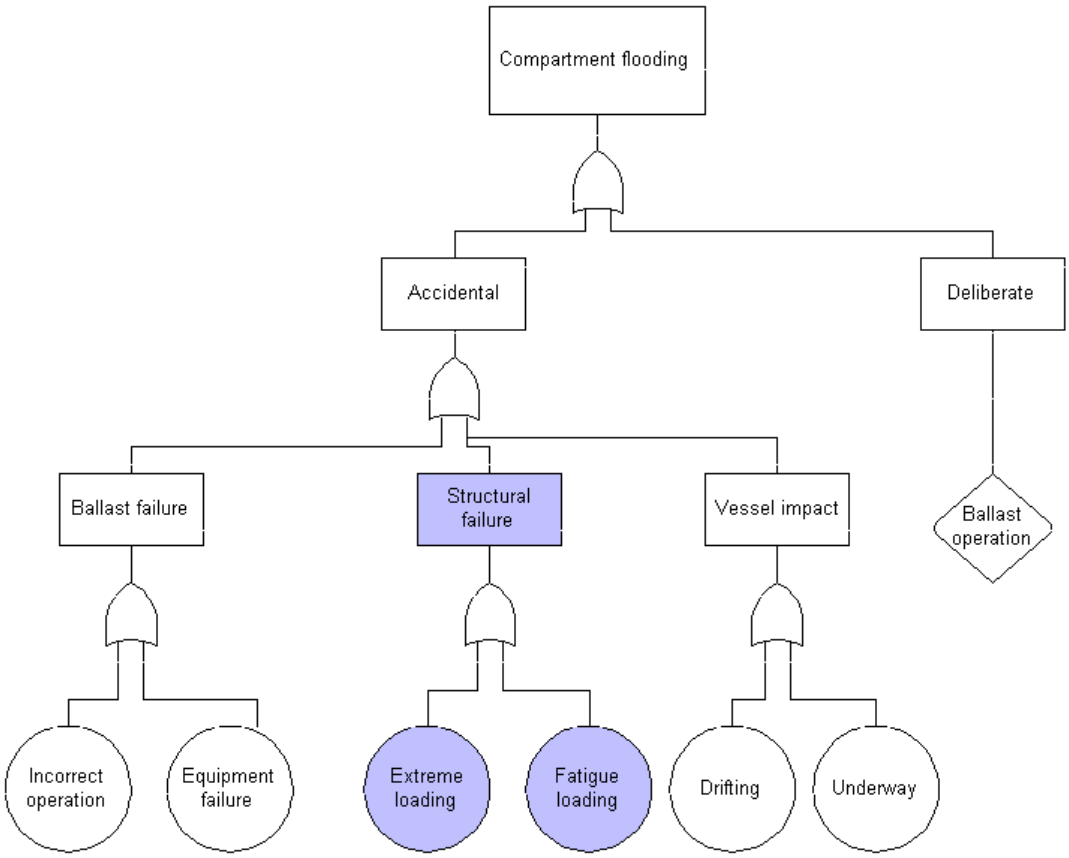

Figure 1: Fault Tree (adapted from Barltrop, 1998)

STRUCTURAL RELIABILITY METHODS AND THEIR LIMITATIONS

Structural reliability as a discipline evolved only during the second half of the twentieth century. The early works of Alfred Freudenthal (e.g., Freudenthal 1956) are cited by many as the origin of the subject. The practical application of structural reliability however became possible only after the pioneering work of C. Allin Cornell in the late 1960s, notably with the introduction of the second moment-based reliability index (Cornell 1969). This index, as originally defined, was found to vary for the same problem depending on the algebraic form of the limit state equation. Hasofer and Lind (1974) solved this invariance problem by transforming the limit state equation to the uncorrelated standard normal space. First order and second-order reliability analysis methods in the standard normal space continued to be developed in the 70's. Development of other means of computing probabilities of rare events, e.g., estimating multinormal integrals, performing Monte-Carlo simulations including variance-reduction techniques etc., proceeded in parallel and went well into the 1980's. Notable contributors during the two decades of explosive growth in SRA (structural reliability analysis) include Cornell, Shinozuka, Ang, Ditlevsen, Turkstra, Lind, Ravindra, Galambos, Wen, Ellingwood, Der Kiureghian, Melchers and Rackwitz.

Depending on the degree of approximation and on the format of application, reliability analysis methods were sometimes categorized as *Level 1, Level 2* and *Level 3*; in addition, the term *Level 4* signified methods that incorporated economic and social data as well. However, the boundaries separating the different "levels" are not distinct, the terminologies have become archaic and should be abandoned.

By the early 1980's, structural reliability was mature enough as a discipline to be ready for practical

applications such as probability-based design code formulation. Commercial software packages also began to appear.

The traditional formulation of SRA is element-based in that it starts from a single failure mode of a structural element. Consideration of randomness (including time-dependent randomness) is confined to the load variables (including environmental variables), the geometric variables, the material properties and in the mathematical models (e.g., models relating loads to load-effects). Uncertainties in the failure criteria itself is considered sometimes, however, those arising from gross errors are not.

The limit state equation in the basic variables (i.e., the variables relevant to the problem as listed above) separates the failed state from the safe state. Broadly two kinds of failure are investigated in SRA: (i) the "overload" type in which a single and distinct high load during the life of the component causes the first excursion from the safe domain into the failed domain, and (ii) the "cumulative" type in which some form of damage continues to accumulate within the component (usually at a random non-stationary rate) which finally leads the component away from the safe domain. Various analytical and numerical methods exist for evaluating element failure probabilities.

System failure is generally represented as a Boolean combination of element-level failures, and methods of varying accuracies are available for computing system reliabilities. Tools traditionally used in computing system reliability in electrical, electronic and process industries are hardly applicable in SRA: (i) The element-level failures are statistically dependent owing to shared loads and common construction processes and materials, (ii) structures are usually highly redundant and load redistribution occurs once an element fails, and (iii) because the order in which elements fail is critical, the identification of failure paths can be challenging even in a simple structure.

Perhaps the greatest success story in the application of SRA is the development of probability-based design codes around the world. Examples include AISC (1994) LRFD Manual for steel, API (1993) LRFD Guide for Fixed Offshore Platforms, ISO (1998) Principles on Reliability for Structures, US Navy's LRFD Rules (NSWCCD 1999) etc. A common feature of current probability-based design guides is that they are element-based – the assumption is that if elements are designed safely, the safety of the system is assured. This philosophy works as long as there exists sufficient experience in the design and behavior of the system under consideration and the pace of innovation is slow. Nevertheless, this philosophy has the potential to perpetuate sub-optimal designs (for details, see Bhattacharya et al. 2001).

In spite of its rational basis and considerable success in application, SRA continues to have certain limitations. As described above, the limit state probability reflects uncertainties in loads, material properties, geometries and mathematical models. Around 80% of all structural failures nevertheless occur due to gross (or "human") errors, and not due to overloads or damage accumulation. A gross error is an unintended departure from standard practice (ignorance, negligence, irresponsibility etc.) and may occur in any one of the three stages, i.e., the concept, construction and operation stages in the life of the structure. Gross errors are not generally included in SRA. Established structural reliability principles are not well-suited to incorporate gross errors since they usually alter the very nature of the problem by changing the probabilistic models of the basic variables and even the form of the limit state equation (Ellingwood 1992). As a result, failure probabilities predicted by SRA are not likely to converge with actuarial data since the latter include failure from all causes. This is one of the reasons why failure probabilities predicted by structural reliability analysis are characterized as "notional" by some authors.

Traditional SRA also does not consider interaction of structural failures with non-structural failures, especially at the system level. This interaction however can be crucial in the failure of floating systems. In addition, the application of structural reliability principles to floating structures in particular has certain difficulties that arise from the dynamic nature of the problem. Despite these, structural reliability techniques remain the only viable and rational means to including a large class of uncertainties in structural analysis and design.

BEHAVIOR OF FLOATING STRUCTURES UNDER EXTREME CONDITIONS

The difficulties and limitations in applying structural reliability principles in the context of a QRA were outlined above.

For the purpose of illustrating the solutions offered in response some of the challenges outlined in the previous section, the semisubmersible floating offshore platform is used as a convenient framework. This section discusses general issues concerned with the ultimate behavior of semisubmersibles and how this issue is treated in typical design procedures. In preparation for subsequent material in this paper broader aspects of failure of semisubmersibles are discussed, particularly the interaction between structural and non-structural failure modes, and multiple failure modes. While the focus is on

semisubmersibles, much of the discussion is applicable to all floating structures, including ships.

Ultimate Behavior

Risk is generally concerned with extreme events. In the context of structural design the concern is mainly with the behavior of the structure in ultimate conditions (of course the serviceability i.e., functional, aspects are also important). The types of hazard that offshore installations can be exposed to were listed earlier. Many of these can ultimately lead to structural failures of the type that compromise the ability of the structure to maintain watertight integrity. If the loss of watertight integrity is severe enough buoyancy is lost possibly leading to capsizing and sinking.

Offshore installations are exposed to several hazards, more than is associated with comparable land-based facilities. The types of accident that offshore installations suffer were listed earlier in the paper. Table 1 presents a summary of the percentage frequency of each type of initiating event that leads to a severe accident.

Examining major accidents that have occurred can be instructive. The most severe such accidents involving semisubmersibles include the following:

- *Transocean 3* – Jan 1, 1974. A leg broke away in rough weather in the North Sea and led to the capsize of the semisubmersible.
- *Alexander Kielland* – Mar 27, 1980. A fatigue failure originating in a brace led to the capsize of the 5-column semisubmersible. This accident also occurred in the North Sea.
- *Ocean Ranger* – Feb 15, 1982. Human error combined with ballast system failure in severe weather led to capsizing of the vessel off the coast of Canada.
- *Petrobras P 36* – March 20, 2001. After a series of explosions and fires in a column and subsequent flooding of pontoons, the installation sank off the coast of Brazil.

The "last line of defense" against capsize and sinking of a semisubmersible is often the structure. There are two features of the initiating event and its subsequent behavior that are useful in characterizing failure:

- Size of the initiating event
- Time-scale of initiating event

The initiating event can be very local but lead progressively to other structural failures in which more and more of the structure participates ultimately leading to collapse. This is what the *Alexander Kielland* experienced where a fatigue failure that occurred in a bracket lead to failure of a brace and rapidly to the loss of the installation.

In other cases the initiating event is more global and involves a substantial proportion of the structure from the beginning of the event. An explosion that may be caused by a gas leak, for example, may damage structure to the extent that watertight integrity is compromised. This is what appears to have happened in the recent loss of the *Petrobras P 36* semisubmersible.

Table 1: Initiating events causing severe offshore platform accidents

Initiating event	*Frequency (%)*			
	Fixed Platforms	*Jack-up rigs*	*Submersible rigs*	*Semisubmersible rigs*
Blowout	34	23	50	28
Fire/explosion	25	6	14	6
Collision	9	5	3	11
Capsizing	8	9	10	3
Structural damage	8	32	7	13
Drifting, grounding	-	8	3	20
Weather, flooding	3	6	10	9
Other	8	11	3	10

Source: Quoted in Stewart and Melchers (1997) after adaptation from Bertrand and Escoffier (1991)

Treatment of Ultimate Behavior in Design

Modern structural standards, codes, and design guides recognize the need to build in the structural system inherent resistance to the kind of hazards outlined above.

For example the Draft ISO standard, currently under development (ISO 2000), for floating structures built in steel requires that designs incorporate "damage tolerance" and "robustness". Towards that end the standard requires consideration of accidental limit states and the evaluation of:

- Structural damage caused by accidental loads
- Ultimate capacity of structures with damage

The standard requires, where relevant, that the overall integrity of the structure be investigated following failure of an individual brace. It also requires that the structural integrity of the unit be considered for accident conditions such as collision, fire and explosion.

Similar features were incorporated in a Classification Guide, developed by ABS (ABS 1999), for application to the Mobile Offshore Base (MOB). The MOB is a family of concepts for a large self-propelled floating ocean structure from which flight, maintenance, supply and other naval support operations could be conducted in forward deployment areas in military situations. Several concept designs were developed as part of the program and many of these envisaged the MOB comprising several large modules connected for operation, and disconnected for transit. The semisubmersible form was selected for the module in most designs.

In addition to the usual element-level structural checks, the MOB Guide requires consideration of the following global limit states:

- Progressive collapse limit state
- Damaged condition limit state

The first of these limit states, progressive collapse limit state, is considered to limit the consequences of a local failure, which may be itself inconsequential, but can precipitate further failures until the integrity of the structural system is threatened. In contrast the initiating event in the damage condition limit state involves more than local structure from the outset. This may be as a result of a collision or explosion, which renders ineffective a significant proportion of the structural system.

The next section takes a closer look at modeling this type of initiating event and its consequences.

ASSESSMENT OF THE SAFETY OF OFFSHORE STRUCTURES

Risk assessments generally comprise the following elements:

- Establishment of scope of assessment
- Definitions of system and system failure
- Logical representation of the system in terms of its elements
- Identification of hazards
- Estimation of probability of hazards being realized
- Estimation of consequences if the hazard is realized

Large amounts of data have been gathered and numerous tools developed to assist in the task of assessing risk of engineering system.

In the present case the focus is on floating structures, particularly the semisubmersible form. Furthermore, the primary interest is on the safety of the assets, chiefly the structure. In broader, more comprehensive, studies safety assessment will also encompass issues concerned with environmental threats and risks to human life; these are not considered here.

This section is concerned with illustrating the issues raised earlier in this paper in regard to interaction of structural and non-structural failure modes. For this purpose a high-level fault tree is presented. This is used as the basis for subsequent discussion.

Figure 2 presents a preliminary fault tree for capsize and/or sinking of the vessel. "Structural failure" in this diagram is intended to mean gross failure, e.g. the loss of a leg, or a pontoon in a semisubmersible.

It is clear that there is opportunity for interaction between failure modes. Consider explosions for instance. An explosion may, at one extreme, be severe enough to cause substantial damage to the structural system to the extent that the installation is lost through capsizing or sinking. On the other hand, a less severe explosion, which results in a local rupture below the waterline, may lead to flooding and eventual capsizing or sinking, even though the structural integrity of the system is not threatened. Or, the explosion may be such that both structural and watertight integrity are compromised.

A similar scenario can be envisaged where the initiating event is collision below the waterline of a pontoon in a semisubmersible may lead to partial flooding. This may not lead to capsizing or sinking if the watertight bulkheads are capable of resisting the loads imposed on it in this accident situation.

The use of fault trees is a useful way to examine system behavior under ultimate conditions. Some features of this type of analysis in which it is possible to treat structural and non-structural failure modes in a systematic framework are illustrated in the subsections presented below. The fault tree in Figure 2 is used for this purpose.

The modeling of the system in terms of a fault tree diagram is discussed below. This is followed by a description of the system is algebraic form. This form allows the calculation of the probability of system failure on the basis of estimates of the probabilities of the initiating events. Representative data is input in order to illustrate issues relevant to this study.

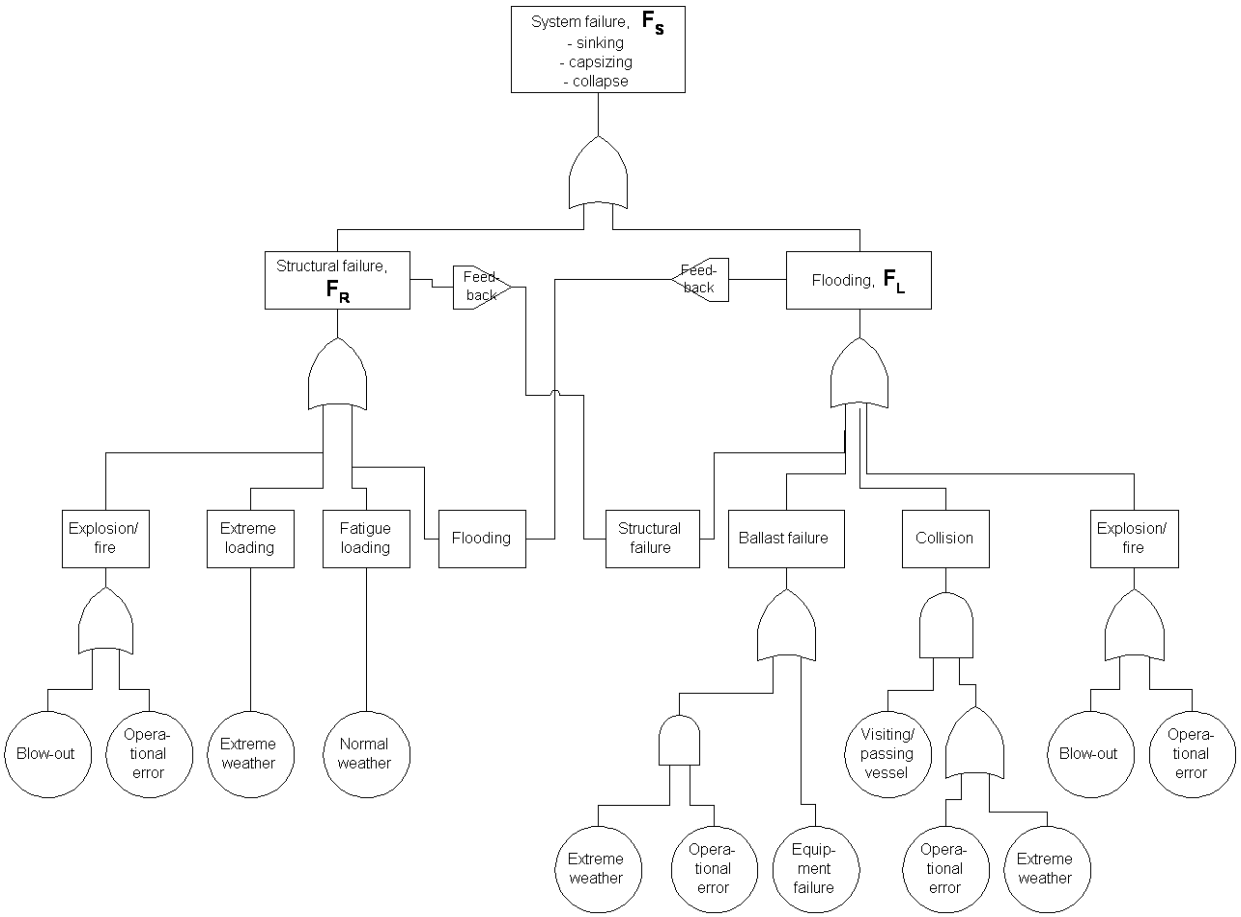

Figure 2: Preliminary fault tree diagram for system failure of a semisubmersible

Representation of Events Leading to System Failure

The fault tree is limited in scope. Only the safety of the asset, i.e. the structure, is considered. Hence, only initiating events that have some finite probability of leading to system failure are included in the scope. Furthermore, as is inevitable in studies of this type there is a significant element of subjectivity implicit in the analysis.

Hence, several hazards of the type that may impact the safety of humans, or may lead to a pollution incident are not included. As a consequence riser and pipeline leaks, hydrocarbon events, fires etc. are not addressed.

The fault tree diagram in Figure 2 must be regarded as preliminary, and designed primarily for the purpose for illustrating the arguments presented below. It is critical that the key initiating events are recognized and modeled in the fault tree, and that the essential interrelationships are captured. While the fault tree diagram in Figure 2 is a simplification, it is based on observed experience and also engineering judgment.

For semisubmersibles the major causes of system failure has been either structural failure due to extreme or fatigue loading or due to ballast system failure. In most cases it was a not a single failure, but rather a dominant initiating event exacerbated by other contributory actions. In regard to the latter it is often bad weather.

Algebraic Representation of System

As noted above "System failure" (F_S) encompasses capsizing, sinking and total collapse. "Structural failure" (F_R) in this diagram is intended to mean gross failure, e.g. the loss of a leg, or a pontoon in a semisubmersible. "Flooding" (F_L) in this diagram refers to major flooding of watertight boundaries involving several compartments. System failure occurs if either structural failure or flooding or both occur.

Intermediate events that lead to F_R or F_L include explosion/fire, ballast failure, environmental loads and collision. Events that are considered to be "basic" in Figure 2 are blowout, operational error, equipment failure, extreme weather and normal weather. In a more detailed analysis some or all of these events may be resolved into more basic events. The "feedback" loops indicated are not explicitly modeled, but are accounted for the development presented below.

For the sake of clarity inhibitor gates (i.e., conditional probabilities) are not shown in Figure 2, but they are assumed to exist between any two consecutive events. For example, a blowout (B) or an operational error (E) does not automatically lead to an explosion (X). The probability of explosion is

$$P[X] = P[X|B]\,P[B] + P[X|E]\,P[E] - P[X|BE]\,P[BE] \tag{1}$$

It is clear that there is dependence among the different failure paths owing to the repetition of the basic events in the various cut sets. Interaction between intermediate failure modes, as described above, is shown explicitly in the Figure at the level of F_L and F_R with the feedback loops. Depending on the location and extent of structural failure, major flooding may be initiated. Conversely, progressive flooding of watertight compartments may be the result of a series of structural collapses (see Pires et al. 2000).

The interaction of structural and non-structural failures as discussed above may also be illustrated with the help of the system failure probability, P_f:

$$\begin{aligned} P_f &= P\left[F_S(F_R \cup F_L)\right] \\ &= P\left[F_S(F_R\overline{F_L} \cup F_R F_L \cup \overline{F_R}F_L)\right] \\ &= P\left[F_S F_R \overline{F_L}\right] + P\left[F_S F_R F_L\right] + P\left[F_S \overline{F_R} F_L\right] \end{aligned} \tag{2}$$

where the three events within square brackets are all disjoint. Using conditional probabilities P_f can be further expanded to

$$\begin{aligned} P_f = {} & P\left[F_S \mid F_R\overline{F_L}\right] P\left[F_R \mid \overline{F_L}\right] P\left[\overline{F_L}\right] \\ & + P\left[F_S \mid F_R F_L\right] P\left[F_R F_L\right] \\ & + P\left[F_S \mid \overline{F_R} F_L\right] P\left[F_L \mid \overline{F_R}\right] P\left[\overline{F_R}\right] \end{aligned} \tag{3}$$

Using the reasonable assumptions that F_L and F_R are low-probability events (i.e., $P\left[\overline{F_L}\right] \approx P\left[\overline{F_R}\right] \approx 1$), some terms can be eliminated from above:

$$\begin{aligned} P_f \approx {} & P\left[F_S \mid F_R\overline{F_L}\right] P\left[F_R \mid \overline{F_L}\right] \\ & + P\left[F_S \mid F_R F_L\right] P\left[F_R F_L\right] \\ & + P\left[F_S \mid \overline{F_R} F_L\right] P\left[F_L \mid \overline{F_R}\right] \end{aligned} \tag{4}$$

Let us consider the three terms in right-hand side of the above equation one at a time. The first term gives the system failure probability as a result of structural failure in the absence of any flooding (i.e., without considering any non-structural failure). This in fact is the result from a purely structural reliability analysis. The third term gives the system failure

probability on account of flooding damage (i.e., non-structural damage) when gross structural failure is not considered. This is the output of a damaged stability analysis. The middle term, however, deals explicitly with the interaction of structural and non-structural failures. It is of course more difficult to estimate this interaction effect, and is usually ignored. The numerical exercise in the following sub-section demonstrates the relative importance of the three terms.

Interaction of Structural and Non-Structural Failures

The probability of failure of the system accounting for purely structural, purely non-structural failures and also interactions involving the two is expressed by Eq (2). This model is explored using representative failure data.

All numerical probabilities in this subsection are in terms of "per rig-year". Preliminary analysis of failure data (all taken from Spouge 1999) suggest that:

(i) The "average frequency of significant structural damage" to semisubmersibles in the North Sea is $2.1\text{x}10^{-2}$ per rig-year. It is reasonable to assume that structural damage in this case does not preclude flooding of vital spaces. Hence for the purpose of this numerical exercise,

$$P[F_R] = 2.1\times10^{-2} \tag{5}$$

(ii) The theoretical failure frequency of semisubmersibles due to structural failures alone is approximately 10^{-5} per year. Hence for the purpose of this exercise,

$$P[F_S F_R \overline{F_L}] = 10^{-5} \tag{6}$$

(iii) The ballast system failure frequency resulting from human error and involving one tank is $7.0\text{x}10^{-4}$ and that involving two tanks is $1.3\text{x}10^{-5}$. It is reasonable to assume that these scenarios do not arise from structural failures, and hence for the purpose of this exercise,

$$P[F_L \overline{F_R}] = 7.1\times10^{-4} \tag{7}$$

(iv) Given ballast system failure, the deck failure probability is 0.1. Hence for the purpose of this exercise,

$$P[F_R \mid F_L] = 0.1 \tag{8}$$

(v) Finally, the capsize frequency as a result of ballast failure is $5.9\text{x}10^{-5}$. Hence, for the purpose of this exercise,

$$P[F_S \overline{F_R} F_L] = 5.9\times10^{-5} \tag{9}$$

The following results are derived from the above numerical values:

$$P[F_R \cup F_L] = P[F_R] + P[\overline{F_R} F_L] = 2.17\times10^{-2} \tag{10}$$

$$P[F_L] = P[F_L \overline{F_R}] / P[\overline{F_R} \mid F_L] = 7.9\times10^{-4} \tag{11}$$

$$\begin{aligned} P[F_R F_L] &= P[F_R] + P[F_L] - P[F_R \cup F_L] \\ &= 9.0\times10^{-5} \end{aligned} \tag{12}$$

Hence, the total system failure probability can be given using Eq (2) as:

$$\begin{aligned} P_f &= P\left[F_S F_R \overline{F_L}\right] + P\left[F_S F_R F_L\right] + P\left[F_S \overline{F_R} F_L\right] \\ &= 10^{-5} + P\left[F_S \mid F_R F_L\right] P\left[F_R F_L\right] + 5.9\times10^{-5} \\ &= 6.9\times10^{-5} + 9.0\times10^{-5} P\left[F_S \mid F_R F_L\right] \end{aligned} \tag{13}$$

The only unknown in Eq (13) is $P[F_S \mid F_R F_L]$. Without additional information, the bounds on P_f are wide:

$$6.9\times10^{-5} \le P_f \le 1.6\times10^{-4} \tag{14}$$

Thus, it may be insufficient to perform a purely structural reliability analysis, and/or a pure stability analysis. In some situations at least, it may be of critical importance to model system behavior under combined structural failure and flooding, and hence to estimate the failure probability when the two modes interact.

Discussion

The result represented by Eq (14) suggests that the probability of failure of the system cannot be known accurately without explicit consideration of interactive effects. The type of data required to characterize the middle term of Eq (4) is not generally available.

Accident data, upon which the numerical values used in the exercise in the subsection above are based, may not be a useful source. Accidents involving ultimate system failure are fortunately very rare. Hence, for the purpose of quantifying overall risk of system loss, numbers based on actuarial data may not be sufficiently accurate, i.e. they have wide confidence limits.

Instead, analytical modeling of the system, with the purpose of estimating the terms in Eq (4), is likely to be more fruitful. A set of fault tree analyses of smaller (or local) susbsystems, that include structural and non-structural interactions, may be performed for this purpose. Top event probabilities from these smaller fault trees may be evaluated using actuarial data. Actuarial data on the elements of these smaller fault trees is likely to be more readily available and statistically stable.

CONCLUDING REMARKS

The origins and the application of risk principles in assessing the safety of offshore installations are reviewed. The parallel development of structural reliability analysis was also reviewed. While the underlying principles of both QRA and SRA are essentially the same, the way in which they have been formulated for use in practice has been quite different; this is clearly because of the differing scope of each and a reflection of the industries in which they were developed.

The limitations of SRA as commonly applied, in the context of the problem considered in this study, are summarized. Principal among these are the reliance on element-level checks to infer adequacy at the system level, and the lack of techniques for incorporating non-structural failure modes.

The case is made that for certain complex facilities, floating offshore installations for example, in addition to considering both structural and non-structural failure modes, it is critical that their interaction is also considered. The semisubmersible form is used as a vehicle to illustrate the concepts and methodologies described in this paper. The types of hazard this form faces in the offshore oil industry are described. Also described is how these hazards, if realized, can lead to failures involving several modes, which may be both structural and non-structural. Some examples of semisubmersible failures are provided to illustrate the issues raised in the paper. While the focus of this paper is on the semisubmersible form as employed in the offshore oil industry, many of the issues are relevant to the semisubmersible form used for other applications. Indeed, much of the discussion applies to other forms of floating structures as well.

A high-level fault tree is presented to demonstrate the complexity of the failure mechanisms that combine to lead to system failure. The fault tree as presented differs from traditional fault trees in that interactions, often ignored to make the problem tractable, are shown. Nevertheless, the fault tree is useful for subsequent development of an algebraic representation of system behavior. Using actuarial data a case is made for the importance of considering interaction between structural and non-structural failure modes. To develop this line of argument further it is necessary to establish probability data on failures involving interactions. Fault tree analyses of the relevant subsystems are suggested as a more likely source for probability data, rather than actuarial data. The latter source of data is considered unreliable because the events are very rare.

The limited study presented above shows that it is possible to develop a rigorous approach to investigate complex system failures involving structural and non-structural failures. However, to develop such an approach so that it can be applied in a comprehensive and complete manner requires the development of certain sub-models of structural behavior, reanalysis of existing data, and perhaps the gathering of other data.

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