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Safety assessment of offshore structure

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ABSTRACT: Reliability of a system is the probability that it will function as intended for the required period of time. The opposite of reliability is failure probability per unit time or over time, such as a life cycle. Following a review of existing reliability codes and approaches, comprehensive approaches to assess the reliability of offshore structures are described, including probabilistic analysis by employing fault tree model.

Keywords: *Fault Tree; ISO; Offshore Structure; Reliability*

INTRODUCTION

Reliability of an offshore structure is its ability to function as intended for a specific period of time. For offshore structures, functions include protection of life and the environment, ability to produce an economic return. In this paper, only reliability in terms of life and environmental safety is considered. Productivity and economic considerations are variable from owner to owner, and in general do not constitute part of a regulatory regime as do life and environmental safety. Recent catastrophic failures of the Alexander Kielland (1980), P-36 (2001), and the Ocean Ranger (1985) illustrate life safety failures or lapses in reliability. Piper Alpha (Fig. 1) was destroyed by a natural gas fire. P-36 failed as a result of loss of the buoyancy control system, in a manner essentially similar to the failure of the Ocean Ranger caused by a buoyancy control system failure. The Alexander Kielland failed due to fatigue induced structural failure. The four offshore tragedies cited were caused by significantly different causes; buoyancy failure, control system, fire, and fatigue structural failure. Indeed, in terms of reliability, if reliability criteria are restricted to structural failure causes such as overloading or fatigue failures, only a restricted aspect of reliability will be considered. Although the citation of the above four offshore catastrophe causes is by no means a statistical analysis, it does show that failures of offshore installations can be attributed to causes other than strictly structural failure. Three out of the four disasters were not caused by structural failures. Hence, in assuring the reliability of offshore structures, for installations, it is essential that all failure causes be considered in order to assure adequate reliability in terms of both life and environmental protection. These causes should not be restricted to load resistance interactions, as many codes do, but rather, must consider both accidental actions which are often considered to be the domain of quantitative risk analysis (QRA), as well as load resistance actions. And similarly, the load resistance reliability measures should not be restricted to setting limits for only a single load combination, but rather must integrate the total failure probability attributable to all credible load combinations. In this paper, following this introduction, objectives of offshore structural reliability analysis are generally discussed, definitions which will be used throughout this paper are presented, a survey of representative codes and approaches is reported, and an optimal approach for offshore structural reliability assessment is given, followed by conclusions and recommendations.

Fig. 1: piper alpha disaster (1989)

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MATERIALS AND METHODS

The objectives of reliability regulation

The objective of reliability regulation is to provide adequate protection for life and environment from the operation of an offshore structure servicing an offshore activity. Clearly, reliability generally also includes its productivity, economic feasibility, project integrity – but these are issues which each individual operator must tackle using their own criteria for adequacy. Life and environmental safety, however, is a public concern, and as such, generally falls into the domain of regulators having jurisdiction. Thus, in the context of this paper, adequate reliability means adequate protection for life and environment as a result of the operation of an offshore structure. Because it is the structure itself that is the subject of reliability, as discussed herein, environmental and personal safety hazards such as pathogenic events or intentional effluents – which do not impair the integrity of the structure but rather cause environmental damage – are not included. All causes of structural failure, including overloads, fatigue, fires and explosions, collisions with objects, losses of buoyancy, and any other credible causes, are included.

Definitions for offshore structural reliability

The following definitions are provided as a basis for the discussion of structural reliability in the balance of this paper:

§ *Reliability* – The probability that a process or system will function as intended for a given period of time.

§ *Failure Probability* – The probability that a system or process will cease to function as intended within a given period of time.

§ *Catastrophic Failure* – An event that results in a structure losing its capability to function as intended, and requiring immediate emergency evacuation of any personnel and/or containment of emissions and effluents to avoid significant environmental damage.

§ *Local Failure* – An event causing localized damage, which has the potential for escalating to catastrophic failure.

§ *Environmental Damage* – Damage to the environment, including biota, water, atmosphere, and earth.

§ *Casualty* – A human fatality or severe injury resulting in irreversible health effects.

§ *Life Safety Targets* – Generally expressed as annual probabilities of casualty, or individual risk targets, these targets indicate the maximum tolerable annual casualty probability for specified classes of individuals

§ *Environmental Safety Target* – Generally expressed as maximum tolerable probabilities of significant environmental damage. For example, an environmental safety target could be a maximum probability of 1 in 1 million per year of the spillage of 1,000 bbl or more of crude oil.

Survey of representative codes and approaches to offshore reliability

Table 1 summarizes the results of a survey of representative codes and approaches, including national and international codes both in the developmental and promulgated state. The commentary in the table is done in the context of the stated objectives of structural reliability requirements, to protect people and environment from all causes of structural failure. It should be noted that this commentary is focused on this subject, so that indicated limitations do not necessarily invalidate the codes discussed; the codes or regulations serve a useful purpose as guidelines for designers and provide much useful information which implicitly results in safer and better structures.

ISO 1990-2: Fixed steel offshore structures

This ISO Standard for fixed steel offshore structures proscribes a limit state design approach for specific return periods for any of the possible individual load combinations. It describes a variety of safety classes and consequence potential categories. However, neither individual load nor total reliability targets due to the probabilistic sum of loads are required. ISO 19902 is an example of a useful design guide for fixed steel offshore structures, but does not provide for adequate reliability to protect life and the environment.

ISO CD/1990-6: Offshore structures

ISO 1990-6 goes further than ISO 1990-2 by not only providing design guidance and load return periods, but also reliability targets for individual load combinations. These reliability targets are shown in Table 2, for individual load combinations. In addition, the ISO 1990-6 provides an optional design check using an integrated reliability approach, with integrated reliability targets as shown in Table 3.

Table 1: Offshore structures reliability codes and standard

Code	**Title**	**Approach**	**Classes**	**Comment on classes**	**Quantitative targets**	**Target rationale**	**Status**	**Comment**
ISO 1990-2	Fixed steel offshore structures	Required limit state design approach with prescribed load return periods for individual load combinations	Class 1,2,3 on safety, category 1,2,3 on consequence potential	Descriptor not quantitatively defined, hence subjective.	None	N/A	Mandatory	Design guidance only
ISO CD/ 1990-6	Arctic offshore structure	Required limit state design approach with prescribed load return.	Class 1,2,3 on safety, category 1,2,3 on consequence potential	Descriptor not quantitatively defined, hence subjective.	See table 2 and 3	None	Mandatory	Not limit on the number of loads
API RPS1-LFRD	Recommended Practice for Planning, Designing, and constructing Fixed Offshore Platforms-- Load and Resistance Factor Design	Design	Class 1,2,3 on safety, category 1,2,3 on consequence potential	Descriptor not quantitatively defined, hence subjective.	None	None	Mandatory	Useful design guide which does not assure adequate reliability
CSA S741	General requirements, design criteria, the environment, and loads (for offshore structures)	Individual rather than integrated Loads approach. Targets pertain to one load case with no limit on Number of load cases. Various Design approaches with prescribed load factors.	Class 1: Great risk to life and/or high environmental damage (unspecified quantities) Class 2: Low risk to life And low environmental damage potential.	Descriptors (e.g., high risk) not quantitatively Defined, hence subjective.	Class 1: 10-5/yr Class 2: 10-3/yr Serviceability : 10-1/yr	None	Mandatory	No limit on the number of loads; hence unrestricted reliability targets; Serviceability is not code issue.
JCSS-OSTL/ DIA	Joint Committee on Structural Safety, 2000, Probabilistic Model Code	Probabilistic design code which requires optimal reliability	Hierarchy of 3 safety classes combining severity consequence and 3levels cost of mitigation.	Unique categorization Involving mitigation cost.	Large cost, maximum consequence 10-4/yr	Optimization cost-risk benefit	Proposed	Fulfills all requirements performance based reliability standards in Context of life safety; excludes environment.

Table 2: Reliability targets for each limit state action combination

Life safety category	Consequence category	Maximum annual limit state probability
S1 Manned non-evacuated	C1	1.0*10^{-5}
	C2	1.0*10^{-5}
	C3	1.0*10^{-5}
S2 Manned evacuated	C1	1.0*10^{-5}
	C2	1.0*10^{-5}
	C3	1.0*10^{-4}
S3 Unmanned	C1	1.0*10^{-5}
	C2	1.0*10^{-4}
	C3	1.0*10^{-3}

Table 3: Integrated reliability targets – all causes

Life safety category	Consequence category	Maximum annual limit state probability
S1 Manned non-evacuated	C1	1.0*10^{-4}
	C2	1.0*10^{-4}
	C3	1.0*10^{-4}
S2 Manned evacuated	C1	1.0*10^{-4}
	C2	1.0*10^{-3}
	C3	1.0*10^{-3}
S3 Unmanned	C1	1.0*10^{-4}
	C2	1.0*10^{-3}
	C3	1.0*10^{-2}

It is intended that Section 7 assure "adequate reliability" through reliability targets (Tables 2 and 3) which assure compliance of the structure reliability with the project's life safety and environmental thresholds. Such thresholds are generally set by the project owner in consultation with regulator(s) having jurisdiction. A protocol setting out the connection between the reliability targets in Section 7, and life and environmental protection thresholds is needed for the standard to have general and practical applicability. For example if the life safety (individual specific risk) threshold is <=10^{-5} per year, the combined probabilistic resultant of the structure LS (all combinations), other structural failure probabilities (e.g., fire and explosion), and mitigation including emergency evacuation reliability, shall not exceed the value of the life safety target, in this example, 10^{-5} per year. Similar reasoning would apply to environmental safety targets. This protocol will also force the designers to consider the quantification of their life safety (EER) system reliability as well as that of any environmental protection measures (e.g., SSSV's, shut-in and disconnect). In addition, if such issues as those associated with a catastrophic event more frequent than that prescribed in the current standard is under consideration (such as an earthquake or ice island), the protocol would also accommodate this while assuring adequate safety. It can be concluded that Section 7 of ISO 1990-6 does not assure "adequate reliability" of the structure in the context of life and environmental safety targets. In fact, in some cases, it may result in excessive reliability, which is also not "adequate" and could result in great over-expenditures.

API RP2A-LRFD: Fixed offshore platforms

Although various publications refer to this code as one which provides significant guidance on reliability, such guidance is restricted to qualitative guidance, without the specification of any particular reliability targets. It again provides various safety classes and categories, but predicates use of only the most stringent ones, while ignoring others which may also be relevant. The descriptors of the safety classes are not quantitative and hence will be subjectively interpreted. The standard provides useful design guidance, but does no assure adequate reliability as defined in this paper.

CSA S741: General requirements for offshore structures

This Canadian standard again provides a design guide with recommended load factors for different individual load combinations. It predicates two design classes: Class 1 which is associated with "great risk to life and or high environmental damage", and Class 2 which is associated with "low risk to life and low environmental damage". Again, descriptors of these classes are not quantitative, and hence must be subjectively interpreted. Quantitative targets are provided for reliability, as follows:

§ Class 1: 10^{-5} per year
§ Class 2: 10^{-3}per year
§ Serviceability: 10^{-1} per year

No rationale is provided for these targets, other than industry experience. This suggests that the targets are simply *status quo*, rather than ones which will assure what is generally considered to be adequate life and environmental safety. In addition, as suggested in the introduction to this paper, issues such as serviceability should not be included in codes, as they are strictly the domain of each individual operator. Therefore, although this code does not provide sufficient guidance to assure adequate reliability, it exceeds what the authors would consider its domain by specifying serviceability targets.

JCSS-OSTL/DIA: Probabilistic model code

The probabilistic design code developed by the Joint Committee on Structural Safety (JCSS), 2000, provides a novel approach to reliability optimization. It gives a hierarchy of three safety classes, involving low to high life safety consequences, and three levels of cost of mitigation measures. This unique concept of providing consideration of the costs of mitigation measures, as well as magnitude of consequences, is a positive step towards risk cost-benefit optimization. The standard generally applies to all causes of potential casualties, so it fulfills the general requirements of performance-based reliability standards in regard to public safety. Although it suggests use of a quantitative method, it does not provide quantitative targets, but rather well defined qualitative performance targets. Its primary shortcoming is that it excludes consideration of environmental protection.

RESULTS AND DISCUSSION

Integrated reliability approach

The integrated reliability of a structure means the structure's reliability for a particular failure type, considering all possible failure modes and causes, including the effects from environmental, operational or accidental demands, or their combinations thereof. Thus, a catastrophic failure type would consider all failure modes and causes, including those responsible for the P-36, Piper Alpha, and Alexander Kiellandtragedies. Thus, what is needed is a general method for the probabilistic summation or the integration of the failure probabilities for all credible failure causes and their combinations. Reliability targets are the maximum failure probabilities considering the probabilistic combination of all credible failure cause probabilities and their combinations including environmental, operational, or accidental cause probabilities.

Failure probability for each failure mode

The failure probability for a given failure mode is either a function of both the load or action, and the capacity or resistance, or an independent function of an event which causes that failure mode. In the first case (as graphically shown in Fig. 2 from Modarres *et al*., 1999), following the completion of the design calculations, evaluation of the failure probability's probability density (PD) or the pure probability density (PPD) given the load and resistance PD's can be done analytically using well known techniques such as a Warner diagram, or numerically using Monte Carlo simulation. In the second case, for direct event failure causes such as explosions, ignited gas blowouts, or sabotage the PPD is an independent function developed through accepted risk analytic techniques. In either case, the pure probability density (PPD) needs to be produced for each failure mode for each failure type for the structure. When estimating the reliability for a given facility failure type (e.g. Catastrophic), it is not necessary to include the load or other causal parameter magnitude; only the PPD for each Failure Mode occurrence is needed. The designers who generate the PPD for a particular failure cause or combination of load and resistance may quantify the component distributions, including their magnitudes, in a probabilistic manner for use in the design.

Integrated reliability assessment

Fault Tree Analysis (FTA) is an accepted approach for the evaluation of probabilities of events whose occurrence is a function of probabilities of numerous causal events.Consider the high-level fault tree (FT) for Failure Type X of a Specific Facility Type Y, as shown in Fig. 3. Then:

§ The facility can fail in any of ***N*** Failure Modes, e.g., sliding failure.

§ Each Failure Mode can be caused by any of ***M*** Failure Causes, e.g., iceberg impact.

Then, the PPD for the facility failure can be obtained by summing (using distribution algebra or Monte Carlo) all PPDs of the Failure Modes, which in turn are obtained by summing all PPDs of the Failure Causes. Minimal cut set methods shall be used to avoid causal duplication in the quantitative registration of causes in the FT calculation.

As a more specific illustration of the method, Fig. 4 shows a qualitative FT for a concrete GBS Facility Type for a Catastrophic Failure Type. It is the concrete GBS Designers that shall populate this FT (qualitatively and quantitatively), as well as any sub-FTs needed, and input the PPD for each base event for the lowest level causes used in the analysis. FT analysis methods (including minimal cut sets) will then be used in a Monte Carlo or analytical mode to obtain the catastrophic failure PPD. From this we can immediately tell the following:

§ The mean value of the failure probability.

§ The failure probability of exceedance at any confidence interval

The mean value of the failure probability and its variance shall then be registered against the relevant reliability target as discussed below.

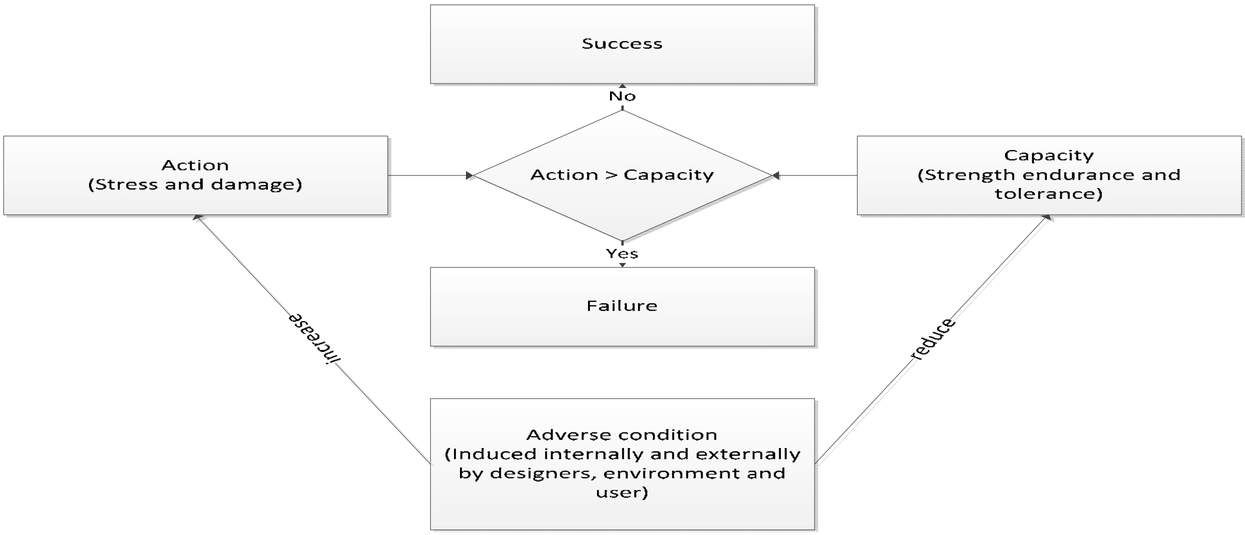

Fig. 2: Safety assessment modeling framework

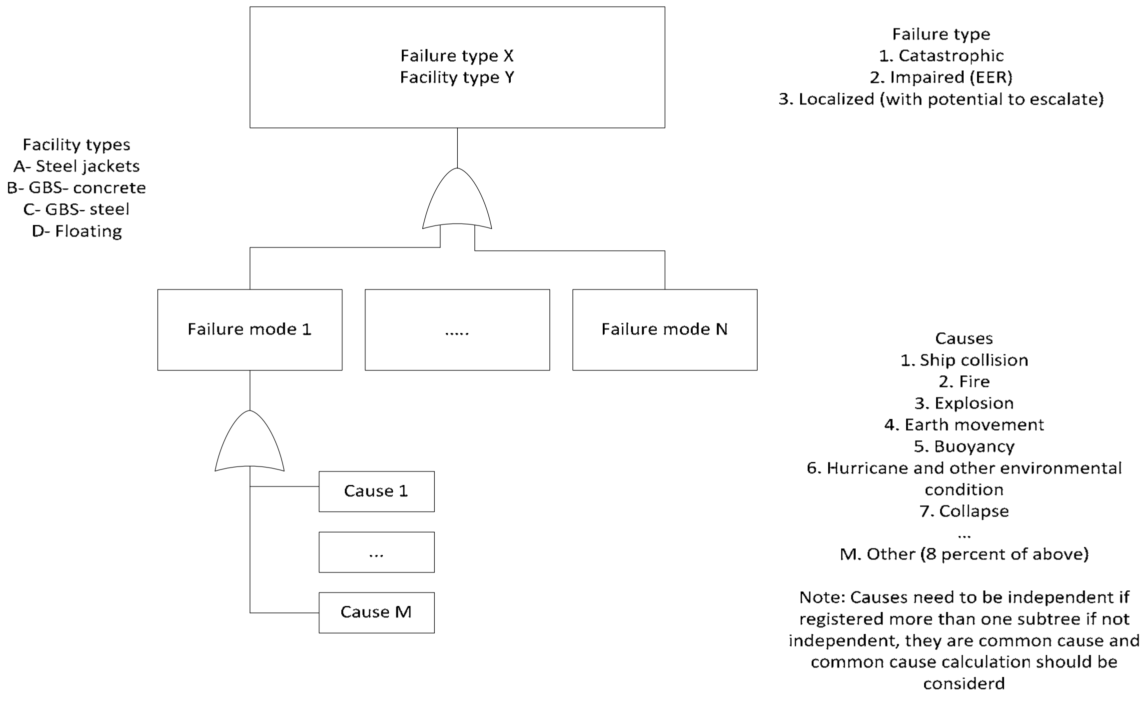

Fig. 3: Offshore structures generic fault tree

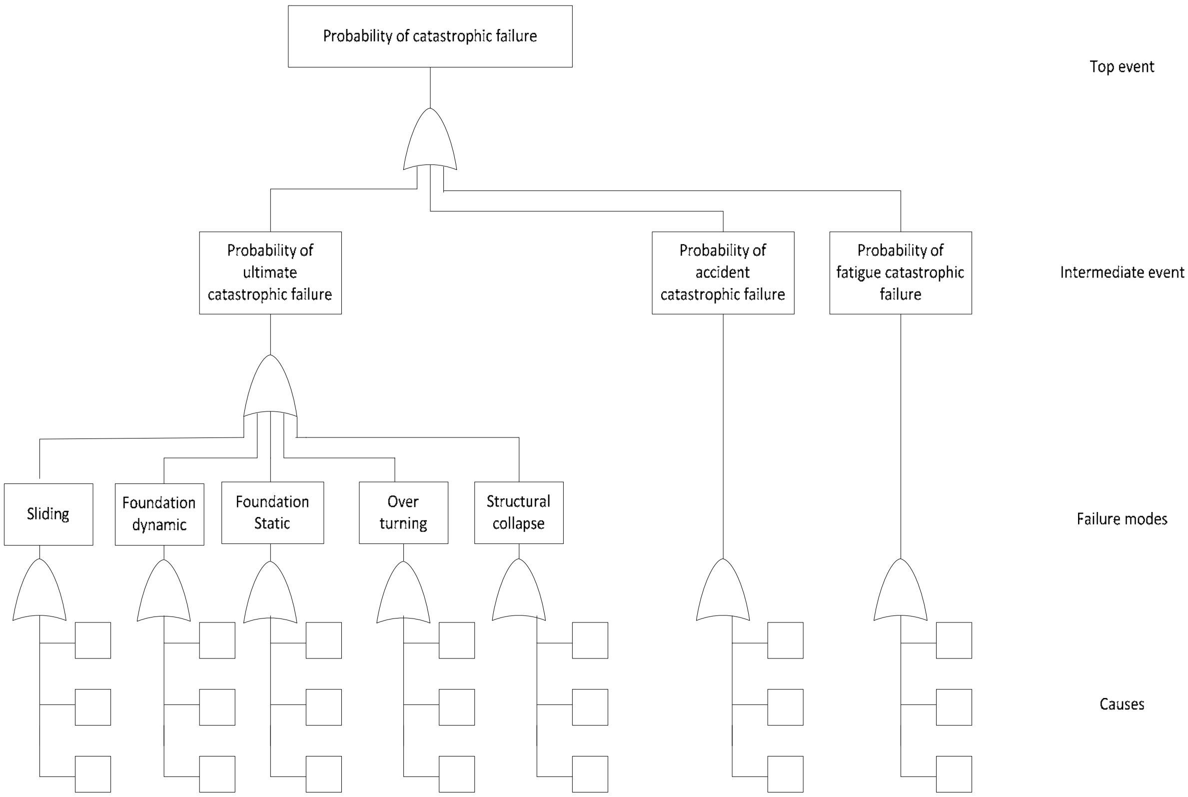

Fig. 4: Catastrophic failure fault tree

Safety Classes and Consequence Categories

As mentioned earlier, certain safety classes relating to the amount of personnel and environmental and asset exposure and consequence categories relating to themagnitude of the threat or hazard have been postulated in the ISO/CD 19902 Protocol (ISO, 2001b). These safety classes and consequence categories are summarized below.

Safety Classes are as follows (ISO/CD 1990-2):

§ S-1 = Manned – Non-evacuated

§ S-2 = Manned – Evacuated

§ S-3 = Unmanned.

Categories for consequences of failure (ISO/CD 1990-2) are as follows:

§ C-1 = High consequence of failure.

§ C-2 = Medium consequence of failure.

§ C-3 = Low consequence of failure.

Reliability targets

A Reliability Target is the minimum annual average reliability expressed as a maximum failure probability for a given Safety Class, Consequence Category, and Failure Type. Table 4 gives a set of integrated Reliability Targets in the form of maximum average annual failure probabilities for different combinations of Safety Class, Consequence Category, and Failure Type.

The probability of failure during the life of the structure can be estimated for any of the annual reliability targets by means of the following equation:

$P = 1 - (1 - p)^n$ (1)

Where:

§ P = Failure probability

§ p = Average annual or constant annual failure probability

§ n = Number of years in life cycle

Fig. 5 shows the life cycle maximum Catastrophic Failure probabilities for all safety classes and consequence categories for a range of life cycles from 1 to 100 years.

These Reliability Targets should be interpreted and used within the context of the Life and Environmental Safety Targets for a specific structure and operation. The Targets in Table 5 for the Catastrophic Failure type are predicated on an average per demand reliability of the escape, evacuation, and rescue (EER) system of 90% (Bercha *et al.,* 2004). EER failure is defined as the probability that one or more casualties will occur during an EER process. Thus, with an average EER on demand failure rate of 10%, the catastrophic failure rate of 1.0 E-4 translates into a casualty probability rate of 1.0 E-5. If the safety targets were to be more stringent, say at 1.0 E-6, the EER failure rate and/or the Reliability Targets would need to be adjusted, in this case to1.0E-5. It is their protocol that must be the central mandate of a code which assumes adequate reliability; currently, all codes – even ISO 1990-6 do not assure adequate life and environmental safety, as their reliability targets are not linked to life and environmental safety targets.

Table 4: Integrated reliability targets

Life safety category	**Consequence category**	**Failure type**	
		Catastrophic	**Local**
	C1	$1.0*10^{-4}$	$1.0*10^{-3}$
S1 Manned non-evacuated	C2	$1.0*10^{-4}$	$1.0*10^{-3}$
	C3	$1.0*10^{-4}$	$1.0*10^{-3}$
	C1	$1.0*10^{-4}$	$5.0*10^{-3}$
S2 Manned evacuated	C2	$1.0*10^{-3}$	$1.0*10^{-2}$
	C3	$1.0*10^{-3}$	$5.0*10^{-2}$
	C1	$1.0*10^{-3}$	$1.0*10^{-1}$
S3 Unmanned	C2	$1.0*10^{-2}$	$1.0*10^{-1}$
	C3	$1.0*10^{-1}$	$1.0*10^{-1}$

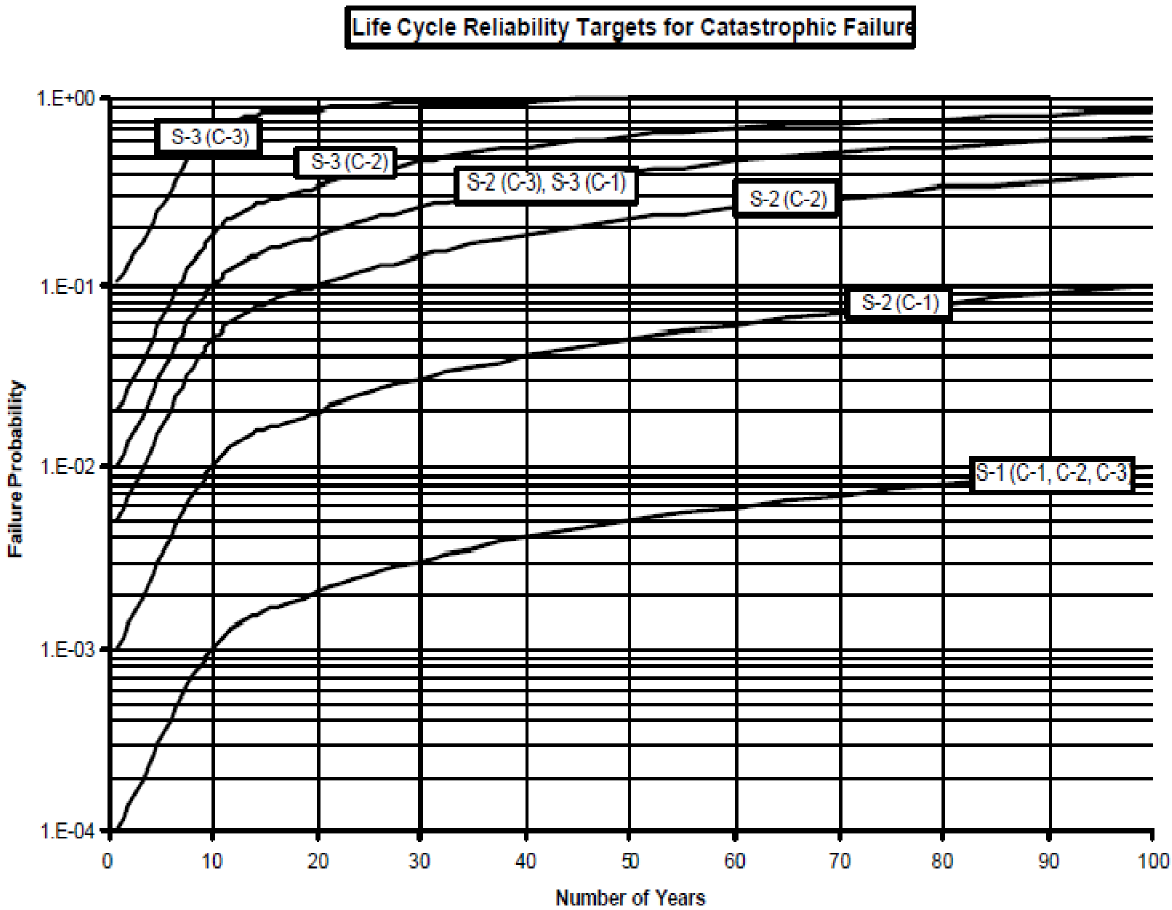

Fig. 5: Life cycle reliability target for catastrophic failure

CONCLUSION

Life threatening and fatality producing failures of offshore structures have occurred as a result of a wide range of failure causes, including fires and explosions, buoyancy losses, and structural overloads. Thus, a realistic value of the catastrophic failure probability, or its complement, the reliability, should consider all credible causes of failure. Current reliability requirements in codes and regulations in the context of offshore installations only consider a limited number of causes such as environmental loads. Reliability which considers all credible causes of failure is termed an Integrated Reliability. A general method for evaluating the integrated reliability of an installation is set out. The general methodology consists of the application of network methods such as fault trees to combine the probabilities of all factors that can cause a catastrophic failure, as well as those which can cause a local failure with the potential to escalate to a catastrophic failure. A protocol for setting credible reliability targets, including the consideration of Life Safety Targets and escape, evacuation, and rescue (EER) success probabilities is proposed. A set of realistic reliability targets for both catastrophic and local failures for representative safety and consequence categories associated with offshore installations is set out on the basis of a protocol linked to Life and Environmental Safety (LEST) Targets. The reliability targets are expressed as maximum average annual failure probabilities. The method for converting these annual figures into life cycle figures is also given.

Designers of offshore installations will require guidance on how to proceed with the standard design methods such as calibrated partial factors, limit state design, or probabilistic design, in a fashion which will enable them to link design values to reliability targets. Because many of the design methods recommended in the ISO 19906 series relate to partial load factors, future work in the reliability area should be directed at creating a framework that will provide an interface between design methods, reliability targets, and LEST. The following recommendations are provided:

1. That adequate reliability of the structure can be defined as one fulfilling generally accepted life and environmental safety thresholds (LEST). These LEST shall be set by the owner and regulator(s) having jurisdiction.
2. That both all load combinations and the integrated reliability, in combination with the planned life safety (EER) and environmental protection measures, be required to meet the LEST thresholds. Clearly, integrated reliability needs to be mandatory, rather than as an optional check.

REFERENCES

American Institute of Chemical Engineers (AICHE), (1999) .Chemical Process Quantitative Risk Analysis, or latest edition.

American Petroleum Institute (API), (1995). Recommended Practice for Planning, Designing, and Constructing Structures and Pipelines for Arctic Conditions. API Recommended Practice 2N, Second Edition,.

American Petroleum Institute (API), (1993). Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms –Load and Resistance Factor Design. API Recommended Practice2A-LRFD, First Edition, 1 July.

Bercha, F. G.; Radloff, E.; Abel, W., (2003). Development of Canadian Performance-Based EER Standards. Proceedings of the 13th International Offshore and Polar Engineering Conference (ISOPE), Honolulu, USA.

Bercha, F.G.; Cerovsek, M.; Abel, W., (2004). Reliability of Assessment of Arctic EER Systems. IAHR Symposium, St. Petersburg, Russia.

Canadian Standards Association (CSA), (2002). Reliability, Availability, and Maintainability (RAM) Definitions, CSA Standard Q361-97.

Canadian Standards Association (CSA), (2004).General Requirements, Design Criteria, the Environment, Loads, CSA Standard S471-04.

ISO, (2003). Petroleum and Natural Gas Industries Specific Requirements for Offshore Structures – Part 2: Seismic Design Procedures Criteria,ISO/DIS 19901-2,.

ISO, (2001a). Petroleum and Natural Gas Industries General Requirements for Offshore Structures, ISO/DIS 19900.

ISO, (2001b). Materials, Equipment, and Offshore Structures for Petroleum and Natural Gas Industries – Floating Offshore Structures Including Station Keeping, ISO/CD 19904.

ISO, (2000). Petroleum and Natural Gas Industries Arctic Offshore Structures, ISO/CD 19906, November, 2007.Joint Committee on Structural Safety (JCSS), ”Probabilistic ModelCode – Part 1 – Basis of Design”, 12th Draft, 10-11.

Modarres, M.; Kaminsky, M.; Krivtsov, V., (1999).Reliability Engineering and Risk Analysis – A Practical Guide. Marcel Dekker, Inc., New York.

Oil Rig Disasters, (2008). Piper alpha. Photo: 1. Thepiperalpha after the accident (photo sourced to:www.nrk.no), URL: http://home.versatel.nl/the_sims/rig/alk.htm,accessed April.

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