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# Developing target reliability for novel structures: the case of the Mobile Offshore Base☆

Baidurya Bhattacharya, Roger Basu*, Kai-tung Ma

*American Bureau of Shipping,16855 Northchase Drive, Houston, TX 77060-6008, USA*

**Abstract**

Reliability-based design criteria are usually calibrated to existing structures (of the same class) having a history of successful service. However, as the offshore industry continues to witness innovations, some novel structures clearly exceed the scope of existing design standards. A reliability-based design is attractive in such cases, but the calibration exercise is not feasible and target reliabilities need to be derived from more fundamental considerations. This paper describes a general risk-based methodology for identifying significant limit states and deriving corresponding target reliabilities for such novel structures. Reliabilities of various existing structures and available analytical methods for determining target reliabilities are reviewed. Careful consideration is given to failure consequences, both tangible and intangible, and reliabilities of intact as well as damaged structures are considered. The methodology is illustrated with the US Navy's Mobile Offshore Base concept, which is a unique offshore structure in terms of function and size, and for which no precedence or industry standard exists. © 2001 Elsevier Science Ltd. All rights reserved.

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## 1. Introduction

The objective of every structural design is to develop a structure that is able to perform its functions while meeting the constraints of safety and cost. A well-designed structure should be safe enough against every failure mode, but just so, if it has to be

☆The views expressed in this paper are those of the authors and not necessarily those of the American Bureau of Shipping.

* Corresponding author. Tel.: + 1-281-877-6608; fax: + 1-281-877-5931.
*E-mail address:* rbasu@eagle.org (R. Basu).


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economical as well. A reliability-based design can address the issue of safety in a transparent and quantitative manner. An important element in this process is the specification of maximum permissible probabilities of failure (or non-compliance) in all modes that are relevant to the given kind of structure.

The target reliability, which is the complement of the maximum permissible failure probability, should depend foremost on the consequence of the type of failure in question. Possible failure consequences are injury or loss of life, direct and indirect economic losses (including repair/replacement costs, loss of revenue, compensation for damages, etc.), environmental pollution and so on. Consequences should be measurable, and all relevant consequences should be included in the analysis. One may choose to discount future consequences to their present values, and it has been argued [1] that future loss of lives be discounted as well. Target reliabilities should also depend on the method of reliability analysis, types of uncertainties included in the analysis and on future maintenance strategies (e.g., [2]).

The question, "How safe is safe enough?", needs to be asked when setting the reliability target for a structure. Conventional structures that have a history of successful service, such as concrete buildings, highway bridges and steel vessels, can be deemed sufficiently safe, and their reliability levels (determined by analyzing representative structures) may be used as the targets for new structures of the same kind. This, in principle, is done when a new reliability-based code is developed for a given class of structures having a successful history of use [3]. The objective of the new code development is to produce more uniform levels of safety and more optimal structures.

### 1.1. The case of novel structures

Calibration of the above sort, however, is difficult or even impossible, if the structure is novel with no history of use, or has unusual failure consequences, or if the pace of innovation in the industry is relatively fast. The offshore industry is continuing to witness innovations in structural concepts and designs. Some of these new concepts clearly exceed the domain of applicability of existing codes and structures. The rational decision for such structures is to adopt a reliability-based design (e.g., [4]). A reliability-based approach also allows comparison of different competing designs on a common basis.

The target reliability (and partial safety factors if an LRFD format is used) required in the reliability-based design of such novel structures therefore needs to be derived from less direct, but more rational and, ideally, more fundamental, considerations. This paper presents a general methodology for establishing target reliabilities for non-generic structures or structures with unusual failure consequences, that is, in situations where calibration is infeasible or insufficient. The methodology is illustrated with the US Navy's Mobile Offshore Base concept (MOB, described in Section 1.2), which is a unique offshore structure in terms of function and size, and for which no precedence or industry standard exists.

A representative set of reliabilities in various existing codes and structures and expert recommendations for target reliabilities are first summarized (Section 2), following which some of the available analytical methods for deriving target reliabilities are listed (Section 3). In Section 4, we demonstrate how target reliabilities for different limit states and failure consequences are derived.

### *1.2. The Mobile Offshore Base*

The Mobile Offshore Base (MOB) is conceived as a self-propelled floating naval base that can provide a mile-long flat horizontal runway for air operations in the open oceans. It is intended to combine many of the attributes of aircraft carriers, troop transport and cargo vessels [5]. The MOB will be a unique marine structure in terms of both function and size. Several innovative design concepts have been proposed for MOB. These concepts variously consist of three to six self-propelled semi-submersible-type modules (also called SBUs for single base units) connected in series. Concepts for the inter-module connectors range from rigid, hinged or flexible bridge-type physical devices to purely functional connectors where relative positions of the SBUs are maintained by dynamic positioning. There is no precedence, no validated design capability, no fabrication or operational experience, and no industry standard for a marine structure as large as MOB.

The American Bureau of Shipping (ABS) is developing a reliability-based Classification Guide for MOB [6] applicable to the range of concepts mentioned above. A rigorous process is being followed for identifying all significant limit states and for establishing corresponding target reliabilities. Careful consideration is given to failure consequences, including loss of mission, lives and structure. The influence of socio-political factors like national prestige is also incorporated. This process has yielded target reliabilities presented in Section 4 of this paper. Studies are currently underway to establish the practical impact of these criteria on structural design, and it may be necessary as a consequence of this exercise to adjust target reliabilities such that the conflicting demands of performance, safety, economy and feasibility are met in a balanced fashion.

## 2. Existing reliability levels

This section compiles target reliability levels, explicit or implicit, in existing codes and structures. It should be noted that some cases listed here report annual target reliability, and others report life-time target reliability. One should also note, while comparing these values, that "failure" may be defined differently (e.g., yield or plastic collapse) and certain uncertainties (especially Type II uncertainties) may have been neglected in the analyses of some of the codes and projects summarized here.

The terms "reliability" and "failure probability" both are used in this paper. The relation between reliability ($L$) and failure probability ($P_f$) is

$$L = 1 - P_f. \tag{1}$$

Reliability can also be expressed in terms of the generalized reliability index, $\beta$:

$$\beta = \Phi^{-1}(1 - P_f), \tag{2}$$

Table 1
$P_f$ and generalized reliability index, $\beta$

| $P_f$ | $10^{-1}$ | $10^{-2}$ | $10^{-3}$ | $10^{-4}$ | $10^{-5}$ | $10^{-6}$ | $10^{-7}$ | $10^{-8}$ |
|---|---|---|---|---|---|---|---|---|
| $\beta$ | 1.28 | 2.32 | 3.09 | 3.71 | 4.25 | 4.75 | 5.20 | 5.60 |

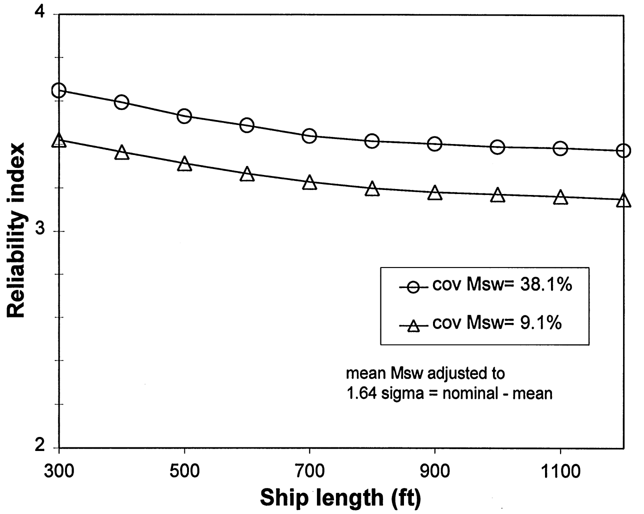


Fig. 1. Reliability index implied in ABS Steel Vessel Rules.

where $\Phi$ is the normal distribution function. For convenience, relation between the two is listed in Table 1.

### *2.1. Reliability levels in existing rules/standards*

#### *2.1.1. ABS rules for ship structures*

Mansour [7] calculated the reliability index for existing ships designed to ABS rules. The limit state was of hull girder bending against still-water ($M_{\text{sw}}$) and wave-induce bending moments. It is found that the life-time reliability indices implied in ABS rules range from 3.15 to 3.65 (Fig. 1).

#### *2.1.2. API codes for offshore structures*

The average annual failure probability in API RP 2A LRFD code has been estimated as $4 \times 10^{-4}$ [8]. See also Sections 2.2.2 and 2.2.4.

#### *2.1.3. CSA codes for offshore structures*

The Canadian Standards Association [9] defines two safety classes and one serviceability class for the verification of the safety of the structure or any of its structural elements (Table 2).

Table 2
CSA's annual targer $P_f$ [9]

| Safety class | Consequence of failure | Annual target $P_f$ |
|---|---|---|
| Safety class 1 | Great risk to life or high potential for environmental pollution or damage | $10^{-5}$ |
| Safety class 2 | Small risk to life or low potential for environmental pollution or damage | $10^{-3}$ |
| Serviceability | Impaired function and none of the above | $10^{-1}$ |

Table 3
DNV's annual target reliability [10]

| Type of structural failure | Less serious consequence | Serious consequence |
|---|---|---|
| I — Redundant structure | $10^{-3}$ | $10^{-4}$ |
| II — Significant warning before the occurrence of failure in a non-redundant structure | $10^{-4}$ | $10^{-5}$ |
| III — No warning before the occurrence of failure in a non-redundant structure | $10^{-5}$ | $10^{-6}$ |

*2.1.4. DNV rules for offshore structures*

DNV suggests that minimum values of target reliabilities should be calibrated against well-established cases that are known to have adequate safety [10]. If, however, it is not possible to establish target reliability by calibration against similar structures, then the minimum target reliability values may be based upon accepted decision analysis techniques, or taken in accordance with Table 3.

*2.1.5. ISO principles on structural reliability*

The International Organization for Standardization [11] suggests that target reliability against structural collapse should primarily depend on the possibility of injury or fatality as a result of that collapse. Based on individual fatality, the maximum allowable annual $P_f$ is given by

$$P_f = P[\text{death}\backslash\text{failure}] \leqslant 10^{-6}/\text{yr}. \quad (3)$$

If a large number of people are at risk of being killed by structural collapse, the allowable annual $P_f$ is

$$P_f \leqslant AN^{-\alpha}/\text{yr}, \quad (4)$$

where $A$ and $\alpha$ are constants, and $N$ is the number of lives involved. Suggested values are $A = 0.01$ or 0.1, and $\alpha = 2$.

Table 4
Life-time $\beta$'s in structural standards [12]

| Standard | Remarks | $\beta$ |
|---|---|---|
| AISC LRFD 1984, ANSI A58.1 1982 | Gravity loads (dead, snow and live loads) | 3.0 |
| | Gravity + wind | 2.5 |
| | Gravity + earthquake | 1.75 |
| Canadian codes for steel, concrete buildings, bridges | 30 yr lifetime | 3.5 |
| Eurocode | Normal construction | 3.5 |
| Nordic Code (Denmark, Finland, Iceland, Norway and Sweden) | | 4.3 |

Table 5
Critical $\beta$'s for four ships in four limit states [15]

| Limit state | Cruiser 1 | Cruiser 2 | SL-7 | Tanker |
|---|---|---|---|---|
| Initial yield | 7.40 | 4.54 | 4.20 | 3.31 |
| Ultimate | 4.09 | 3.09 | 2.67 | 0.81 |
| Secondary | 3.75 | 1.73 | 2.11 | 0.04 |
| Tertiary | 3.71 | 2.39 | 3.58 | 2.30 |

#### 2.1.6. AISC and other structural codes

Target $\beta$ values implicit in various structural design codes are summarized in Table 4, taken from [12]. Note that these values correspond to component failure and not collapse of the structure.

The component (i.e., girder) target reliability implicit in the AASHTO LRFD bridge code [13] is $\beta = 3.5$ in the ultimate limit state [14]. See also Section 2.2.5.

### 2.2. Target or recommended reliabilities for existing structures

#### 2.2.1. Ship structures

Mansour et al. [15] analyzed the reliabilities of two military and two commercial vessels (Table 5). Two kinds of loading situations were considered: short term and long term. The failure modes were: (i) primary (initial yield), (ii) primary (ultimate strength), (iii) secondary (gross panel buckling in deck or bottom of ship), and (iv) tertiary (buckling of a single stiffened panel), each of which was applicable to hogging and sagging modes. Based on their analyses, survey and professional judgment, Mansour et al. [15] recommended a set of life-time target reliability levels for naval and commercial ship structures (Table 6).

#### 2.2.2. Jacket structures and jack-up rigs

The implicit reliability levels in two reliability-based codes — the API RP2A for fixed jackets and the SNAME T&R Bulletin 5-5A for jack-ups — were determined by

Table 6
Recommended life-time target $\beta$'s [15]

| Limit state | Commercial ships | Naval ships |
|---|---|---|
| Initial yield | 5.0 | 6.0 |
| Ultimate | 3.5 | 4.0 |
| Secondary | 2.5 | 3.0 |
| Tertiary | 2.0 | 2.5 |
| *Fatigue* | | |
| Minor | 1.0 | 1.5 |
| Significant | 2.5 | 3.0 |
| Severe | 3.0 | 3.5 |

Table 7
Recommended FPS target reliability [17]

| Unit | Failure probability |
|---|---|
| Monohulls | $10^{-5}$–$10^{-3}$ |
| *Semi-submersibles* | |
| Hulls | $10^{-4}$–$10^{-3}$ |
| Moorings | $2\times10^{-3}$–$10^{-2}$ |
| *TLPs* | |
| Hull | $10^{-4}$–$10^{-3}$ |
| Tethers | $10^{-5}$–$10^{-4}$ |

analyzing two representative structures (a jacket and a jack-up respectively in the UK sector of the North Sea) built to the two standards [16]. The $P_f$ of the jacket was found to be $5.9\times10^{-5}$ at the component level and $4.2\times10^{-6}$ at the system level. The corresponding values for the jack-up were $1.1\times10^{-3}$ for component and $4.5\times10^{-5}$ for the system.

### 2.2.3. *Floating production systems*

A specialist panel of the 13th ISSC [17] presented a set of recommended target system reliability levels for floating production systems which are listed in Table 7. These are based on expert opinions and judgments. Corresponding component reliabilities are about an order of magnitude higher.

### 2.2.4. *Miscellaneous floating structures*

Another specialist panel of the 13th ISSC [8] also compiled a set of reliabilities implicit in the design of various floating structural components and systems (Table 8).

### 2.2.5. *Bridge structures*

Nowak et al. [14] recommend a (life-time) target component reliability index of 3.5 and a target system reliability index of 5.5 in the ultimate limit states for bridge

Table 8
Annual $P_f$ in existing structures [8]

| Type of structure | Relevant code | Remarks | Annual $P_f$ |
|---|---|---|---|
| Production ship | "current codes" | In North Sea | $10^{-4}$ |
| | | In the tropics | $< 10^{-4}$ |
| Merchant vessels | "current codes" | In North Sea | $10^{-3}$ |
| *Floating platform hulls* | | | |
| Cylindrical shells | NPD/DNV, API RP2T | Normal distribution for wave load effects | $10^{-6}$–$10^{-4}$ |
| | | Lognormal distribution for wave load effects | $10^{-5}$–$5\times10^{-4}$ |
| Stiff. flat plates | NPD/DNV, API RP2T | | $10^{-5}$–$5\times10^{-4}$ |
| Stiff. panels | API RP2T, RCC/API Bul-2U | | $10^{-4}$ |
| Shell plates | API RP2T, RCC/API Bul-2U | | $10^{-3}$ |
| Stiff. shell bays | API RP2T, RCC/API Bul-2U | | $3\times10^{-4}$ |
| Fixed offshore structures | API RP2A LRFD | | $4\times10^{-4}$ |
| | CSA S471 | | $10^{-5}$–$10^{-4}$ |

structures. For serviceability limit states, they recommend a target component (i.e., girder) reliability index of 1.0 in tension and 3.0 in compression. Nowak et al. [14] also compute component reliabilities of different kinds of bridges (reinforced concrete, prestressed concrete and steel built to AASHTO 1992 and BS 5400 specifications) in bending, shear and serviceability limit states.

Ghosn and Moses [18] suggest the following reliability requirements to ensure adequate redundancy of a highway bridge structure:

$$\beta_u - \beta_1 \geqslant 0.85, \quad \beta_f - \beta_1 \geqslant 0.25, \quad \beta_d - \beta_1 \geqslant -2.7. \tag{5}$$

The subscripts $1, f, u$ and $d$ refer, respectively, to first member failure, functionality limit state, ultimate state and damaged condition limit state.

The design of the Confederation Bridge (Northumberland, Canada) required that load and resistance factors be calibrated to "a $\beta$ of 4.0 for ultimate limit states, for a 100 year life" [19]. Sarveswaran and Roberts [20] chose an acceptable annual failure probability of bridge collapse in UK equal to $2\times10^{-5}$ which corresponded to an FAR of 2 (FAR is discussed in Section 3.4.2).

### *2.2.6. Aircraft structures*

The international Civil Aviation Organization has set the maximum probability of collision with a stationary object during aircraft landing at $10^{-7}$ [21].

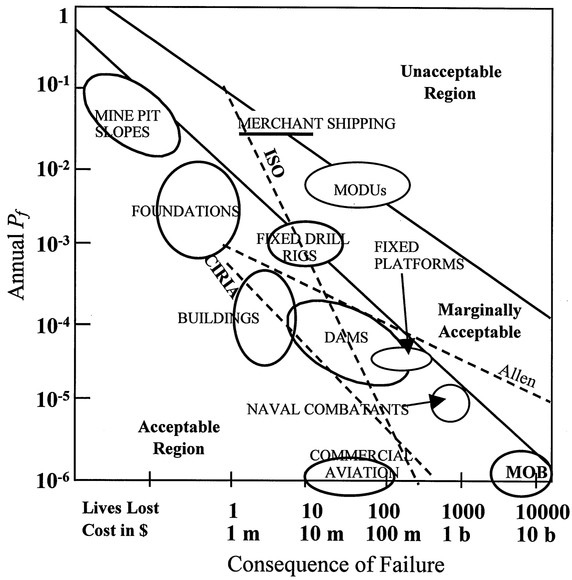


Fig. 2. Risk diagram (based on [22,23]).

## 3. Analytical methods

The techniques of evaluating risk and reliability continue to mature, and several methods are available for determining target reliabilities in a rational manner. Some of the methods are summarized in this section.

### 3.1. Risk-based approach

In a probabilistic context, risk from an undesirable event is defined as

$$\text{Risk} = pC, \tag{6}$$

where $C$ is the consequence of the event and $p$ is the probability (or likelihood) of occurrence of the event. Possible failure consequences are discussed in Section 1. Fig. 2, based on [22,23] and the survey presented in Section 2, describes the risk levels in different industries. The equivalence between lives lost and dollar costs should not be interpreted as absolute. The failure probabilities are based on historical rates of accidents. The consequences are based on monetary costs (actual costs, insurance payments and judicial awards) or fatalities that have been associated with failures. The two solid straight lines indicate acceptable and marginal combinations of likelihoods and consequences. The dashed straight lines represent ISO, CIRIA and Allen's formulas (discussed in Section 3.4) as identified in the figure.

Initial estimates suggest that the cost of an MOB is of the order of 10 billion US dollars. Assuming that the acceptable level of risk for an MOB is comparable to that shown in Fig. 2, the acceptable annual $P_f$ of an MOB is of the order of $10^{-6}$.

### 3.2. Life-cycle cost analysis

Target reliabilities can be chosen to minimize the expected total cost over the service life of the system. A simplified expression for the expected total cost, $E[C_T]$, is

$$E[C_T] = C_I + C_F P_f, \tag{7}$$

where $C_I$, and $C_F$ are, respectively, initial and failure costs. $C_I$ is generally an increasing function of the reliability index, $\beta$ (see, e.g., [24]). Recall that $\beta$ is related to $P_f$ through Eq. (2). $E[C_T]$ may be minimized with respect to $\beta$, with or without constraints as appropriate, yielding the target reliability index. Recent applications of this method, which include discounting of future costs, can be found in [25,26]. This is a versatile and attractive method. However, estimates of $C_I$ as a function of $\beta$ are not yet available for an MOB.

### 3.3. Experience and calibration

Design standards traditionally evolve with experience and judgment. Factors that affect this process include improved analysis tools, new materials, better insight into structural behavior, and, notably, serious accidents. Ronin Point, Alexander Keilland, Exxon Valdez and failures of bulk carriers over the last decade or so are examples of disasters resulting in enhancement of codes/rules. When new reliability-based design codes are developed, they take advantage of this knowledge-base through calibration and other checks. However, as mentioned in Section 1.1, this type of exercise is suitable for near-generic structures with sufficient history, and therefore inadequate for novel structures or structures with unusual failure consequences.

### 3.4. Social acceptance criteria involving fatalities

#### 3.4.1. Acceptable annual probabilities of failure

Society's general reaction to hazards of different levels [27] are listed in Table 9. If exposure to an activity is voluntary, the acceptable level of risk is generally higher. Various agencies and researchers have investigated levels of probability that are acceptable to society for events causing fatalities, as described in the following. The acceptable probabilities depend on the nature of the hazard, and decrease with increasing number of fatalities. However, it needs to be underlined that a society's sense of tolerable risk for a given activity may change with time.

In a CIRIA report [28], Flint developed an empirical formula for setting the annual target failure probability as

$$P_f = \frac{K_s}{n_r} p'/\text{yr}, \tag{8}$$

where $p'$ is the basic annual probability of death accepted by an individual member of society. According to this reference, a typical value in the UK is $10^{-4}$. $K_s$ is the social criterion factor. It accounts for the voluntary nature of hazardous activity (a person

Table 9
Society's general reaction to hazards [27]

| Probability | Society reaction |
|---|---|
| $10^{-3}$ | This level is unacceptable to everyone. When probability approaches this level, immediate action should be taken to reduce the hazard |
| $10^{-4}$ | People are willing to spend public money to control hazards at this level. Safety slogans popularized for accidents in this category show an element of fear (e.g., the life you save may be your own) |
| $10^{-5}$ | Though rare, people still recognize these hazards, warn children (e.g., drowning, poisoning). Some accept inconvenience to avoid such hazards (e.g., avoid air travel) |
| $10^{-6}$ | Not of great concern to the average person. People are aware of these hazards, but feel "it can never happen to me" — a sense of resignation if they do (e.g., an "act of God") |

Table 10
Typical values of activity and warning factors [29]

| Type of activity | $A$ |
|---|---|
| Post-disaster activities | 0.3 |
| *Normal activities* | |
| Buildings | 1.0 |
| Bridges | 3.0 |
| High-exposure structures (construction, offshore) | 10.0 |
| **Nature of warning** | $W$ |
| Fail-safe condition | 0.01 |
| Gradual failure | 0.1 |
| Some warning likely or gradual failure hidden from view | 0.3 |
| Sudden failure without previous warning | 1.0 |

may be willing to increase his exposure by a factor of $K_s$) and its typical value is 5. $n_r$ is the aversion factor defined as the number of lives involved. Public aversion to an accident is assumed to be directly proportional to the number of lives involved. However, other non-linear relations have also been proposed, as described in the following.

Allen [29] proposed a somewhat different formula for annual target failure probability that incorporated the nature of warning available for the impending failure:

$$P_f = \frac{A}{W\sqrt{n_r}} 10^{-5}/\text{yr}, \tag{9}$$

where $n_r$ is the aversion factor, $A$ the activity factor, and $W$ the warning factor. The factor $10^{-5}$ was ascertained from data on building collapse in Canada. The range of values for $A$ and $W$ is reproduced in Table 10. Note that Eq. (9) uses $\sqrt{n_r}$ rather than

$n_r$ in the denominator implying that the rate of growth in risk aversion decreases with the number of fatalities.

More recently, ISO [11] has tied the acceptable failure probability to the square of the number of lives involved (Eq. (4)), signifying perhaps a decrease in the public's sense of tolerable risk in engineered systems.

To set the target reliability for MOB from social acceptance criteria, assume there are 1000 personnel onboard. Flint's formula (Eq. (8)), using $K_s = 5$, yields an annual target failure probability of $5 \times 10^{-7}$. Alternately, Allen's formula (Eq. (9)), with $A = 10.0$ and $W = 0.1$, gives the annual target of $3.2 \times 10^{-5}$. At the other end of the spectrum, the ISO requirement (Eq. (4) with $A = 0.1$) yields the target of $10^{-7}$/yr. The three formulas are compared in Fig. 2. It should be noted here that military structures are expected to be governed by a different set of parameters $p', K_s, A, W$, etc. which, unfortunately, are unavailable for an MOB at this stage. Nevertheless, it is observed that there is a wide variability in the acceptable annual target reliabilities proposed by methods that consider fatalities alone.

### 3.4.2. Fatal accident rate

A somewhat different measure of hazardous activities that accounts for exposure time is the fatal accident rate (FAR). The FAR for an activity is the number of fatalities per 100 million hours of exposure to that activity (i.e., 1000 people working 2500 h a year and having working lives of 40 yr each):

$$\text{FAR} = 10^8 P[F]/T_h, \tag{10}$$

where $P[F]$ is probability of fatality, and $T_h$ is the exposure time in person-hours. Typical values of FAR in the UK [30] range from 5 (chemical processing industry) to 67 (construction industry). FARs for various activities in Japan are listed in [31] and these range from 0.2 for fires, 4.3 for railway travel to 46.3 for civil aviation. The present study, however, has not been able to locate acceptable FARs (or similar criteria) for military activities.

## 4. Developing target reliabilities

A general methodology for setting target reliabilities for all relevant limit states of a novel structure is presented in this section. The target system reliability is selected first. The component target reliabilities are then assigned on a uniform risk basis. The basic steps are (Fig. 3):

1. *Identify system failure consequence:* Clearly define the structural system and identify all system failure modes. Identify all consequences of total structural system failure, and express consequences in measurable quantities (dollars, lives, etc.). Note any unusual or intangible failure consequence. Define scope of reliability analysis including types of uncertainty to be included in the analysis.
2. *Select target system reliability:* Using a combination of analytical models, survey of existing codes and structures, socio-political considerations and basing on

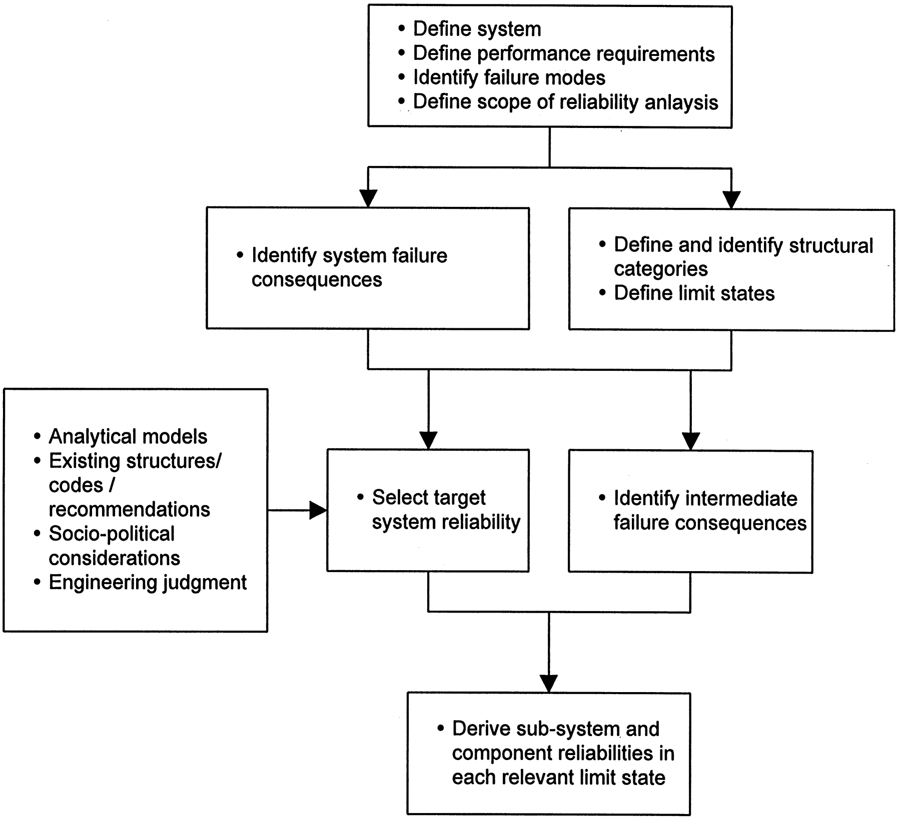


Fig. 3. Derivation of target reliability for novel structures.

engineering judgment, select the target reliability against total structural system failure.

3. *Define structural categories and limit states:* Depending on the size, type and function of the structural system, define structural sub-systems and components. Identify all sub-systems and components in the structure. Identify those structural components that are non-redundant. Identify all relevant limit states for the structural sub-systems and components.
4. *Define intermediate failure consequences:* Depending on the functional complexity of the system, define two or more levels of failure consequences — e.g., catastrophic (i.e., total system failure), serious and minor. It is suggested that successive consequences differ by one order of magnitude.
5. *Derive sub-system and component reliabilities:* Determine the consequence of failure (from step 4) of each structural category in all relevant limit states (from step 3). Based on the failure consequence of each structural category–limit state pair, assign corresponding target failure probability in inverse proportion to the system

target selected in step 2:

$$P_f^{i,j} = \frac{C_{\text{sys}}}{C_{i,j}} P_{f,\text{sys}}, \tag{11}$$

where $C_{\text{sys}}$ and $P_{f,\text{sys}}$ are, respectively, the consequence and target probability of system failure. $C_{i,j}$ and $P_f^{i,j}$are, respectively, the consequence and target probability of component (or sub-system) $i$ exceeding limit state $j$. Note that only ratios of consequences are required.

Application of this general methodology to an MOB structure is described in Sections 4.1–4.5. It is based on the material presented in Sections 2 and 3, as well as on the deliberations conducted over two years in the MOB Standards and Criteria Working Group formed as part of the MOB Science and Technology Program.

### *4.1. System failure*

The MOB is a mile-long ocean-going floating structure that is required to maintain an approximately straight and horizontal runway surface up to moderate sea states. The possible total system failure (i.e., global failure) modes of an MOB are: (i) sinking, (ii) capsizing, and (iii) loss of station-keeping.

It is important to note that for a floating structure, system failure may take place in a sequence of structural failures, flooding events or an inter-dependent combination of these. The cause of failure may be extreme environmental events, weapons effects or accidental explosions; or failure may simply be triggered by equipment failure (valves, hatches, etc.) or operational failures (e.g., loss of dynamic positioning).

The consequences of total failure of MOB structural system include:

1. *Loss of lives:* Up to 3000 troops [5] and a large crew can be onboard a fully operational MOB.
2. *Loss of mission:* The MOB will be a floating naval base required to conduct flight, maintenance, supply and other military support operations.
3. *Loss of morale and national prestige:* The MOB will be a high-visibility one-of-a-kind military asset.
4. *Loss of property and assets:* According to initial estimates, the cost of building MOB is of the order of 10 billion US dollars.
5. *Pollution:* The MOB is expected to carry liquid as well as solid cargo, some of which may be hazardous.

### *4.2. Target system reliability*

While determining the target system reliability for an MOB, it is noted that (i) there is no truly comparable floating structure (in terms of cost and complexity) that could provide a reliable benchmark, and (ii) there are "intangible" consequences of MOB failure (like mission failure and loss of national prestige) to which it is difficult to assign dollar or loss-of-life values. Nevertheless, an optimal target needs to be found so that a very high reliability does not come in the way of performance and efficiency.

Table 11
Comparative estimates of target $P_f$

| Source | Allowable system failure probability |
|---|---|
| Risk analysis (Section 3.1 and Fig. 2) | $10^{-6}$/yr |
| CSA — safety class 1 (Table 2) | $10^{-5}$/yr |
| DNV — serious consequence (Table 3) | $10^{-6}$–$10^{-5}$/yr |
| ISO — 1000 people | $10^{-7}$/yr |
| Professional recommendations — naval ships, ultimate strength (Tables 6 and 7) | $10^{-5}$ life time |
| Social criteria — 1000 people (Section 3.4) | $10^{-7}$–$10^{-5}$/yr |
| Existing structures (Section 2.2, Fig. 1, Tables 4, 7 and 8) | $10^{-7}$–$10^{-3}$/yr |

The following qualitative observations can be made about MOB reliability:

1. The MOB system reliability should exceed those of all commercial floating structures such as merchant ships, jacket platforms, jack-up rigs, etc.
2. The MOB system reliability should be greater than those of bridge and building structures, and MOB component reliabilities should be greater than those of bridge and building structure components.
3. The reliability of MOB should be greater than other naval vessels taking into account its (MOB's) value and strategic importance.

Table 11 lists various estimates based on which MOB target system reliability may be assigned. These include (i) reliability levels implicit in existing rules and standards as discussed in Section 2.1, (ii) computed reliabilities of existing structures and target reliabilities recommended by experts as discussed in Section 2.2, and (iii) analytical methods as discussed in Section 3.

Based on Table 11, a value of $10^{-7}$/yr may be proposed for MOB system $P_f$. However, Table 11 does not take into account intangible consequences of failure, and we therefore introduce, somewhat arbitrarily, a factor of two to account for such additional consequences. This factor may be modified as a result of a more rigorous analysis undertaken at the acquisition phase. The desired target annual $P_f$ that produces the same level of risk is then $5\times10^{-8}$. Based on a 40 yr life, the target life-time failure probability is $2\times10^{-6}$.

In general, let us denote the target life-time failure probability by $q^*$ (row 4b in Table 12). The consequence of the loss of one module is roughly an order of magnitude lower than that of the entire MOB, and the life-time target $P_f$ of one module is set at $10q^*$ (row 4a in Table 12).

The proposed life-time target $P_f$'s for all limit states and structural categories are presented in Table 12. The derivation is presented in Sections 4.3–4.5. The column of maximum permissible $P_f$'s pertains only to structural integrity and not to other systems such as dynamic positioning, etc. Unless otherwise noted, these are unconditional life-time probabilities.

Table 12
Proposed life-time target reliability levels (40 yr life)[a]

| Class of limit state | No. | Consequence | Scale of participating structure | Maximum permissible life-time $P_f$ |
|---|---|---|---|---|
| Serviceability/ operability | 1a | Minor | Structural element or assembly | $10^5 q^*$ |
| | 1b | Moderate | Structural sub-system or one module or fully connected MOB | $\min(10^4 q^*, 1 - A_1)$ |
| Fatigue | 2a | Minor | Structural element/assembly (redundant and accessible) | $10^5 q^*$ |
| | 2b | Moderate | Structural element/assembly (redundant but inaccessible) | $10^4 q^*$ |
| | 2c | Serious | Structural element/assembly (non-redundant) | $10^3 q^*$ |
| | 2d | Serious | Inter-module connector (redundant design) | $\min(10^3 q^*, 1 - A_2)$ |
| | 2e | Critical | Structural element/assembly (non-redundant) or sub-system | $10^2 q^*$ |
| | 2f | Critical | Inter-module connector (non-redundant design) | $\min(10^4 q^*, 1 - A_2)$ |
| Strength | 3a | Moderate | Structural element (redundant) | $10^4 q^*$ |
| | 3b | Serious | Structural element/assembly (redundant) | $10^3 q^*$ |
| | 3c | Serious | Inter-module connector (redundant design) | $\min(10^3 q^*, 1 - A_2)$ |
| | 3d | Critical | Structural element/assembly (non-redundant) or sub-system | $10^2 q^*$ |
| | 3e | Critical | Inter-module connector (non-redundant design) | $\min(10^2 q^*, 1 - A_2)$ |
| | 3f | Critical | Structural sub-system subject to weapons effect/accident of specified magnitudes | $10^4 q^*$ (conditional) |
| *Global failure/survivability* | | | | |
| (i) Progressive collapse | 4a | Catastrophic: loss of one module | One module | $10 q^*$ |
| | 4b | Catastrophic: loss of all modules | Fully connected MOB/all modules | $q^*$ |
| (ii) Damaged condition | 4c | Catastrophic: loss of one module | One module after loss of one subsystem | $10^5 q^*$ (conditional) |

[a] $q^*$ = life-time target failure probability of entire MOB, assumed less than $10^{-5}$; $A_1$ = minimum permissible availability of one module; $A_2$ = minimum permissible availability of connector.

MOB target reliabilities are specified as life-time targets (based on a 40 yr life), instead of annual targets that are sometimes provided for floating structures. Life-time targets are preferred as they implicitly take into account structural degradation due to operational and service conditions. This is particularly relevant in view of the MOB's maintainability options, namely, long time-intervals between scheduled maintenance, and lack of dry-docking during its entire life.

### 4.3. Structural categories and limit states

Current MOB concepts variously envision an MOB to be composed of 3–6 modules connected in series. Each of these modules, which typically have a semi-submersible form, is also capable of operating and transiting individually. Like any complex structural system, an MOB is composed of various structural subsystems, which in turn are composed of numerous structural elements and assemblies. Since target reliabilities are assigned based, among others, on scale of structural involvement, it is important to define these terms precisely:

1. *Structural element*: A structural element is the simplest structural unit, such as a tubular member, a longitudinal, a stiffener or a connection.
2. *Structural assembly:* A structural assembly is a collection of elements structurally connected, such as a stiffened plate panel or a bulkhead. Several structural elements constitute a structural assembly. An element or an assembly is also referred to as a *structural component.*
3. *Structural sub-system*: A sub-system refers to a major constituent of an SBU, such as deck, pontoon or column. Several structural elements and assemblies constitute a structural sub-system.
4. *Structural system:* The structural system refers to the entire MOB in its connected state, and to an individual SBU (module) when disconnected. Several structural sub-systems constitute the structural system.
5. *Connector:* Due to the uniqueness of the inter-module connectors and the wide differences in their concept designs, inter-module connectors have been placed in a separate category, but are equivalent to a structural sub-system in importance.

More detailed definition may be necessary when a particular MOB concept is selected for further evaluation.

Four classes of limit states, listed in Table 13, are considered for an MOB. The first three are essentially component-level (or sometimes sub-system level) limit states, while the last one pertains only to the entire system. Exceedance of a component-level limit state may have different consequences depending on (i) the type, position, size and function of the component, (ii) accessibility of the component for inspection and repair, (iii) the degree of structural redundancy in that failure mode, etc. Levels of failure consequence are discussed next.

### 4.4. Consequences of failure

For the purpose of setting target reliabilities, MOB failure consequence are classified into five levels. These range from discomfort to total structural failure, and in increasing order these are: minor, moderate, serious, critical and catastrophic. The five levels are arranged in Fig. 4. Measured in consistent units (dollars, lives, etc.), successive consequence levels differ, in broad terms, by one order of magnitude.

Exceedance of serviceability limit states can only lead to minor or moderate consequences. Exceedance of fatigue limit states, depending on structural scale,

Table 13
MOB structural limit states

| Limit state | Scale of structural participation | Definition of limit state |
|---|---|---|
| Serviceability/operability | Mostly elements/assemblies, sometimes sub-system and system | Disruption of normal use (including military operations) due to excessive deflection, deformation, motion or vibration |
| Fatigue | Element/assemblies, inter-module connectors | Critical level of cumulative fatigue damage accumulation, or crack growth to critical size determined by functional or strength considerations |
| Strength | Element/assemblies, inter-module connectors | Local failure such as rupture, instability, plastic mechanism, and buckling |
| Global failure (total system failure)/survivability | Entire system (fully connected MOB, or single module when disconnected) | Loss of entire structure (i.e., capsizing, sinking, loss of station-keeping) (i) as a result of *progressive collapse* starting from a small initiating event, or (ii) *collapse in damaged condition* after sustaining severe damage in a sub-system. Includes non-structural initiating events such as fire, explosion, failure of other systems such as dynamic positioning or power generation |

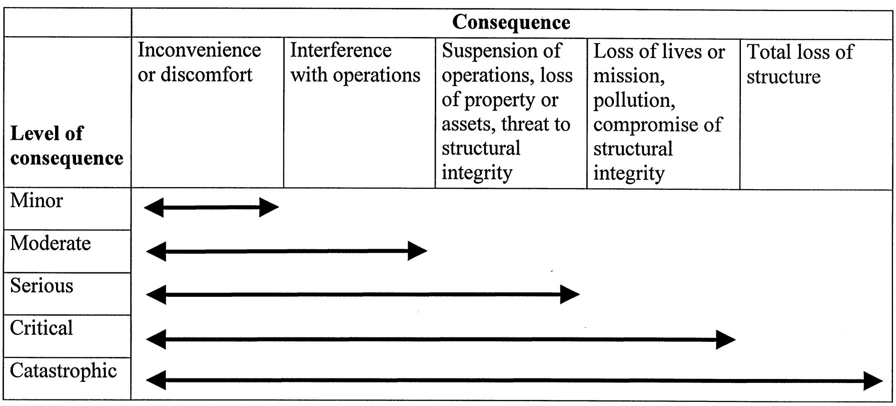


Fig. 4. Description of MOB failure consequences.

accessibility and redundancy, can have any of the first four levels of consequence. Exceedance of strength limit states cannot have a minor consequence, but depending on structural scale and redundancy, can have moderate, serious or critical consequences. Finally, the catastrophic consequence is reserved for the global failure limit

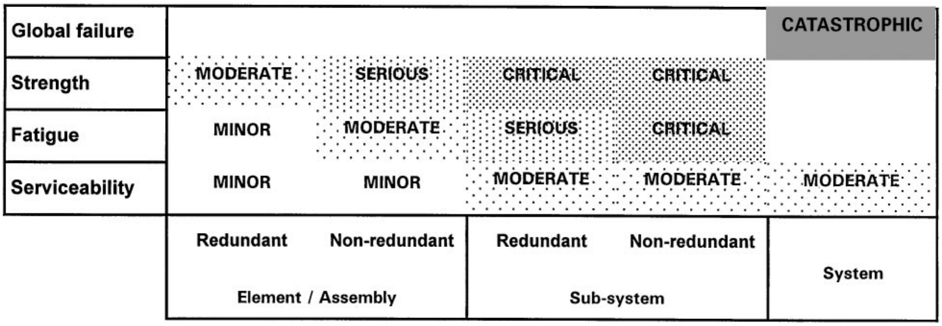


Fig. 5. Consequence matrix based on structural participation.

state. The possible consequences of limit state exceedance and scale of structural involvement are provided in Fig. 5.

### 4.5. *Proposed target reliabilities for different limit states*

The MOB global failure limit state has the most severe consequence, and the target reliability for this limit state is selected first (Section 4.2). The target reliabilities for the component and sub-system level limit states are then derived as described in Section 4.5.1. An MOB is expected to encounter a range of accidental loads (occurring from collision, grounding, accidental explosions, etc.), and weapons effects. Section 4.5.2 discusses target reliabilities against these events.

#### 4.5.1. *Target reliability of elements/assemblies, sub-systems and connectors*

The reliability of elements/assemblies, connectors and sub-systems is assigned according to Eq. (11) on a uniform risk basis. The consequence (Fig. 4) of exceeding a given limit state is identified according to Fig. 5. rows 1a, b, 2a–f and 3a–f of Table 12 list target reliabilities for different structural categories under serviceability, fatigue and strength limit states. This scheme assumes that $q^* < 10^{-5}$, which in turn is based on the assumption that there is an order of magnitude difference between successive levels of consequence.

Since an MOB is required to fulfill mission requirements in addition to having structural integrity, operational availability limits are also incorporated in target reliabilities where appropriate, specifically in rows 1b, 2d, 2f, 3c and 3e of Table 12. Values of $A_1, A_2$ will be specified during the acquisition phase.

#### 4.5.2. *Target reliability against accidents and weapons effects*

It is likely that during its service life an MOB will be subject to accidents and weapons effects. However, unlike environmental loads and dead and live loads, probabilistic characterization of accidents and weapons effects is generally not practical. A full reliability analysis is therefore not feasible under these types of loading and corresponding target reliabilities are prescribed in a conditional format.

The sub-system target reliability under weapons effect (row 3f of Table 12) is conditional on a specified weapons load or a specified accidental event. This event occurs at any potential location within the sub-system and is expected to cause substantial local structural damage at the element/assembly level.

The damaged condition limit states represent global failure occurring after the MOB sustains severe damage in a structural sub-system. Such damage may be the result of accidents (e.g., grounding, collision, fire) or weapons effects (explosions, shock waves, etc.), and is quantified by removal of a structural sub-system at a time. Consequently, irrespective of how the damage occurs, row 4c of Table 12 prescribes the target reliability conditional on the damage.

## 5. Summary and conclusion

This paper addresses the problem of setting design criteria for structures for which there is no direct experience; the subject structure in this case is the US Navy's Mobile Offshore Base. As discussed in the paper, a reliability-based framework is considered the most appropriate for such structures, where the criteria are expressed in terms of target reliabilities. The reliability-based framework should also specify future maintenance strategies and the scope of the reliability analysis including uncertainties that should be considered in the analysis.

A survey of reliability levels in existing design standards and engineered structures, target reliabilities recommended by experts, and analytical models for establishing acceptable failure probabilities is presented.

In the absence of experience and history, "calibration", as commonly applied in the development of LRFD standards, is not an option. This paper presents a general methodology for establishing target reliabilities for novel or unique structures or for structures with unusual failure consequences. A risk-based approach is employed to develop a hierarchy of target reliability levels which takes into account the failure mode considered and the consequence of failure. A key parameter is the extent of participation of the structure in the failure mode in question.

The methodology is illustrated with the MOB. The MOB target reliabilities presented here are subject to modification in the actual acquisition phase when more input becomes available. It is emphasized that setting target reliabilities for high-value novel structures is not an engineering decision alone: active involvement on the part of the owners and policy-makers is also required.

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## References

[1] Lind NC. Target reliability levels from social indicators. Proceedings of the Sixth International Conference on Structural Safety and Reliability, Innsbruck, Austria, 1993. p. 1897–904.
[2] Moan T. Target levels for reliability-based reassessment of offshore structures. Proceedings of the Seventh International Conference on Structural Safety and Reliability, Kyoto, Japan, 1997. p. 2049–56.
[3] Ellingwood B, Galambos TV. Probability-based criteria for structural design. Struct Safety 1982;1:15–26.
[4] Moan T. Current trends in the safety of offshore structures, vol. IV. Proceedings of the Eighth International Offshore and Polar Engineering Conference, Honolulu, 1997.
[5] Remmers G, Zueck R, Palo P, Taylor R. Mobile offshore base. Proceedings of the Eighth International Offshore and Polar Engineering Conference, Montreal, Canada, 1998.
[6] American Bureau of Shipping (ABS). Draft mobile offshore base classification guide (proprietary publication subject to restricted distribution). ABS, Houston, TX, 1999.
[7] Mansour AE. An introduction to structural reliability theory. Ship Structure Committee Report SSC-351, Washington, DC, 1990.
[8] Committee IV.1. Design principles and criteria. Proceedings of the 13th International Ship and Offshore Structures Congress, Trondheim, Norway, 1997.
[9] Canadian Standards Association. General requirements, design criteria, the environment, and loads, a national standard of Canada. CAN/CSA-S471-92, 1992.
[10] Det Norske Veritas. Structural reliability analysis of marine structures, classification notes no. 30.6. DNV, Norway, 1992.
[11] International Organization for Standardization. General principles on reliability for structures. ISO 2394, 1998.
[12] Galambos TV. Design codes. In: Blockley D, editor. Engineering safety. New York: McGraw-Hill, 1992.
[13] American Association of State Highway and Transportation Officials. LRFD bridge design specifications. AASHTO, Washington, DC, 1994.
[14] Nowak AS, Szerszen MM, Park CH. Target safety levels for bridges. Proceedings of the Seventh International Conference on Structural Safety and Reliability, Kyoto, Japan, 1997. p. 1897–903.
[15] Mansour AE, Wirsching P, Luckett M, Plumpton A. Assessment of reliability of existing ship structures. Ship Structure Committee Report No. SSC-398, Washington, DC, 1997.
[16] MSL Engineers Limited. Reliability of fixed and jack-up structures. Draft Final Report, 1996.
[17] Committee V.6. Structural design of floating production systems. Proceedings of the 13th International Ship and Offshore Structures Congress, Trondheim, Norway, 1997.
[18] Ghosn M, Moses F. Redundancy in highway bridge superstructures. Report 406, Transportation Research Board, Washington DC: National Academy Press, 1998.
[19] MacGregor JG, Kennedy OSL, Bartlett FM, Chernenko D, Maes MA, Dunaszegi L. Design criteria and load and resistance factors for the Confederation Bridge. Can J Civil Engng 1997;24:882–97.
[20] Sarveswaran V, Roberts MB. Reliability analysis of deteriorating structures — the experience and needs of practising engineers. Struct Safety 1999;21:357–72.
[21] Polky JN, Held JT. Analysis of the collision risk for aircraft operation on a mobile offshore airfield. Proceedings of the 22nd UJNR Marine Facilities Panel Meeting, Arlington, VA, 1998.
[22] Whitman R. Evaluating calculated risk in geotechnical engineering. J Geotech Engng ASCE 1984;110(2):145–88.

[23] Cullen HN. The public inquiry into the Piper Alpha disaster. Technical Report, The Parliament by the Secretary of the State for Energy, UK, 1990.
[24] Bea RG. Reliability based design criteria for coastal and ocean structures. Australia: The Institution of Engineers, 1990.
[25] Ang AH-S, De Leon D. Determination of optimal target reliabilities for design and upgrading of structures. Struct Safety 1997;19:91–103.
[26] Wen YK, Kang YJ. Minimum life-cycle cost design criteria. Proceedings of the Seventh International Conference on Structural Safety and Reliability, Kyoto, Japan, 1997. p. 1047–54.
[27] Keese DL, Barton WR. Risk assessment and its application to flight safety analysis. Sandia National Laboratories, SAND89, 1982.
[28] Construction Industry Research and Information Association. Rationalization of safety and serviceability factors in structural codes. CIRIA, Report No. 63, London, 1977.
[29] Allen DE. Criteria for design safety factors and quality assurance expenditure. Proceedings of the Third International Conference on Structural Safety and Reliability, Trondheim, Norway, 1981. p. 667–78.
[30] Mander JB, Elms DG. Quantitative risk assessment of large structural systems. Proceedings of the Sixth International Conference on Structural Safety and Reliability, Innsbruck, Austria, 1993. p. 1905–12.
[31] Suzuki H. Safety target of very large floating structure used as a floating airport. Proceedings of the Third International Workshop on Very Large Floating Structures. Honolulu, Hawaii, 1999. p. 607–12.
[32] Bhattacharya B, Ma K-T, Basu R. Developing target reliability for novel structures: the case of the Mobile Offshore Base. Proceedings of the Third International Workshop on Very Large Floating Structures, Honolulu, Hawaii, 1999, p. 398–407.