Chapter 2
Past Developments

Abstract Offshore platforms are only 65 years old and are fairly new compared to other types of civil engineering structures. The first steel platform was installed in Gulf of Mexico (GOM) in 1947. In this chapter, brief overview of the past work done in this area is outlined. American Petroleum Institute (API) was the first to publish the code for offshore Jacket platforms, namely API RP2A WSD in 1969. API LRFD was published in 1993 with errata in 2003 and has not yet been revised. ISO 19902 was published in 2007 and is the most updated LRFD code available for steel Jacket platform design today.

2.1 Design Codes of Practice for Jacket Platforms

API WSD code has been updated throughout these years until recently an erratum was issued for 21st edition in March, 2008. It was followed by DNV in Norway and separate guidelines for United Kingdom. Canada and Australia published their own codes for offshore platform design. LRFD format of code is a probability-based code. For API RP2A LRFD code development, the target reliability was set against API WSD. The target reliability for a probabilistic code is by using the reliability of platforms designed by existing codes, personal judgement and the safety requirement. The hydrocarbon exploring companies such as Shell and PETRONAS have developed their own technical standards with respect to geographically specific regions [1, 2]. These standards refer to API RP2A WSD or ISO 19902 for the detailed design and assessment. API WSD is still in practice in most parts of the world due to non-availability of regional environmental load factors presented in ISO 19902.

Structural design codes provide a set of minimum technical guideline for satisfactory design. They also provide a path for research findings to create their way into practice of this field [3]. The LRFD method treats the load according to their types and the loads dominated by environment are treated appropriately.

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2.1.1 API RP2A-WSD

API WSD uses safety factor which is same for all types of loads, whereas API LRFD and ISO use different factors based on each type of stresses. WSD code safety factors have been found empirically [4]. In WSD, allowable stresses are either expressed implicitly as a fraction of yield stress or buckling stress or by applying a safety factor on critical buckling stress [5]. WSD strength of component or joint can be evaluated by using Eq. (2.1),

$$\frac{R}{\mathrm{FS}} \geq D_l + L_l + E_l \tag{2.1}$$

where R = resistance effect, FS = factor of safety, D_l = dead load, L_l = live load and E_l = environmental load. WSD method has safety factor provided only to the resistance of the material without considering the uncertainties related to the loads as shown in Eq. (2.2),

$$Q < ØR \tag{2.2}$$

where Q = load and Ø = material strength safety factor, and it covers the randomness of material and load. This safety factor theory assume the concept that probability distributions of Q and R exist but not known [6]. Thus, a large value of load $Q = Q_1$ is taken and low value of resistance $R = R_1$ is taken (allowable yield strength is less than the specified yield strength of steel), the factor of safety takes into consideration the uncertainties as shown in Eq. (2.3),

$$\mathrm{FS} = R_1/Q_1 \tag{2.3}$$

where R_1 and Q_1 are resistance and load typical values. If $Q_1 < R_1$ i.e. if load is smaller than resistance, structure is safe but if $Q_1 > R_1$, then it means failure of structure. So, to avoid any damage to structure, safety factor is provided in advance at design stage.

In working stress, design resistance is divided by a factor of safety but LRFD takes into consideration the inherent natural uncertainties in applied action and resistance of components [7]. Due to this discrepancy, LRFD method of design has been introduced to replace WSD. In the limit state design, these uncertainties of load and resistance are considered more realistically by using reliability analysis methods. The drawbacks of WSD code have been outlined as it is excessively conservative and did not provide engineer any insight of degree of risk or design safety of Jacket [8]. It has no risk balanced capabilities, and there is little justification for safety factors. Bilal reports that uncertainty using deterministic factors of safety could lead to inconsistent reliability levels and may produce over design. WSD does not provide insights into the effects of individual uncertainties and real safety margins [9]. The main disadvantages of deterministic measure are shown below:

(i) Structural model uncertainty
(ii) Uncertainty of external loads
(iii) Human error

2.1.2 API RP2A-LRFD/ISO 19902

The first code using limit state design using probabilistic analysis was formulated by Canada for cold formed steel members in 1974 [10]. Denmark and Norwegian Certifying Authority, DNV was the first to introduce the limit state design code for Jacket platform which was published in 1977 [7, 11–13]. In 1993, API RP2A-LRFD was published and it has been updated by ISO 19900 series of codes for offshore structures. In this method, resistance and load are factored using uncertainty. This type of design is described as balanced design as it provides a balanced allocation of resources [14]. LRFD provides a safe and economically efficient way of designing Jackets to different environmental load conditions. It is also able to incorporate regional and geographical conditions in the design. Instead of factor of safety, load and resistance factors are used. In LRFD, the load combination equation is shown in Eq. (2.4),

$$ØR_n \geq \gamma_D D_\mathrm{l} + \gamma_L L_l + \gamma_w E_l \tag{2.4}$$

where, R_n = nominal resistance, γ_D = dead load factor, D_l = Nominal dead load, γ_L = live load factor, L_l = Nominal live load, γ_w = environmental load factor, E_l = Nominal environmental load (100-year extreme). LRFD format can be represented in more general way in Eq. (2.5),

$$ØR = \sum_{i=1}^{n} \gamma_i Q_i \tag{2.5}$$

where R = characteristic/nominal value of resistance, Q_i = characteristic or nominal value of load, Ø = resistance factor (for uncertainty in stress), γ_i = load factor (for uncertainty in load), n = number/type of load components (Gravity load and environmental load).

2.1.3 Benefits of Limit State Design Code

LRFD approach provides logical thinking while designing the structures, i.e. it considers the uncertainties of resistance and load. Semi-probabilistic approach simplifies the design process. Safety factor calculation remains deterministic one, but load and resistance factors are established depending on the requirement of structures whose reliability is chosen in advance. Nominal load and resistance values can be same in WSD and LRFD codes. LRFD code use factors which are chosen taking into consideration uncertainty in relation to action and resistance, i.e. spread of values and insufficient data. We can derive resistance and load factors using probabilistic methods design criteria. Factors are adjusted with a uniform degree of reliability to all structural elements in a given class of structure [6]. For instance, each type of stress can be dealt accordingly like axial compression or axial tension. Furthermore, as more test data on variables become available, these factors can be modified as per the updated statistical parameters of random variables.

Dead, live and environmental loads are treated separately using probabilistic methods and each type of load is taken after making statistical analysis. These factors can be increased in case of structures which are at high risk like nuclear power plants or offshore structures but can be decreased for low-risk structures. WSD uses same factors for both types of structures. The benefits of LRFD can be outlined below:

(i) It gives superior consistency in the reliability of offshore Jacket platforms.
(ii) LRFD has efficient utilisation of materials compared to factor of safety design method, i.e. WSD.
(iii) Randomness and uncertainties can be taken care off more specifically.
(iv) Platforms can be designed as per the actual requirements of operator, i.e. specific for certain location, type and life span.
(v) This is by use of logical interpretation of new research.
(vi) Since deck is designed using AISC (2005) which is reliability-based design code, it is logical that Jacket should also be designed using LRFD code.
(vii) LRFD provides incentives for research with regard to uncertainties, which take part for determination of partial load factors.

2.1.4 Safety Factor

Any structure designed and built with latest knowledge cannot claim to be free from chance of failure. The safety factor is used to give allowance for variation of material and load uncertainties of Jacket platforms. Optimal safety margin for design of Jacket may be observed as problem which involves trade-off between cost and acceptable failure probability [15]. It is a known fact that design involves many uncertainties which are not clear at the time of design. Thus, the structural engineer uses probabilistic reasoning for design of structure. The selection process of partial safety factors is called code calibration [16]. The calibration of safety factor is done in such a way that large safety factor is provided in presence of large uncertainties, whereas small safety factor is provided in small uncertainties. Code developers assume certain values for basic parameters, which are expected to cover for the uncertainties involved with the material properties during the entire life of the structure. By the use of these uncertainties, the model equations are developed which contain some factors. These are called factors of safety in WSD and load and resistance factors in limit state design and provide a high level of assurance that the structure will perform satisfactorily. This is defined as ratio of expected strength of response of Jacket to expected applied loads [17].

Despite all these safety factors, due to some unforeseen load condition, some member resistance problem may cause the failure of structure [6]. Structural failures demonstrate that however the design is considered safe still accident happen. Offshore accidents cause not only loss of lives but also produce economic losses and environmental catastrophe.

Fig. 2.1 Jacket platform under fabrication at a yard

2.2 Geographic Region of Offshore Malaysia

Brunei in 1929 became the first country in South East Asia to produce hydrocarbons [18]. In 1992, there were 65 number of platforms in Baram delta Sarawak and 120 in rest of Malaysia [18]. For offshore Malaysia, Baram delta is the biggest and has platforms with integrated drilling, production and quarters facilities [18]. Figure 2.1 shows platform under fabrication at a yard.

2.2.1 History of Offshore Oil Production

The ever increasing demand for oil and gas has forced engineers to go for offshore exploration, specifically during the energy crises of 1970s. Prior to 1947 offshore Jacket model for most of offshore operations were used to be wooden piled decks, connected to shores through trestles [19]. In 1947, Kerr Mcgee-Phillips-Stanolind group used 22 piles to support a drilling deck in Gulf of Mexico in 6.1 m water depth opened a new chapter in marine soil operations. Jacket piles were driven through vertical legs and acted as anchors. Today Jacket platforms in water depth of more than 300 m are built to withstand the huge forces of nature such as hurricanes and typhoons [20]. The demand for more hydrocarbons has forced us to go into ever deeper ocean waters with hostile environment for exploration and production. Nowadays, offshore structures taller than the Eiffel tower are designed to withstand extremely rare waves of more than 30 m high, collision with ships, scour at mud line, earthquakes or other environmental hazards [21].

The work for finding load and resistance factors for different offshore regions has made much progress such as North Sea, Mediterranean Sea, Canada, Australia, South China Sea, Bohai Sea and Gulf of Guinea. API RP2A LRFD has been adopted for use in the North Sea, UK sector after an initial transition period during which appropriate load factors were developed. Large majority of platforms installed in the UK sector after 1995 were also designed using the LRFD format in preference to the WSD [13, 22]. The effect of load variables is significant in different regions of world depending on geography. Specifically, the regions near equator, where climate is mild and there is less chance of rare events occurring significantly.

2.2.2 *Jacket Platform Design in Malaysia*

In Malaysia, API RP2A WSD is used by offshore design and fabrication industry along with PETRONAS technical standard (PTS), for local environmental load parameters. Soon ISO 19902 code will be used to design the Jackets platform with an environmental load factor of 1.35. The application of environmental load factors which is optimised for GOM offshore region and materials may be not be reasonable for Malaysian waters [23]. The calibration of load factor has never been done so far in this region.

2.3 Uncertainty

Load and resistance are considered as random variables. The main uncertainties deal with the tolerance to which structural members are built and the loads and environmental conditions to which they will be exposed throughout their life [21]. This variation is stated by the probability distribution function and their correlation function if it is considered. In this book, random variables are treated as independent and no correlation is taken into consideration. Figure 2.2 shows the types of uncertainty used for reliability analysis.

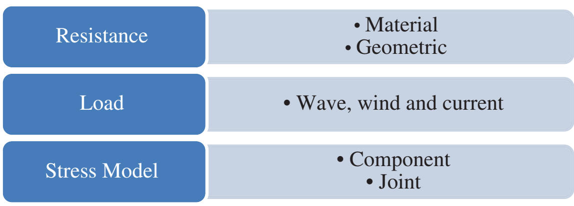

Fig. 2.2 Types of uncertainties

2.3.1 Uncertainty of Loads and Resistance

Structural design depends on uncertainties which come from environmental loads and resistance of material. The geographical variation of environmental load is so much that ISO 19902 has reported that due to uncertainty of load and resistance load factors should be ascertained in each region separately. Structural design assumes load and resistance which are random in nature. The case of offshore Jacket platforms needs special importance, because it deals with loads which are not simple random variable. Environmental loads are not like live loads acting on land-based structure but are more severe due to unpredictable weather conditions. This environmental load can act with unexpected severity on offshore structures. The resistance can also be reduced due to sudden damage to Jacket. Thus, probabilistic techniques are required for estimating the design loads and resistance. This book highlights the reliability analysis of Jackets and significance of different structural and load variables including their respective uncertainties influencing the safety of Jackets.

2.3.2 Basic Uncertainty

Uncertainty modelling is the first important step for the reliability analysis for the Jacket platforms. Parameters of modelling of uncertainty are mean (central tendency), variance (dispersion about the mean) and probability distribution functions [24]. Structural reliability is based on the theory of probability and its treatment to different uncertainties whose role is dominant as far as behaviour of structure is concerned. These uncertainties, if not treated properly, may cause failure, collapse or damage to structure which may become unserviceable and threat to environment. These problems can only be solved by introducing the probability to account for the risks involved in the uncertain design of offshore Jacket platforms. Uncertainties are dealt with by taking into consideration random variable parameters of load and resistance. The reliability analysis is significantly dependent and very susceptible to uncertainty modelling [25].

Structural analysis calculations of offshore platforms are also subject to uncertainties. Uncertainties are analysed by using how much basic information is available about that random variable parameter [26]. Modelling uncertainties are introduced by all physical models used to predict the load effects and the structural response [27]. The results are geometric and material variability. Equation (2.6) defines the risk and probability of failure of structure. Probabilistic calculation techniques enable these uncertainties to be taken into account. They provide a probability that it will resist the load, (probability that it will not resist the load, known as the failure probability of the member) which characterises its reliability.

$$\text{Risk} = 1 - \text{Reliability} \tag{2.6}$$

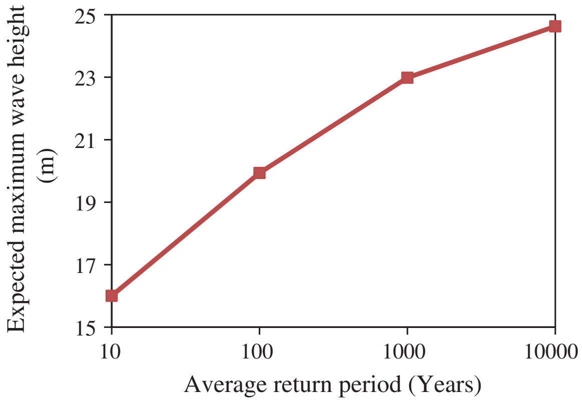

Fig. 2.3 Exceedance probability curve for wave height in GOM [107]

Jacket will fail if the strength is less than the applied load and probability of failure is shown by Eq. (2.7),

$$P_f = \text{Resistance(strength)} < \text{Load} \tag{2.7}$$

Uncertainty reflects lack of information which could be on the load side or on resistance side [28]. Uncertainties deal with how much load we shall consider for design (loading) and how much load a structure can withstand (resistances). We do not know how big are the largest waves the Jacket will be exposed to throughout the expected design life of the Jacket. This will depend on the geographic location and the design life of Jacket. For instance, in GOM, chances of rare event occurring within expected design life will be higher than in Malaysia. This extreme and rare wave height for design is assumed to occur once every 100 years thus it has a probability of 0.01 of occurrence in a given year. Figure 2.3 shows the exceedance probability curve for wave height at GOM site up to 10,000 years.

Probabilistic calibration is done to find safety factors in a balanced manner. This takes into consideration the sources of uncertainty in environmental loads and material resistance [29]. Failure of structures has shown us that it is impossible to build a risk-free structure. This is due to the nature of extreme environmental loads and uncertainty in material, fabrication, construction, human error and structural analysis of Jacket platforms [30]. Failure of ocean structures has huge impact on oil industry. Such failures have catastrophic effect on the industry. The notable ones are Alexander Kielland (Norway-1980), Ocean ranger (Canada-1985), Piper Alpha (North Sea, UK 1988) Petrobras-36 (Brazil 2001), Deepwater horizon (USA 2011). The failure mode of above five structures was fatigue, buoyancy control system failure, natural gas fire, buoyancy control system failure and explosion and fire, respectively.

2.3.3 Sources of Uncertainty

Uncertainty determination depends on computational tools. This enables the determination of analytical results by determining the component and joint safety, subjected to the uncertain variable loads and resistances during design [26]. There are many sources of uncertainty which are defined below.

2.3.3.1 Natural

This comes from randomness of loads and material resistance and is difficult to control. An example is the tsunami which hit Japan in 2011. Natural and inbuilt randomness of environmental loads and earthquake, which are acting on the structure such as wave, wind and current contain uncertainty of time, period, interval magnitude and parameters (height and direction). The Jacket may be exposed to 100-year wave height during its service life. Deterministic calculations verify that each member of the structure can withstand the hundred-year wave. The material uncertainty includes yield strength, ductility and elongation. These can be due to operating, i.e. fatigue or extreme environmental, i.e. storm or extreme natural calamity, i.e. earthquake [26].

2.3.3.2 Statistical Uncertainty

This type of uncertainty is related to statistical modelling of distribution of the random parameters [14, 18]. If the number of data points is increased, this type of uncertainty is reduced.

2.3.3.3 Human Mistakes

This type of uncertainty depends on knowledge of person designing the structure, construction and operation of the structure such as piper alpha disaster in 1988 caused by communication gap between platform operators. Statistical analysis of failure shows that 90 % of these failures are due to human errors [10].

2.3.4 Parameters of Uncertainty

Variability of member resistance and environmental load parameters can be found through collection of data and fitting of it using probability distribution. Statistical parameters (mean, standard deviation, coefficient of variation, etc.) can be obtained for the random variables.

2.3.4.1 Random Variables

For structural design, it is extremely important to evaluate the probability of failure and safety levels of a Jacket, especially in the event when variables are random. The variables used for reliability analysis for Jacket platforms are geometric, material properties and loads are not considered as deterministic [31]. The structural safety is shown by two independent properties, i.e. load effect forces (moments, axial, and shear forces) acting on the structure or its components due to applied forces and strength or resistance, both are random variables. In the case of load effects, these are the forces caused by man, material and nature, and for the case of resistance these are due to the mechanical and geometrical properties of material.

2.3.4.2 Bias

Bias is defined as a ratio of actual capacity to calculated capacity [32]. It is also defined as mean value over nominal value. It will always be there for geometric variables. For resistance variables, mean bias is found by average of measured values against the actual test results or dimension provided by design engineer. If mean value is not equal to 1.0, it shows that it has a bias in the model [33]. Some risk of bias of the analysis will be there always when using computational models, which can define safe and unsafe platforms [34].

2.3.4.3 Return Period

API and ISO objectives report that offshore structures should have ability to withstand the 100-year storm load. The environmental loads acting on the structure are random variables. This makes the reliable estimation of offshore loads for their design life difficult. Random nature of offshore environment can only be estimated by taking into consideration return period of probabilistic models of environmental loads. For Jacket design, it is 100 years and for reassessment and life extension, it is 10,000 years. In North Sea with 100-year wave, the 10-year return period of current has been used as further explained in Chap. 3.

2.3.4.4 Distribution Types

Type of distributions for random variables is an important factor for reliability analysis. For rare events, the extreme types of distributions are used and for geometric and material resistance, commonly normal or lognormal distributions are reported in texts. Distribution and their parameters are compulsory tools for level III reliability which is explained in Chap. 7.

2.3.5 Types of Resistance Uncertainty

2.3.5.1 Geometrical and Material

This uncertainty relates to the randomness due to geometrical and material variations. This is related to straightness, diameter, thickness, length, yield strength, elongation and tensile strength. In previous study, diameter, thickness, young's modulus and yield strength variables are considered for material uncertainty [4]. This type of uncertainty can be dealt properly with the application of controlled manufacturing and fabrication by using international standards and quality control. Many researchers have been working on resistance uncertainty, such as [30, 35–37]. Material properties used for assessment should be estimated using actual material properties of existing structures [38]. Still present day, there are minor but important variations remain between characteristic values mentioned on structural drawings and fabricated Jacket components placed at site as shown in Chap. 3.

2.3.5.2 Physical Stress Model

Model uncertainty is due to deviation of material strengths, from component or joint stress biases, with respect to actual strength acquired from tests results [29]. This type of uncertainty accounts for possible deviation of model assumptions of the resistance of a given section from the actual resistance of geometrical properties. The load model may also show variation due to natural variation in loads. This type of uncertainty is related to shortage of knowledge, information or unavailability of software. These can be reduced by applying the more detailed methods [14]. Norwegian Design regulation requires, "Design loading effects and design resistances should be computed by using deterministic computational models". These models shall aim at giving expected average values without introducing any increase or reduction in safety. The uncertainty of the computational models is being included in the partial coefficients [34]. Table 2.1 shows the stress model uncertainty considered in this research.

Table 2.2 shows the model uncertainty (X_m) from Mediterranean Sea. It should be remembered that it depends on API RP 2A WSD 18th Ed. There have been large changes in API RP 2A 21st Ed. published in 2008 particularly for joint models.

Table 2.1 Uncertainties in model predictions

Component		Joint
Tension	Tension and bending	Tension
Compression column buckling	Compression (column buckling) and bending	Compression
Compression local buckling	Compression (local buckling) and bending	In-plane bending
Shear	Tension and bending and hydrostatic pressure	Out-plane bending
Bending	Compression (column buckling), bending and hydrostatic pressure	
Hydrostatic	Compression (Local buckling) and hydrostatic pressure	

Table 2.2 Model uncertainty for Mediterranean Sea using API WSD 18 ED [85]

Tubular member		X_m	COV
Tension and bending		1.093	0.058
Compression (column buckling) and bending		1.075	0.053
Compression (local buckling) and bending		1.222	0.064
Hydrostatic		0.99	0.095
Tension and bending and hydrostatic pressure		1.018	0.106
Compression (local buckling) and hydrostatic pressure		1.082	0.104
Joints			
K	Tension/compression	1.32	0.028
	IPB	1.185	0.183
	OPB	1.113	0.179
T/Y	Tension	2.207	0.401
	Compression	1.306	0.291
	IPB	1.296	0.328
	OPB	1.388	0.354
X	Tension	2.159	0.546
	Compression	1.145	0.144
	IPB	1.595	0.250
	OPB	1.147	0.250

2.4 Resistance Uncertainty-Background Study

ISO 19902 Clause 7.7.4 requires that the test/measured data should be validated by simulation for the resistance of material taking into account the structural behaviour variability of material [39]. DNV report 30.6 recommends that for resistance model, normal distribution should be considered for the reliability analysis of Jacket platforms [33]. The difference between strength and load variable is highlighted by the fact that strength variable is considered unsuitable if its value is less than the mean value as it may cause failure. For model equations, the mean value should be greater than 1.0 which shows the conservativeness of code equations and usually normal distribution is assumed for it [40]. The load variable is unsuitable, if it is greater than its mean value which can cause failure. Previous studies on resistance of material have been made by many authors [12, 16, 35, 41–43]. Currently no information is available about any similar study conducted in Malaysia.

Structural design strength depends on characteristic values of basic random variables of resistance. The behaviour of these variables of strength may vary in such a way that they become unsafe at any time throughout design life. Structure can fail if the characteristic value of load exceeds the characteristic

Table 2.3 Resistance uncertainties for jacket platforms

Types of resistance uncertainty	Example
Material uncertainty	Yield strength, modulus of elasticity, elongation, tensile strength
Geometric uncertainty	Diameter, thickness
Fatigue uncertainty	Degradation of material
Corrosion uncertainty	Degradation of material

load carrying capability. Uncertainty determination depends on computational tools available at hand. This enables correct analysis by determining the component safety, subjected to the uncertain variable loads and resistances during design [26]. Generally, load tends to increase with time, whereas resistance tends to decreases with time. Thus, uncertainty of load and resistance increases with time [46]. Ellingwood [44] says that the result of uncertainty is risk, which is defined as "the product of the probability of failure and costs associated with failure of structure" [45]. High probability of failure means low reliability thus cost of failure will be high. These problems can only be solved by introducing the probability into account for the risks involved for the uncertain design of offshore Jacket platforms.

The strength of Jacket depends on the variability of its components from which the member is built. The primary members of Jacket are piles, legs, horizontal periphery braces, horizontal internal braces and vertical diagonal braces. Jacket members are in seven different types of stresses, and joints are in four types of stresses. Code provides equations to find these stresses of resistance of random variables from which members are fabricated. Table 2.3 shows the uncertainties related to offshore Jacket platforms. In this book, material and geometric uncertainties are discussed, due to their relevance to ultimate limit state design, which is the most significant limit state design as compared to other types of limit states.

The probability of failure can be updated if changes in COV are known, i.e. after the design of Jacket members or joints. This is possible after the material tests results or actual geometrical properties statistical analysis. For instance at design stage, the COV taken was 0.15 but when actual material test report was issued and it becomes known that the actual COV was 0.1. Using the reliability analysis, new probability of failure can be determined [28]. In this book, fatigue and corrosion uncertainty are not discussed further.

2.4.1 Material Uncertainty

Materials like steel have variability due to construction practices. The basic strength or resistance uncertainty includes yield strength, elastic modulus (Young's modulus). ISO takes yield strength distribution for North Sea as lognormal. Bias of 1.127 and standard deviation of 0.057 was achieved in one study [43]. Duan [12] takes yield strength distribution for China as normal, with a bias of 1.0 and COV of 0.05 was achieved.

2.4.2 Characteristic Resistance

Characteristic resistance should have low probability of being exceeded at any specified design life of Jacket. It is defined as that value below which not more than 5 % of the test results of large number of test would fall [46] or it is 0.05 fractile of a lower end of normal distributions [47, 48]. Characteristic strength should be equal to guaranteed yield strength but shall not exceed 0.8 times the guaranteed tensile strength [34] or minimum of upper yield strength. Characteristic values of geometric quantity are the dimensions specified by the design engineer [47].

2.4.3 Geometric Uncertainty

The structure can fail due to resistance failure from variation in dimension and fabrication errors. The geometrical uncertainties include diameter, thickness and length and effective length factor. ISO reports following results for statistical properties of geometry of tubular members [43]. Normal distribution was taken for diameter, thickness, length and effective length factor for leg and brace. Mean bias of 1.0 and COV of 0.0025 was achieved for diameter. Mean bias of 1.0 and COV of (0.004 + 0.25/T) was achieved for thickness. Mean bias of 1.0 and COV of 0.0025 was achieved for length. Mean bias of 1.1 and standard deviation of 0.0935 was achieved for effective length factor for leg member. For braces, the mean bias was achieved as 0.875 and COV of 0.097. Further details can be found in Chap. 4.

2.4.4 Resistance Model Uncertainty

The modelling uncertainty is predicted from the ISO code equations. Seven component stresses and four joint stresses for each joint type are modelled for resistance. The uncertainty model for resistance (X_m) is shown by Eq. (2.8),

$$X_m = \frac{\text{Actual Resistance}}{\text{Predicted Resistance}} \tag{2.8}$$

This model uncertainty depends on the statistical parameters for basic variables, i.e. diameter, thickness, yield strength and modulus of elasticity. The detailed results from literature are shown in Chap. 4.

2.4.4.1 Single Stresses

The variation of model uncertainty for single stress has been reported by ISO and BOMEL [39, 43]. Mean bias for tensile strength was achieved as 1.0 with standard deviation of 0.0. For column buckling strength, from experimental tests results it was found to be with a bias of 1.057, COV of 0.041 and standard deviation of 0.043. For local buckling, mean bias was 1.065, COV of 0.068 and standard deviation of 0.073. For bending, the experimental bias was reported to be 1.109, COV was 0.085 and standard deviation was 0.094. The experimental bias for hoop buckling was found to be 1.142, COV was 0.124 and standard deviation was 0.1416.

2.4.4.2 Double Stresses

The variation of model uncertainty for two combined stresses has been reported by ISO and BOMEL [39, 43]. For tension and bending, the bias was found to be 1.109 and standard deviation was 0.094. For compression and bending, the experimental bias for compression (local buckling) and bending was found to be 1.246, COV was 0.067 and standard deviation of 0.084. For compression (column buckling), mean bias was 1.03, COV was 0.082 and standard deviation was 0.084.

2.4.4.3 Three Stresses

The variation of model uncertainty for three combined stresses has been reported by ISO and BOMEL [39, 43, 49]. For tension, bending and hydrostatic pressure, the experimental bias for axial tension, bending and hydrostatic pressure was found to be 1.075, COV was 0.098 and standard deviation was 0.105. For compression, bending and hydrostatic pressure, the experimental bias for compression (short column), bending and hydrostatic pressure was found to be 1.199 and COV was 0.134 and standard deviation was 0.161. The experimental bias for compression (long column), bending and hydrostatic pressure was found to be 1.197, COV was 0.091 and standard deviation was 0.109.

2.4.5 Critical Review of Resistance Uncertainty

Safety and risk are associated concepts though different in character, i.e. risk is quantifiable but safety is not, it is something to be achieved or assured [50]. The safety of Jacket platforms can be assured within risk management by considering the hazards to which they are subjected. It is emphasised by ISO code that resistance modelling has to be done for each geographic region. ISO and China studies report that the geometrical variables are normally distributed. The yield strength distribution was found to be lognormal for ISO in North Sea but Det Norske

Veritas (DNV) in one of its reports takes it as Normal. Study made in China reported it to be normal as will be shown in Chap. 4. The difference in variables is not much high, as is expected due to quality control on fabrication and manufacture of materials nowadays. Literature on resistance uncertainty is not available in Malaysia and therefore this issue will be dealt in this book. The influence of yield strength and model uncertainty on reliability analysis is emphasised by many researchers working in this area of study.

2.5 Load Uncertainty

The variability of load is considered random in nature and during reliability analysis, probability distribution and its parameters are used instead of a deterministic value. Proper estimation of load is the most important step for the design of structure. Sustainable development requires structural robustness of Jacket platforms against extreme environmental events. Environmental load uncertainty considered safe during design of a Jacket platform may become unsafe during one hurricane event in GOM. This was experienced during hurricane Ivan in 2004. Reliability analysis of Jacket platforms requires load models should be the probability distribution based due to random nature of loads.

Extreme value distributions, i.e. Fretchet, Weibull and Gumbel, are three theoretical distributions which are commonly applied to model load uncertainty parameters [51]. These distributions are formulated for the maximum, of an infinite number of events. It is easy to apply them as they represent the maximum load intensity to capture the tail characteristics of these distributions. Many researchers have assumed Weibull distribution for environmental load uncertainty for their study [52–54].

2.5.1 Load Uncertainty Parameters

There are two basic approaches to find the environmental load factor parameters, i.e. energy spectral density and statistical analysis method [55]. In this book, the second approach is adopted.

2.5.1.1 Characteristic Load

Characteristic value is taken as the most probable extreme value with a specified return period. The characteristic value of environmental load for extreme conditions is defined as the most probable largest value in a period of 100 years [34]. The nominal value is the value of random variable which has a probability of not being exceeded during reference period of 100 years as prescribed by ISO 19902. It is the maximum value corresponding to load effect with a standard probability of exceedance. It is the fractile in upper end of normally distributed function of load [48]. Primary environmental loads for fixed Jackets include waves, wind and currents but most of time waves produce the dominating load effect [34, 56].

2.5.1.2 Return Period Probability

Return period probability is shown in Eq. (2.9),

$$P = 1 - p^n \tag{2.9}$$

where n = platform life in years (30 years), p = annual probability that the event will not occur. Probability of occurrence of an event in 100 years is given by,

$$1/100 = 0.01$$

A return period of 100 years means an annual probability of occurrence of 0.01 or probability of non-occurrence of 0.99

$$P = 1 - (0.99)^{30} = 0.26 \,\text{or}\, 26\,\%$$

The results show that probability that it will experience at least one event with a return period of 100 years during its life is 26 %.

2.5.2 Statistical Data Uncertainty for Environmental Load

Environmental loads vary significantly due to uncertainty of wind, wave and current. Environmental loads are highly variable and the Jacket may fail from overloading effects as they sometime may produce loading effect which is more than the design loads. The COV of extreme environmental loading for North Sea is 65 % and GOM is 77 % [57]. The intense tropical cyclones (typhoons) in the Pacific Ocean create governing extreme conditions in these areas. Storm is termed as three phase progress of severe sea involving a development, a peak and decay phase as shown in Fig. 2.4. The total duration may be between 12 and 39 h of sea state, characterised by development phase, i.e. growth (0–18) h, a peak duration of 3 h (18–21) and subsequent decay phase duration of 21–39 h, i.e. 18 h [58–60].

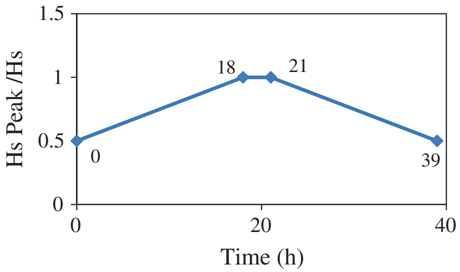

Fig. 2.4 Development of storm growth, peak and decay [59, 60]

The wave is the dominant load here along with gravity loads. The effects of any load which are less than 10 % of the effects of any other type of load may be ignored like wind loads [61].

The extrapolation of probabilistic models depends on distribution functions plotted in straight ascending lines. The wind speed, wave height, time period and current speed are plotted against the return period. Straight line is fitted to the plotted data and it is extended beyond the available data to acquire the estimation of extreme values for the desired return periods. This straight line which fits to the data may be subject to some errors on uncertainty of extrapolation [53]. The errors can only be decreased by increasing the data points with extended time period.

2.5.2.1 Collection of Data

ISO code points out that the statistics of long-term estimation of metocean parameters requires that the individual number of storms used for the statistical analysis must be statistically independent. Wave height taken at hourly rate depends on the wave height of the previous hour. Thus, situation of independence of wave is not achieved. To produce independent data points, only numbers of storms are considered for the statistical analysis. Collection of data for wave height is made in two steps:

(i) Long-term statistics uses the highest significant wave height and its associated period. The data are taken from storm data. It is taken for average of 20 min time periods and recorded after 3 h intervals.
(ii) Short-term statistics uses expected amplitude of highest wave. Such an extreme sea state is estimated, from assumption of linearity. Thus, the higher peaks are taken as Rayleigh distributed.

2.5.2.2 Weibull Distribution

Weibull 2-parameter distribution is an extreme value distribution. It is used to capture the variability of rare event which may occur once during the return period. The variable x has the CDF as shown in Eq. (2.10),

$$F(x; a, b) = 1 - \exp\left[-\left(\frac{x}{a}\right)^{b}\right] \tag{2.10}$$

Parameters a = scale and b = shape, $Fx(a, b)$ = Cumulative Distribution Function (CDF) of variables a, b. Their linear form can be shown by taking the natural logs twice of CDF of Eq. (2.9) in $x_{(i)}$, Eq. (2.11) [62] which shows that,

$$\ln\left\{-\ln\left[1 - F\left(x_{(i)}\right)\right]\right\} = -b\ln(a) + b\ln\left(x_{(i)}\right) \tag{2.11}$$

The plotting of $\ln\left\{-\ln\left[1 - F\left(x_{(i)}\right)\right]\right\}$ against the data $x_{(i)}$ results in a straight line, if the data came from Weibull distribution. The parameter “a” is found from intercept and "b" by slope of straight line. The slope corresponds to shape and intercept to scale parameters. Scale parameters are used for the model "F" on the measurement axis by using its scale. This parameters show the horizontal stretching or contracting of the model "F". They are shown always in the following form as "a" in $\frac{x-b}{a}$. The shape parameter determines the basic shape of function "F", gives a measure of dispersion. This parameter does not relate to x in a set arrangement common to all models "F" [62].

2.5.2.3 Gumbel Distribution

The Gumbel distribution variable x has the CDF as shown in Eq. (2.12),

$$F(x; c, d) = \exp\left\{-\exp\left[-\frac{x-c}{d}\right]\right\} \tag{2.12}$$

Parameters $c =$ location and $d =$ scale. Their linear form can be shown by taking the natural logs twice of CDF as shown in Eq. (2.13) in $x_{(i)}$, [62]

$$-\ln\left\{-\ln\left[F\left(x_{(i)}\right)\right]\right\} = -d(\mathrm{c}) + d\left(x_{(i)}\right) \tag{2.13}$$

The plotting of $-\ln\left\{-\ln\left[F\left(x_{(i)}\right)\right]\right\}$ against the data $x_{(i)}$ results in a straight line, if the data came from Gumbel distribution. The parameter "d" is found from intercept and "c" by slope of straight line. The slope corresponds to location and intercept to scale parameters. Location parameters locate the model F on its measurement axis. They are identified by their relation to x in the function "F", i.e. $(x - c)$ in (2.12). Scale parameters scale the model "F" on the measurement axis. This parameter shows the horizontal stretching or contracting of the model "F" [62].

2.5.2.4 Wave

The primary parameter in the classification of sea states is the wave height, which is calculated from peak to trough. The actual selection of design wave height, to be used for specific platforms deign, is a matter of engineering knowledge and judgement. Jacket platforms are inherently more sensitive to waves than current and winds [54, 63, 64]. This is due to peak response always occurs at the time of maximum wave height [63, 65]. During a conventionally short time period of 20 min for a sea state to be regarded as statistically stationary, the most important measure is significant wave height, which is a average wave height of highest one-third of the waves. Only wave parameters are taken into consideration for calibration of environmental load factor for API RP 2A LRFD. Mean bias and COV was set up as 0.70 and 37 % [39]. This was same as for wind, therefore only wave was considered for reliability analysis. Weibull distribution fits well with significant wave height [66]. Design wave height is obtained by multiplying the significant wave height by a factor in range of 1.8–2.0 [67].

2.5.2.5 Current

Currents can play significant role in total forces acting on Jacket platform. Current refers to motion of water which arises from sources other than surface waves. Tidal currents arise from astronomical forces and wind-drift currents arise from drag of local wind on water surface [68]. When extreme waves along with superimposed current occur in same direction, velocities from both can combine and produce large wave pressure [23]. Independence of wave should be assumed because there is no reason to believe that extreme wave will occur at the same time as extreme current [4]. The maximum wave height and maximum current occurred only once simultaneously out of 38 storms in North Sea [69].

This current load may never reach the probability of failure of 10^{-1} in the region of Malaysia. During storm conditions, current give rise to horizontal structural forces equal to 10 % of the wave-induced forces [70]. Even in Norwegian continental shelf, current load experienced is not higher than 10-year load with yearly probability of exceedance of 10^{-1} [71]. That is the reason why ISO code considers 1–5 years time period for operational conditions for South China Sea instead of 1 year as is considered for Gulf of Mexico or North Sea. In North Sea, the current speed used for design of offshore Jacket platform is of 10 year maximum with associated 100-year design wave [72].

2.5.2.6 Wind

During storm conditions, wind could have significant effect on design of Jacket platforms and it can induce large forces on exposed parts. The effect of wind force depends on size and shape of structural members and on wind speed. Wind force arises from viscous drag of air on component and from difference in pressure on windward and leeward sides [67]. For Jacket platforms, wind load can be modelled as deterministic quantity [73, 74]. Wind force is small part, i.e. less than 5–10 % of wave force [64, 75]. Wind is measured at 10-m reference height. Wind influences the build up of waves which can take significant time, i.e. many hours. This shows that the short-term variations of wind speed and sea elevation may be considered independently [29]. Wind is responsible for generation of surface waves [76]. Bias and COV for wind was found to be as 0.78 and 37 %. This was almost same as wave parameters [39]. Wind was assumed to be 2 parameters Weibull distribution for northern North Sea [77].

2.5.2.7 Environmental Load Modelling Uncertainty

Environmental load model uncertainty was taken as normal distribution with COV of 0.15 and mean bias value of 1.09 [43].

2.5.3 Critical Analysis of Load Uncertainty

The gravity loads and environmental loads both are random variables. The gravity load statistics have been taken from literature in this book. Gravity loads are taken as normal and environmental load are selected as Weibull and Gumbel but Weibull is preferred choice of engineers. The load uncertainty has large COV which influences the probability of failure significantly as will be shown in Chap. 7. The data collection is very important for reducing this uncertainty. Therefore, if this uncertainty is to be reduced, then more accurate data collection method should be applied.

2.6 Environmental Load Modelling of Jacket Response

The environmental load model is necessary for the development of load factor using reliability index. Total wave force on platform equals to square of wave height [78]. In this book, the responses of Jacket (strength of components) in terms of basic applied loads which govern its behaviour are modelled. This can be represented by stochastic processes or random variables. For the FORM analysis, it is necessary to use random variable formulations [79]. Different methods for finding the response of offshore Jackets subjected to random ocean forces have been widely published [4, 16, 80–82] and two are shown below. Methods suggested by SHELL for development of load factors for ISO are shown in Eq. (2.14) [43, 83, 84].

$$W = aH_{\max}^2 + bH_{\max} + cV_{\mathrm{c}}^2 + dV_{\mathrm{c}} + e \tag{2.14}$$

where W = Load effects, $H_{\max}$ = variable annual maximum wave height, V_c = variable current speed, coefficients of a, b, c, d and e are found from curve fit tool of MATLAB. Another method is proposed by Heidman which is shown by Eq. (2.15) [20],

$$W = a_1(H_{\max} + a_2 v_c)^{a_3} \tag{2.15}$$

Coefficients of a_1, a_2 and a_3 are found from curve fit tool of MATLAB, $H_{\max}$ = maximum wave height and v_c = current speed. Here a_1 factor depends on the size of load area of Jacket [14].

2.6.1 Environmental Load Uncertainty Model

The environmental load model uncertainty (X_w) was used in development of API LRFD and ISO codes. ISO and BOMEL take it as normal distribution with mean bias of 1.09 and COV of 0.18 [43].

2.6.2 Dead Load

ISO categorises the dead load into 2 classes. Permanent load action, G_1, includes self-weight of structure and associated equipment. This is self-weight part of gravity load. Permanent load action, G_2, represents the self-weight of equipment and other objects that remain constant for long periods of time, but which can change from one mode of operation to another. It is treated as normal random variable. The statistical parameters of bias (mean over nominal) are taken from ISO code. The distribution was considered as normal with mean bias of 1.0 and COV of 0.06 [39, 64, 85–88]. In South China Sea, mean bias is 1.0 and COV of 0.08 which is reported in literature [86, 88].

2.6.3 Live Load

It is the permanently mounted variable load Q_1 and variable action, Q_2, represents the short duration action. The distribution is considered as normal with mean bias of 1.0 and COV of 0.1. These values are used for calibration of Jacket platforms in GOM and North Sea [85, 39]. The same values are used for calibration of load and resistance factor design for platforms in China [88] but mean bias of 1.0 and COV of 0.14 is suggested by [86].

2.7 Structural Reliability

Risk and safety are two intertwined words. For Jacket platforms, safety can be achieved by management of hazards produced by rare events of wave, wind and currents. Material strength of tubular components and joints plays significant role against risk. After treating the uncertainty of resistance and load, the issue of structural reliability is dealt with for three areas, i.e. component, joint and system. Reliability is defined as an ability, to achieve a desired purpose of platform under operational and extreme conditions, for its designed life. Structural reliability concept consists of structural safety and resistance, serviceability, durability and robustness [38]. Performance of a platform is measured in terms of reliability index or return period (probability of failure). Calibration of North Sea and GOM LRFD code development has used six Jacket platforms [89, 90]. Structural reliability can be found for time-dependent or independent reliability analysis. In this book, time independent reliability is considered.

Before probability-based codes were developed, structural codes contained safety criteria using allowable stress method. Structural system was assumed to act always elastically and inelastic behaviour was never assumed. The risk was catered by reducing the yield strength of member. Actual loads were calculated first and then members were selected so that the allowable member strength remained below certain limit like 66 % of yield strength. Thus, a factor of safety of 2/3 was always there in the member for extreme load combinations. Code developers use this factor using judgement. Reliability analysis methods using probability and statistics, started to gain importance since 1960 under the patronage of CA Cornell, NC Lind and H.S. Ang. It was Cornell who in 1969 proposed second moment reliability index method [91] which was further developed by Hasofer and Lind, who gave a proper format to invariant reliability index [14, 92]. Rackwitz and Fiessler gave an efficient numerical procedure for finding the reliability index by using non-normal probability distributions. Rosenblueth and Turkstra gave load combinations. Moses helped in the development of API LRFD for Jacket platforms on which ISO 19902 code is based [16, 41, 93]. Der Kiuregian developed FERUM software for reliability analysis [94] which uses FORM reliability analysis method.

For normal distribution, the characteristic value used to be taken as 1.645 times standard deviation, i.e. an upper value and a lower value for load and resistance as shown in Eqs. (2.16 and 2.17). On load and resistance curve, the characteristic value is the 0.95 fractile for load and 0.05 for resistance. This shows that on load side 95 % of design load will lie below this value. On resistance side only 5 % values will be below the design strength. Equations (2.16 and 2.17) show the load and resistance characteristic values.

$$\text{Characteristic load } = \mu + 1.645\,\sigma \tag{2.16}$$

$$\text{Characteristic resistance } = \mu - 1.645\,\sigma \tag{2.17}$$

where μ = mean of normal distribution and σ = Standard deviation of normal distribution. It is possible to relate the number of standard deviations to probability of occurrence. One standard deviation both side of mean relates to 67 % of probability of occurrence and two standard deviations equals to 95 % [95].

2.7.1 Reliability Levels

Levels are characterised by amount of information about the problem is provided or it is determined by how many random variable parameters are being used. If characteristic values are used then it is called level I. If standard deviation and coefficient of correlation are also used then it is termed as level II, and if cumulative distribution function is also used then it is level III [14]. If engineering economic analysis is involved then it is level IV.

2.7.2 Parameters of Structural Reliability

2.7.2.1 Limit State

When a structure exceeds a particular limit and the Jacket is unable to perform as desired, then at that particular limit it is said that limit state has reached. If that limit state is exceeded then the Jacket is considered unsafe. Conditions separating satisfactory and unsatisfactory states of structure are known as limit state [38]. There are four categories of limit state. The ultimate limit state is concerned with collapse of structure or component and it is necessary that it must have extremely low probability of failure. This limit state is concerned with maximum load carrying capacity of Jacket [48]. The structure must be able to withstand actions and influences occurring during construction and anticipated use in this limit state [38]. The serviceability limit state is related to interruption of normal use of that Jacket, this includes large deflection, excessive vibration, cracks, etc. Structure must remain fit for use under expected conditions of serviceability limit state conditions [38]. Fatigue limit state is due to cyclic loading and governs for operational conditions. Accidental limit state is used in consideration of accidental loads. It should maintain integrity and performance of Jacket from local damage or flooding [48].

2.7.2.2 Reliability Index

Reliability is a measure of probability of failure of structural member. It is the probability that system will carry out its intended purpose for certain period of time under conditions defined by limit state. This is a truth that it is practically not possible to make a member which does not fail for any kind of load. There will always be some chance or probability that the uncertain load will become large or resistance will be smaller than estimated, which will cause the member failure. It depends on what risks or reliability index value, the related industry is ready to take. For example, if the risks are high, as in offshore industry, higher reliability index or safety index is required but this increases the cost of structure. If risk is low, lower reliability index may also be accepted as in some cases of non-important structures. Table 2.4 shows that as probability of failure decreases the reliability index increases. The same can be shown graphically in Fig. 2.5 that shows the reliability index (β) against probability of failure (P_f). Where (β) can be found through Microsoft Excel function, using Eq. (2.18),

$$\beta = \text{NORMSINV}(P_f) \tag{2.18}$$

Table 2.4 Probability of failure and reliability index relationship [29]

β	Pf	Return period
1.28	1×10^{-1}	1 in 100
2.33	1×10^{-2}	1 in 100
3.09	1×10^{-3}	1 in 1,000
3.72	2×10^{-4}	1 in 5,000
4.26	1×10^{-4}	1 in 10,000
4.75	1×10^{-6}	1 in 1,000,000
5.20	1×10^{-7}	1 in 10,000,000

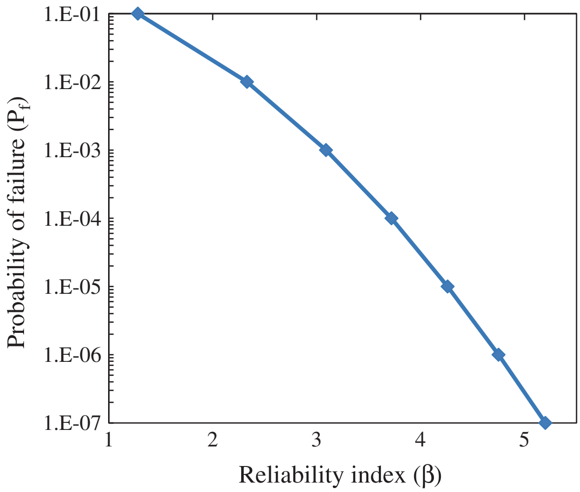

Fig. 2.5 Relationship between safety index and probability of failure [29]

2.7.2.3 Probability of Failure

Risk is defined by probability of occurrence of unfavourable event. There is no risk-free design. Risk depends on degree of overlap of load and resistance probability density curves [8]. Optimised design is reached when increase in initial cost is balanced by decrease in expected failure consequence cost [8]. Reliability model defines load and resistance as probabilistic random variables. It is referred as unsatisfactory performance of components particular performance criteria. Platforms in North Sea are designed for a ductility requirement of 10^{-4}/year with a possible annual failure probability of collapse of 10^{-5}, Efthymiou calls this could be 10^{-7} [96]. Annual failure probability is considered for structures where human life is of concern. Where material cost is of importance, design life of structure is considered for failure probability [39, 97]. The preferred safety level for engineering structures is by using loss of life probability due to structural failure. Individual accepted risk is by use of death due to failure of structure and in developed countries it is 10^{-4}/year [98].

In reliability-based design, an engineer is allowed to select a probability of failure which is proportionate with the failure consequences. This makes design engineer to decide what probability of failure he shall take for a particular Jacket. Thus by this concept, component or joint can be utilised to full capacity, thus making an economical Jacket such as unmanned Jackets [8]. Structure cannot be designed with 100 % surety that it will sustain all types of loads forever, i.e. there is no zero risk structural design. If higher safety margins are provided then the load and resistance curves will move further apart thus it will reduce the probability of failure but it will not totally remove load and resistance overlap [8].

The structural failure is shown as Eq. (2.19)

$$P_f = P(R < Q) \tag{2.19}$$

where P_f = probability of failure and P = probability. Thus, probability of survival can be shown by Eq. (2.20),

$$P_s = 1 - p_f \tag{2.20}$$

where P_s = probability of survival.

2.7.2.4 Target Reliability

Target reliability for offshore platforms depends on either reliability of platforms designed as per the old code like API WSD or on probability of failure acceptable to society. In this book, probability of failure is determined by assessing the effects of wave and current loading which are the most severe loading criteria for design of offshore platforms. Target reliability is required for calibration, in order to make sure that certain safety levels are maintained. It is minimum annual average reliability shown as a maximum failure probability for a given safety class, consequence, category and failure types, provided by the codes of practice for Jacket design. For setting a value, it requires some exercise of engineering judgement [99]. Target reliability is different for manned and unmanned Jacket platforms. For manned platforms, decision is made by required probability of failure, due to environmental loading. It should be small as compared to other high consequences and major risks such as fire, explosions and blowouts [100]. There is agreement among researchers that if annual probability of failure due to some cause is less than 1 in 10,000, then it is small in relation to major risks [100]. Assuming that in North Sea during 30 year, there are 250 platforms, now platform years will be (30 × 250) = 7,500 platform years. Expected number of failures over 30 years period is then P(a) × 7,500, [P(a) = annual probability of failure]. Most probable outcome will be zero failures if [P(a) × 7,500 < 0.5], which leads P(a) < 1 in 15,000 [100].

DNV reports acceptable annual target reliability for redundant Jackets as 3.09 or probability of failure of 10^{-4} [33]. Many researchers have proposed target code of API WSD/API LRFD RP 2A/ISO 19902, for selection of target safety index. Separate partial factors are used for load effect types (axial, bending force, hydrostatic, etc.) [85]. For Ekofisk area, in North Sea, target annual probability of failure is 5×10^{-4} (design should make sure a 2,000-year return period of collapse limit state) [101]. This target failure probability of 1/2,000 per year is chosen as it is consistent with API guidelines for design of new platforms [101]. DNV provides the values for safety index and probability of failure used by the codes. Table 2.5 shows the target reliability for North Sea Jackets.

Table 2.5 Indicative target reliability [120]

Limit state	Annual	Lifetime
Ultimate limit state	3.8	4.7
Fatigue limit state	1.5–3.8	–
Serviceability limit state	1.5	3.0

Table 2.6 Probability of failure recommended for NS jackets [120]

Conditions	P_f
Severe consequence, i.e. (potential fatalities or significant environmental damage)	4^{-4}
Only economic consequences are involved	1^{-3}

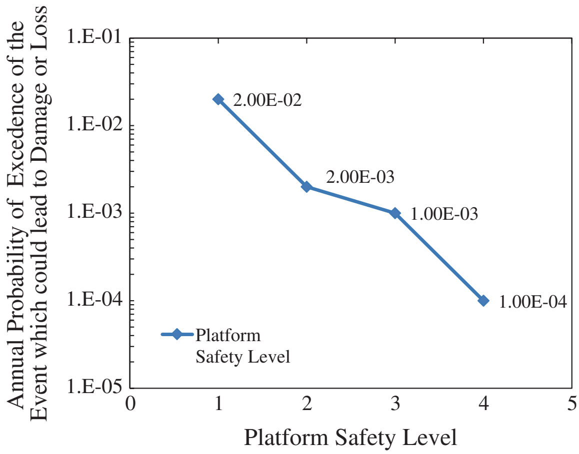

Fig. 2.6 Acceptance criteria for ductile jacket platform at different safety levels [96]

In order to apply reliability methods, it is necessary to find components failure function, uncertainty model, probability calculation method and target safety levels [102]. Table 2.6 shows the target reliability in shape of P_f using consequence of failure of fatalities or economic reasons.

Figure 2.6 shows acceptance criteria for target reliability of Jacket platforms at different safety levels. 1×10^{-4} is used for manned platforms, 1×10^{-3} is used for unmanned platform (high consequence), 2×10^{-3} unmanned platform (low consequence) and 2×10^{-2} closed down platform (ready for removal).

2.7.3 Review of Structural Reliability Methods

There are basically two types of reliability analysis methods, i.e. simulation and analytical. The major example for simulation method is Monte Carlo simulation. Monte Carlo simulation is easy to use, robust and accurate by using large number of samples, though it requires large number of analysis for achieving the good quality approximation of low probability of failure. The problem with this simulation technique is that it produces noisy approximation of probability. Analytical methods include moment-based methods such as First Order Reliability Method [44]. Cornell in 1969 proposed reliability method, i.e. Mean Value First Order Second Moment [103]. It was in 1974 when Hasofer and Lind proposed reliability index using FORM method.

2.7.3.1 First Order Second Moment (FOSM) Method

Probabilistic calibration is done to find safety factors in a balanced manner. It takes into consideration the sources of uncertainty in environmental load and material resistance [29]. This is a level II reliability method. In this, safety is measured by the first and second moments like mean and standard deviation. The method was proposed by Cornell using theory of reliability measurement in 1967 [14]. The safety index depends on mean μ and standard deviation σ which are expressed in Eq. (2.21).

$$\beta = \frac{\mu}{\sigma} \tag{2.21}$$

where β = reliability index, μ = mean (used to express the central tendency for a random variable in a distribution curve), σ = standard deviation (dispersion of random variable). This means that safety index is the distance in terms of standard deviations. It lies between origin and mean values of margin of safety in distribution curve [14]. Probabilistic calculation techniques enable these uncertainties to be taken into account. Probability distributions characterise the uncertainties associated with mean load ($\bar{Q}$) and mean resistance ($\bar{R}$). It is expected that safety factors calibrated for drag-dominated wave loads will be conservative for inertia-dominated load [29]. Equation 2.22 shows the ratio expressed as lognormal distribution. If the coefficients of variation of resistance (v_r) and load (v_q) are less than 30 %, the safety index can be calculated by [89],

$$\beta = \mathrm{Ln}\ (\bar{R}/\bar{Q})/\sqrt{v_r^2 + v_q^2} \tag{2.22}$$

where, $\bar{R}$ = mean resistance, $\bar{Q}$ = mean load, v_r = COV of resistance v_q = COV of load.

2.7.3.2 First Order Reliability Method (FORM)

FORM reliability method has been used for reliability analysis of Jackets by many researchers [36, 40, 42]. This is the most significant tool available to find reliability index and widely being followed nowadays to find reliability. The FORM solution provides geometrical interpretation of reliability index as the distance between origin and design point in standard normal space [32]. The first step is to transform the basic variables which may not be normally distributed into the space of standard normal variables. Thus, it is transformation of limit state surface from given space of basic variables to a corresponding limit state surface in standard normal space. Design point is the point on limit state surface which is nearest to origin and is found by optimisation process. This is taken as the most likely failure point. Here, limit state surface in standard normal space is approximated by a tangent plane at the design point.

2.7.3.3 Simulation Techniques Like Monte Carlo Simulation (MCS)

Monte Carlo simulation is another method used to find probability of failure and reliability index. This is an alternative or complementary tool for estimation of probability of failure [32]. Rubinstein in 1981 was the pioneer of Monte Carlo simulation method. It generates large number of random variable (x) samples through the use of random number generator. If the limit state function is implicit, the computation requires large number of simulations for exact function evaluation. Accuracy in this technique depends on number of simulations [97]. The sample values of random variables generated are extremely large and number of failures is counted. Thus, capacity of computer required to do the analysis is used to be high. The probability of failure can be evaluated by Monte Carlo simulation as shown in Eq. (2.23),

$$P_f = \frac{N_f}{N} \tag{2.23}$$

where N_f = number of failures, N = total number of simulation. COV of failure probability (V_{pf}) can be evaluated by Eq. (2.24),

$$V_{pf} = \frac{1}{\sqrt{P_{f \times N}}} \tag{2.24}$$

However, there are few problems with this method. In this method, approximation of performance function is used to reduce the computational cost. Random sampling used in this method produces inaccuracy in the results [26]. It is because the random numbers generated by the random number generators, which are produced in clusters and not uniformly distributed over the whole design space, may repeat again. The other problem in this method is that estimated probability of failure depends on sample numbers used for simulation. Therefore, if lower order failure probabilities are required, the sample numbers needed are higher which increases the cost of computation [26].

2.8 Component Reliability and Previous Work

Component failure occurs due to formation of plastic hinge, member buckling, joint failure due to fatigue cracking or brittle fracture [103]. Component reliability for Jacket platforms has been determined by researchers such as [27, 38, 40, 42, 79, 104]. The work on component reliability has been done in many regions of world including GOM, North Sea, China, Mediterranean Sea and Gulf of Guinea. Failure probability of each component depends on the magnitude of the stresses and corresponding strengths. Strength of tubular component is function of mechanical properties of material, yield strength and dimensional properties. Only the uncertainties in yield strength are of major importance in governing the failure probabilities of tubular legs and brace components [78]. This is due to the fact that leg members have low slenderness ratio. Failure is governed by yield stress and reliability of component can be increased by using steel with high mean yield strength [78]. Jacket design depends on elastic skeletal frame analysis. Distribution of stresses is found when it is subjected to design environmental loads.

Individual component stresses are evaluated to make sure that no elements fail against the governing criteria [105]. This type of failure is related to stresses which are produced in members like compression (buckling local or global), bending due to yielding of material and hydrostatic. PAFA reports that gravity load dominates the leg members but environmental load dominates the design of brace members [106]. For buckling, governing design condition is in place extreme environmental condition. This condition is valid for majority of structural components in offshore platforms. Most frequent components found in Jacket platform are tubular members under combined compression and bending with ratio of compression to bending stresses being generally high [107].

2.8.1 Component Reliability Index-critical Review

Codes of practice for Jacket design, API WSD and ISO 19902 are both component and joint-based design codes. Component reliability for Jacket platforms in North Sea was made for ISO code development by BOMEL [42]. Environmental load factor for extreme conditions achieved for North Sea was 1.25. For consistency with GOM calibration, environmental load factor of 1.35 was retained for ISO code. Environmental load factor for component proposed for Mediterranean Sea is 1.30 [38]. Therefore, it is high time to evaluate the load factor for offshore Malaysia.

2.9 Resistance Factor

Resistance of tubular members is multiplied by resistance factor which represents the uncertainty related to prediction of failure mechanism [108]. Resistance factor depends on type of resistance, i.e. tension and bending can be predicted more accurately as compared to column buckling. Therefore, ISO resistance factor for tension and bending is 1.05 but for compression it is 1.18.

2.10 Joint Reliability and Previous Work

Joint reliability has been determined by researchers such as in GOM, North Sea, China, Mediterranean Sea and Gulf of Guinea [38, 40, 42, 109–111]. For Jackets, the joints are connected by primary members called chords usually with larger diameter compared to secondary members called braces. In tubular Jacket frame, intersections between main members (chord) and secondary members (brace) are welded together and are called tubular joints [112]. Chord and brace members undergo combined stresses. This is due to hydrostatic pressure and bending moment which arise due to wave and current forces and from load distribution at the nodal points [5]. Joints are the most critical part of truss structure like Jacket. The work on modelling of joint stresses is still very active. With respect to API code, 21st edition published in 2000, the errata published in API 2008 contain many changes in joint design equations.

Out of all three types of joints K, T/Y and X, the X-type is the most preferred one due to its ductile nature. Capacity and redundancy for ductile redistribution of stresses for an X-braced joint contributes to the reserve strength of structural system which may not be the case for K-Joints. X Joint imparts significant ductility, mobilises alternative load paths and gives high frame capacity. Thus, ductile behaviour of X braces at failure and brittle behaviour of K-braced frames suggest that different acceptance criteria may be appropriate for redistribution of forces for structural system [105]. That is, the reason that X-braced frames are more in new Jackets as compared to old Jackets.

2.10.1 Joint Reliability Index-critical Review

Joint reliability for Jacket platforms has been done for ISO code development by BOMEL. Joint environmental load factor for extreme conditions achieved for North Sea is 1.25 [42]. For consistency with GOM, load factor of 1.35 is retained in ISO code. In Mediterranean Sea, joint environmental load factor proposed is 1.20 [38].

2.11 Reliability and Environmental Load Factor

Bilal [9] reports that primary factors affecting the evaluation of load factor are characterisation of failure modes (limit states), assessing implicit reliability levels in existing design code, i.e. API WSD and assigning the target reliability. Target reliability selection depends on calibration of existing code by judgement. Calibration is process of finding reliability levels in components and joints designed using API WSD code [9]. The safety factor in working stress design is evaluated arbitrarily using experience and judgement of designers. Loads are factored on the basis of load uncertainties, i.e. the environmental loads have larger safety factor as compared to gravity loads [108]. The design load action is found from characteristic load multiplied by a load coefficient γ. Characteristic loads are same for ultimate and serviceability limit states and only their load coefficients differ. Serviceability limit state takes γ_w value as 1.0 while for ultimate limit state, ISO and API takes γ_w as 1.35 for environmental loads [33]. In structural engineering, useful function of reliability analysis has been precise in the development of

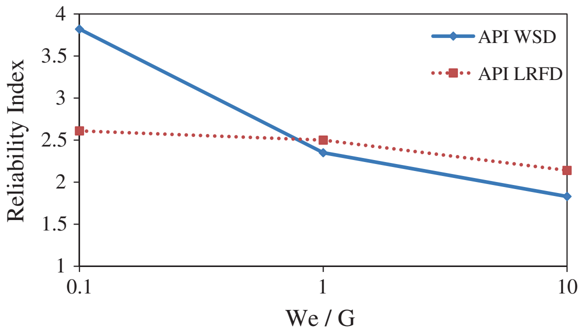

Fig. 2.7 Variation of We/G ratio with reliability index for axial tension [7]

structural codes where the end product has been an optimised set of partial factors [78]. In load and resistance factor design, uncertainties are considered objectively by performing reliability analysis taking characteristic values of statistical variables. The environmental load factor can be decided by using target reliability as shown in Fig. 2.7. Here target reliability is shown by API WSD and ISO gives us the reliability of new code. The new code reliability index at We/G ratio of 1.0 gives higher reliability as compared to API WSD. This higher reliability will give us the required load factor, as this will contain higher reliability than API WSD which has already proved its robustness.

The safety index for LRFD was lower for low environmental to gravity loads ratios and higher for high environmental to gravity load ratios [88]. Theophanatos has proposed environmental load factors for Mediterranean Sea using variation of Reliability Index with Varying W_e/G [38].

2.11.1 Code Calibration

There are various methods used for code calibration such as judgement, fitting, optimisation, or combination of these. Code calibration for ISO is a method to determine the target reliability by decision making or optimisation of the load factors or resistance factors [113]. Optimisation process is used when it is to be enforced for common level of specific designed structures to that particular target reliability. The target reliability should be selected so that structures designed as per the design codes are homogeneous and independent of material and loading (operational and extreme) conditions [87].

2.12 Nonlinear Collapse Analysis

Progressive collapse is a feature of structural system rather than of an individual component. Structural codes specified element design, without giving consideration to assembly of multi-element structures, till “Ronan Point” disaster in 1968.

Structural collapse brought the consideration of problem of progressive collapse commonly referred as “domino effect” [98]. For ultimate limit state, during linear elastic analysis, strength of structure is considered up to first yield. Due to residual stresses, local yielding may occur for loading less than ultimate limit state condition [114]. Ductility of steel makes it possible to redistribute the stresses which make it possible to face some yielding. Structural failure can be explained as full development of yield mechanism. Soreide reports that nonlinear collapse analysis of maximum load criteria simulates the real behaviour of structure during collapse [114]. The allowable stresses are not taken as they used to be in linear elastic analysis but a ratio of design load to collapse strength of structure is evaluated. The work on nonlinear collapse analysis for Jacket platforms has been conducted by [89, 114–117]. This is currently most popular method of analysis for structural system strength in the presence of extreme loads. Chakrabarti reports that for a Jacket with nonlinear analysis will always give near to or lower than the collapse load compared to linear elastic analysis [114]. Structural Analysis and Computer Systems (SACS) software is used for Jacket analysis in this book. SACS uses its collapse analysis module for nonlinear analysis of Jacket.

2.13 System Reliability and Reserve Strength Ratio (RSR)

System reliability of Jackets in North Sea and GOM has been studied by many researchers [70, 117–119]. The comparison of system and component reliability provides a measure of effect of redundancy in reliability index [79]. For system reliability assessment, it is important to evaluate the likelihood of system failure following first component failure [46]. Structural system reliability has been defined as series and parallel. It is a complex approach for evaluating the system strength in case of nonlinear analytical behaviour. An approximate method has been proposed for Jacket system analysis in North Sea [82]. The structure’s model is developed directly as a system and nonlinear analysis and failure modes are evaluated directly [89]. It is important for economic exploitation of hydrocarbon reserves, from new and old Jackets to understand and realistically predict the ultimate response of the Jacket [105]. One clear progress from elastic design to inelastic design is considered to be evolution towards more efficient steel structure design by using system strength evaluation [115]. Failure of a structure is said to be global collapse, i.e. load exceeding the ultimate capacity of the Jacket [120]. System reliability starts with a single member failure but it causes the failure of whole structure. Reliability of Jacket platform depends on performance of components but it is governed by structural system [7]. Reliability of system is a product of individual member reliabilities. System reliability is taken higher than component reliability or system probability of failure is taken lower as compared to component probability of failure [121]. The uncertainties in the Jacket loading model are assumed due to wave height for system reliability. The wave period and current speed are taken as deterministic functions of the wave height [73].

If the Jacket has survived the extreme wave loading without any damage, the uncertainty about the strength should be updated and reduced [70]. This will be checked during application of Bayesian updating. The preloading of Jacket at a load level with probability of exceedance of 10^{-5} or less will prove the safety of platform against similar loading conditions if ever to arise. It is very essential to develop a methodology for optimisation of loads and resistance. RSR is the ratio of maximum tolerable load as per nonlinear analysis and characteristic design load. The RSR should be determined in all directions and the lowest RSR should be taken as Jacket's RSR [114]. Out of all directions, minimum RSR is used to find the reliability as ISO code is looking for optimised Jacket. The most important RSR value is the lowest, which is related to the weakest direction or extreme environmental loading [82]. Graff and BOMEL have given the methodology for finding RSR by considering structural system [82, 122] using North Sea Jacket platforms. RSR against different We/G ratios for North Sea platform has been calibrated previously [82]. With increasing We/G values, RSR is decreasing and high load factor gives high RSR values.

2.13.1 Previous Work on System Reliability and Load Factors

The environmental load factor for North Sea has been proposed by BOMEL by use of system reliability [82]. System environmental load factor of 1.25 is achieved for North Sea Jackets. The environmental load factor of 1.35 is suggested due to consistency with GOM. The target probability of failure is set as 3×10^{-5} proposed by Efthymiou [82] for system reliability as reported by BOMEL. Environmental load factor adopted by ISO are evaluated based on the probability of failure of 3×10^{-5} [82]. The reliability index lies in range of 2.5–5.0, which is higher than component reliability index, i.e. 2.5–3.5 of these platforms as suggested also by Moan [121]. The reliability index against load factor is evaluated for platforms in North Sea for three We/G ratios [82]. The load factor selected here is 1.25 by using notional target reliability of 4.0. Load factor is determined at the point where We/G line crosses the target reliability. This is due to the reason that the target reliability is the required safety level. Therefore, once this is achieved, the load factor will be considered as safe as per the new code.

2.13.2 System-based Environmental Load Factor-Critical Review

During design phase, the lead time is so small that actual site-specific data on environmental load and material are not available with design engineer. Therefore, once Jacket is installed, its probability of failure is evaluated. The API and ISO codes require that system strength should be checked against environmental load of 10,000 years return period. Jacket platforms are designed using component and joint reliability. Environmental load factor for system only shows the redundancy of Jacket, and it is not used during design of Jacket. System-based environmental load factor for Jacket has been evaluated by BOMEL [82]. System strength is evaluated by using collapse analysis of Jacket, base shear, wave and current loads. System environmental load factor shows the redundancy available in Jacket.

2.14 Assessment of Jacket

ISO and API codes require that Jacket should be assessed and monitored for any damages throughout its life. Before Jacket reaches the end of its design life, it is assessed whether it can withstand a load of 10,000-year wave return period as per the guidelines of ISO and API. This is a very important step before extension of service life is decided for Jacket. The cost of new Jacket design, fabrication and installation is quite huge. Thus, extension of life of Jacket will save a lot of money for the operator.

2.14.1 Bayesian Updating and Probability of Failure

Reassessment of Jacket platforms requires that platform must sustain a load of 10,000 years. Jacket failure due to structural design flaw was 10 % of all accidents in offshore industry worldwide [123]. Jacket platforms are designed with limited data available during design phase. This leads to uncertainty for future loads and resistances. The mathematical modelling of the structural design also becomes uncertain in the presence of random uncertainty of load and resistance. The information gathered after the installation of Jacket is used to extrapolate the extreme environmental event for wave height, wind and current speed. This is where probabilistic design comes into account. Codes of practice for Jacket platforms recommend notional failure probability to assess the effects of variable loads or strength problems. The updating of probability of failure with additional information collected on material and load can be used in many engineering applications. There could be variations in loading pattern or material problems arising due to severe environmental weather effects from ocean environment after certain time of existence of Jacket under water. It can be due to change of loading pattern, subsidence of Jacket, development of cracks, degradation due to fatigue or any other reason such as marine growth [114]. These observations at site can be used to update the probability of failure of Jacket by using the Bayesian method of updating. This will give us foresight about the ductile strength of the Jacket. Frieze et al. [79] used it for updating RSR for finding bias in push over analysis.

Bayes' theorem is used in cases when combined knowledge of statistical and judgmental information is available for updating probabilities through observed outcomes [124]. This theorem calculates the probability of occurrence of event "A", which depends on other mutually exclusive and collectively exhaustive event "B", given that event "B" has already occurred [125]. When additional information has become available about an existing Jacket, the knowledge implicit in that information may be used to improve the prior estimate of structural probability of failure [43]. Assessment of existing structure becomes real when damages are observed, use of platform is expected to be changed, deviations from project descriptions are observed, the lifetime is up to extension beyond what is planned and inspection schedules are planned to be revised [126]. Bayesian updating procedures allow the updating of probability for modelling uncertainty parameters and structural global response [127]. Bays theorem uses rational approach for incorporating the prior information or judgment into prediction of future behaviour of structures [128].

Bay's updating is calculated using Monte Carlo simulation. The updating probability of failure for Jacket platforms in North Sea has also been done [114]. Here, the updated probability of failure decreases with increasing of wave height. This is due to the reason that updating depends on both probability of failure and probability of survival results.

2.14.2 Damaged Structural Members

ISO 19902 clearly allows for existing Jackets to be accepted, with limited damage to individual components, provided that reserve strength against overall system failure and deformation remain acceptable [85]. Nonlinear collapse analysis approach is used by removing Jacket members and collapse capacity of damaged members is evaluated by Eq. (2.25) [116]. In this book, minimum RSR values are looked into along with Bayesian updating of probability of failure are discussed in Chap. 10.

$$\text{Damaged Strength Ratio} = \frac{\text{Design load}}{\text{Ultimate collapse capacity}} \tag{2.25}$$

2.14.3 Critical Review of Updating of Probability of Failure

The updating of probability of failure using Bayesian approach has been recommended by [15, 43, 129]. Updating of probability of failure using Bayesian technique has been adopted for Jacket platforms in Norway, for Jacket platform, this is used by [70, 102, 117–119]. This method can be used when the design life approaches its end and Jacket is required to be re-evaluated for its strength and extension of Jacket design life.

2.15 Summary

The critical analysis of this chapter shows that this topic is extremely important for the hydrocarbon industry of offshore Malaysia. If economics are to be considered as primary importance then this book will play some role in future developments of Jacket platform design in offshore Malaysia. The uncertainty models for resistance have never been evaluated in this region. The importance of reliability-based environmental load factor for component, joint and system shows that it should be evaluated. The updating of probability of failure also shows its importance with regard to extension of life of Jackets in Malaysia and for some cases like damaged members. For South China Sea, its use has not been reported in the literature.

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