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# Rationalisation of FPSO design issues

## Relative reliability levels achieved between different FPSO limit states


Prepared by
**Noble Denton Europe Ltd**
for the Health and Safety Executive


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# Rationalisation of FPSO design issues

## Relative reliability levels achieved between different FPSO limit states

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**HSE** BOOKS

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# FOREWORD

This report is an initial pilot study regarding limit state reliability and FPSOs. The work is entirely based on a review of literature and hence the reliability levels quoted exist with varying levels of uncertainty as sources vary from detailed reports to purely judgmental estimates. This should be borne in mind when interpreting any number from the report.

A further piece of work is currently underway to investigate the magnitude of these numbers and any relationships that exist between them.

The essence of this report was presented at the 15th Annual Floating Production Systems Conference, London, 11th - 12th December 2000.

# SUMMARY & CONCLUSIONS

At the request of the Health and Safety Executive (HSE), Noble Denton Europe Ltd (NDE) has carried out a ***qualitative review*** of reliability levels achieved by typical FPSOs for different limit states. This qualitative review has resulted in the identification of bands of probability of failure for the major limit states ***excluding*** risks associated with process systems. This report only deals with failure modes that are initiated by environmental overload or fatigue.

The study has identified 11 limit states with potential for serious consequences:

- Structural Strength – Hull Midship Section
- Structural Strength – Bow Structure / Slamming
- Structural Strength – Cargo Tank / Sloshing
- Structural Strength – Turret
- Station Keeping
- Fluid Transfer System
- Deck & Topside Design / Greenwater (Abnormal Waves)
- Stability – Intact
- Structural Fatigue
- Stability – Damage
- Ship Impact.

A large number of Codes, Rules and Guidelines have been consulted, together with reviews of technical papers dealing with reliability issues for FPSOs. Although a wide variety of possible inputs to the study were sought, the biggest challenge of the study has been to put the resulting reliability levels obtained by many researchers into many different limit states with differing component and system effects and consequences, on a common footing.

Because the study has been qualitative, it is important to realise the limitations associated with the probabilities of failure quoted in this report. Indeed, the failure probabilities estimated are ***unlikely to be better than ±1 order of magnitude.***

The relative criticality of the limit states has been addressed by first assessing the consequences and then by relying upon the work of Whitman (Ref. 20). Three types of consequences were examined - economic (loss of production), environmental (loss of containment) and safety (loss of life).

Three consequence classes were defined for this study. “High” consequence is considered to be one in which fatalities in excess of 10 could occur and/or oil spill in excess of 10000-100000 bbls could occur and/or production loss/delay of about $100 million could occur. “Low” consequence may be

defined as no fatalities and/or negligible oil spill and/or less than $1 million worth of production loss/delay. Medium consequence falls between these two classes.

Notwithstanding the accuracy limitations, Whitman's work provides a yardstick to identify the most vulnerable limit states. It provides a trend line with a reliable gradient, enabling the assessment of relative risk levels associated with the various limit states and assisting in pin-pointing the most critical limit states.

Such a study showed that the following limit states required the greatest attention to be paid in the mitigation of risks:

- Bow Structure Design / Slamming
- Deck & Topside Design / Greenwater
- Station Keeping and Fluid Transfer Systems
- Damage Stability
- Ship Impact.

The review has identified that considerable work has been performed on structural strength reliability, as well as on the reliability of station keeping and fluid transfer systems (Integrated mooring and riser design JIP by NDE). Some work is also currently being done on reliability as regards greenwater and slamming (JIP Marin), but there is still much to do on reliability for all remaining limit states.

Although there are recognised uncertainties with the reliability levels of all of the limit states addressed, the biggest difficulty has been in determining whether or not the reliability levels identified by specialists in the different areas of FPSO design can be compared with confidence. It is the conclusion of this work that at the ends of the spectrum of reliability results, firm conclusions could be drawn. But further work is absolutely essential to quantitatively identify and compare the reliability levels of those limit states that have been identified in this study to be within ±1 order of magnitude.

It is recommended that a ***further phase of work*** is carried out involving appropriate specialists in the various disciplines in a ***HAZID*** so that the current results can be developed further to confirm the qualitative, comparative assessment of probability of failure and consequences.

It is likely that ***much wider industry participation*** will eventually be necessary, through for example a JIP, to rigorously calculate the probability of failure of the various limit states (including SLS) so that quantitative comparisons of the reliability levels of major limit states of FPSOs can be made with confidence. Such an approach will also provide a suitable basis for eventual combination of limit states to determine the overall reliability of FPSOs. This can then assist in addressing the issue of how the system reliability of an FPSO compares to that of a fixed structure, which is more widely understood. This is of particular interest since the FPSO concept has a significantly greater number of structural limit states, with potentially varying degrees of correlation and interaction complexity.

# 1 INTRODUCTION

The deployment of FPSOs for field development in the UKCS is now commonplace. The pace of these FPSO developments have meant that “good practice” from a number of specialisms has been brought to bear on the complete system design without having the opportunity to integrate or balance the reliability levels of different sub-systems which combine to produce the FPSO. This fact has been recognised most explicitly in the industry funded JIP, managed by Noble Denton and MCS which sought to address the reliability levels achieved by mooring and riser systems.

The surge in FPSO projects in the early to mid nineties has significantly expanded the experience base in all of the key specialisms. The objective of the present work was to successfully bring together these experiences in a high level review of FPSO design practice.

The primary objective of this work was to identify the implicit reliability levels in the current design practice for key marine sub-systems of an FPSO based exclusively on published results.

The secondary objective was to develop recommendations for improvements, which would lead to more consistent safety levels within the different marine environmental aspects of FPSO design. Only the naval architectural issues have been considered and no attempt has been made to integrate the storage and process hazards.

The HSE has already commissioned a study that identified such key limit states for FPSOs (ref. 1):

- **ULTIMATE LIMIT STATE (ULS)**
  Structural Strength - Extreme
    Hull Midship Section
    Bow Structure against Slamming (& Green Water)
    Cargo Tanks against Sloshing Pressures
    Turret and Local Structure
  Station Keeping - Extreme
  Fluid Transfer System - Extreme
  Deck Clearance against Green Water

- **FATIGUE LIMIT STATE (FLS)**
  Structural Strength - Fatigue
  Station Keeping - Fatigue
  Fluid Transfer System – Fatigue

- **SERVICEABILITY LIMIT STATE (SLS)**
  Stability - Intact
  Heading Control
  Station Keeping
  Motion Exceedance

- **ACCIDENTAL LIMIT STATE (ALS)**
  Stability - Damaged
  Abnormal Waves: Green Water & Impact
  Ship Impact

This review has focused on the limit states that could have catastrophic consequences. Hence the three serviceability limit states Heading Control, Station Keeping and Motion Exceedance were excluded from this review in so far as they have an impact on serviceability alone. It is recognised however, that these limit states' exceedance could lead to extreme consequences, and such probabilities are taken into account in the relevant ULS cases.

In addition to this, it could be argued that intact stability is an ultimate limit state rather than a serviceability limit state. Indeed, this depends on the definition given to intact stability limit state and on what aspect the emphasis is laid; an over-designed transverse stability may result in stiff-motioned ships, which are uncomfortable (SLS); whereas an under-designed transverse stability can result in poor ship stability and perhaps the entire loss of a ship by capsizing (ULS). In this review, it was necessary to consider intact stability as an ultimate limit state as simple serviceability limit state exceedance is not of concern here. However, doing so means that the effect of an over-designed stability on equipment fatigue, for instance, has been excluded from this study.

Moreover, deck clearance is understood here as the sufficient freeboard so that there is no water on deck. It could be argued that this is not a limit state, in so far as it is not an issue if deck equipment is designed to cope and if heavy weather policies are robust. Actually, for an FPSO, freeboard requirements are not intended to prevent water on deck. Therefore, deck and topside design against green water could be considered as an Ultimate Limit State rather than an Accidental Limit State.

It is also worth noting that, for station keeping systems, the case "one mooring line broken" might be considered as an Accidental Limit State, instead of being included in the Ultimate Limit State.

Limit state parameters and Rules comparison: Each of the previous limit states can be analysed in turn to identify all the parameters that are involved in their assessment, each of them being a potential source of uncertainty. Obviously, this exercise highlights the complexity of the design. As a consequence, the engineer usually needs to make some assumptions to simplify the design of each limit state. These simplifications are intended to be timesaving, and are all the more necessary as the current trend to cut CAPEX costs leads to fast track FPSO projects. The International Rules provide the engineer with several simplified calculations that, though empirically based, have given a good level of operating safety, at least for sea-going Ships. However, the engineer is often confronted with a rather large diversity of assumptions between the Rules. Chapter 3 aims at identifying the parameters involved in the limit state design as well as carrying out a comparison between these Rules. Because of the empirical nature of the Rules and the large diversity of assumptions, there is little consistency in the reliability achieved by different designs.

Present perceived reliabilities: Then, a review of literature (Chapter 4) enables the evaluation of the reliability levels to which the designers believe they are designing. For the limit states that are not well documented in literature, the previous analysis of the Rules with their inherent sources of uncertainty can help to ***estimate*** the reliability levels they achieve. However, it must be emphasised that the deductions made from such reviews must be recognised for what they are; merely, best estimates using the experience gained from performing reliability analyses. The estimates that have been made attempt to recognise the differences to be expected between component and system reliabilities, serious and minor consequences and annual and lifetime reliabilities.

Consequences of limit state failure: Once the current individual reliability levels of each key limit state have been evaluated, it becomes necessary to assess the relevance of their relative levels. Indeed, although commensurate reliability levels are desired in FPSO design, equal reliability levels for different limit states are not. Therefore, Chapter 5 will examine the consequences of different limit state exceedances so that the probability levels can be put in context. The consequences of failure will be categorised into potential loss of life, containment and production.

Recommendations (Chapter 6): Discrepancies between the outputs of Chapters 4 and 5 underline the need to better adjust the relative reliability levels of the identified limit states. This enables ***qualitative*** recommendations to be developed on improving the consistency in reliability between the different limit states so that the overall FPSO reliability can be rationally appreciated. These recommendations must be seen in the light of the limitations associated with ***"qualitative"*** probability estimations.

# 2 LIMIT STATE PARAMETERS AND RULES COMPARISON

## 2.1 INTRODUCTION

For each limit state, the relevant input parameters have been highlighted amongst the many parameters that influence the design (see crosses and shaded table cells). These parameters then influence the intermediate responses (as identified), which then lead to the limit state response such as hull bending moment.

Because of the complexity of the design process, the designer often needs to use well-established Rules, which do not always rely on the main input parameters or on the intermediate response resulting from these. Thus the two alternative design philosophies have been identified in the figures.

Such an approach of identifying all the parameters that are involved in the limit state assessment, helps to localise the major potential sources of uncertainty.

Uncertainty due to **human errors** should be added to all these environmental, physical or operational sources of uncertainty. (e.g. human error during loading or offloading operations may lead to excessive hull girder longitudinal loading and cause structural failure).

The present review has been based on the Rules quoted below. Few of these are tailor-made for the FPSO. It therefore, often becomes necessary to refer to the Rules for Ships (sea-going vessels), which have a larger historical background but are not always relevant for the issues encountered by FPSOs. The rules reviewed are:

- Lloyd’s Register of Shipping, 1996, *Rules and Regulations for the Classification of Mobile Offshore Units*.
- Lloyd’s Register of Shipping, 1999, *Rules and Regulations for the Classification of Ships.* (here referred to as LRS Ships)
- Lloyd’s Register of Shipping, 1999, *Rules and Regulations for Floating Offshore Installations at a Fixed Location*. (here referred to as LRS FOIFL)
- Det Norske Veritas, 1999, *Rules for Classification of Mobile Offshore Units*. (here referred to as DNV MOU)
- Det Norske Veritas, 1999, *Rules for Classification of Ships*. (here referred to as DNV Ships)
- American Bureau of Shipping, 1997 & 1998, *Rules for Building and Classing Mobile Offshore Drilling Units*. (here referred to as ABS MODU)
- American Bureau of Shipping, 1998-1999, *Rules for Building and Classing Steel Vessels*. (here referred to as ABS SV)

- American Bureau of Shipping, March 1996, *Guide for Building and Classing Floating Production Storage and Offloading Systems*. (here referred to as ABS FPSO)
- HSE Guidance Notes, 1990, (Previously Department of Energy), *Offshore Installation: Guidance on Design Construction and Certification*, Fourth Edition, HMSO, London.
- Norwegian Maritime Directorate, 1999, *regulations for MOUs*.
- IMO, SOLAS, 1997 & 1998 amendment, *International Convention for Safety of Life at sea*.
- IMO, Resolution A.749 (18), November 1993, International Maritime Organisation, London.
- IMO, MODU, 1989, *Code for Construction and Equipment of Mobile Offshore Drilling Units (MODU Code)*, International Maritime Organisation, London.
- IMO, MARPOL, 1973, 1978, 1992, *Marine Pollution Regulations*, International Maritime Organisation, London.
- International Convention on Load Lines, 1966.
- Bureau Veritas, Rules for Offshore Units, April 1998. (here referred to as BV OU)
- Bureau Veritas, Rules and Regulations for the Classification of Ships".

## 2.2 STRUCTURAL STRENGTH – EXTREME: HULL MIDSHIP SECTION (ULS)

In most Rules applicable for FPSOs, reference is made to the Rules for Ships, that is to say to Rules adapted to sea going vessels. These are all based on empirical / historical experience, and broadly approved “rules of thumb”.

Even if these Rules now offer computer-based direct design as an alternative, the Rules usually provide the engineers with several formulae to evaluate:

- Design Wave Bending Moments (Hog and Sag) and Shear Forces: Generally, the proposed formulae depend only on the vessel length and beam, on the block coefficient (Cb, and thus on the draft T since Cb = underwater volume / LBT), and on an effective wave height He which is a function of the vessel length only;
- The minimum required section modulus or strength, which is again a function of L, B. Cb, and He only.

Little is said about the still water bending moment.

The Rules also influence the choice of the hull scantling (stiffeners distributions – that may change to decrease the risk of sloshing – single or double sides to prevent oil pollution, etc.).

The Rules give some nominal indications on the plate thickness decreasing with time to make allowances for corrosion.

Finally, permissible stresses (safety factors for static and dynamic loading, for shear, axial and bending stresses) have to satisfy the Rule requirements.

It would have been time-consuming to try to compare the Rule requirements in detail. A comparison of the major assumptions and requirements is made in Table 1. It can be said that the Rules, excluding BV, generally agree on the safety factors to apply for permissible stresses, as well as on the design environment.

In addition to this, if direct design is used, which is allowed by some Rules, it seems that LRS and DNV will lead to rather similar designs and reliabilities.

The trend today is that engineers use 3D Finite Element Analysis to design the hull. Use of this direct design in place of the usual rule of thumb, and provided the computer programs are accurately checked, is likely to improve the reliability level achieved by present designs. The two design philosophies are highlighted in Figure 1.

| | | BV OU | ABS MODU | DNV MOU | LRS FOIFL |
|---|---|---|---|---|---|
| **Design methodology** | 3D FEA or "calculation methods" | X (if duly justified) | | X | X |
| **Design environment** (if direct design is used) | 100-year return | X (100-year *load*) | - | X | X (or less for units for a design life ≤ 10 years) |
| | Ability to withstand shorter period waves of less height | | | | X |
| **Scantling** | Double hull, but no double bottom except where required by National Authorities | | | | X |
| **Longitudinal strength (hull girder strength)** | Safety Factor for: | | | | |
| | Static loading: Shear stress | | 2.50 | | 2.50 |
| | Axial + Bending stress | 1.5 | 1.67 | 1.67 | 1.67 |
| | Design Env + Static Loading: Shear stress | | 1.88 | | 1.89 |
| | Axial + Bending stress | 1.13 | 1.25 | 1.25 | 1.25 |

Table 1: Structural Strength – extreme: Hull Midship Section

**N.B.:** in HSE Guidance Notes, 1990, Section 21.2.3, it is required that "in no case should the calculated tensile stress in a member exceed 60 per cent of the yield stress under operating conditions and 80 per cent of yield stress under extreme loading conditions." This is in rather good agreement with the Safety Factors of 1.67 and 1.25.

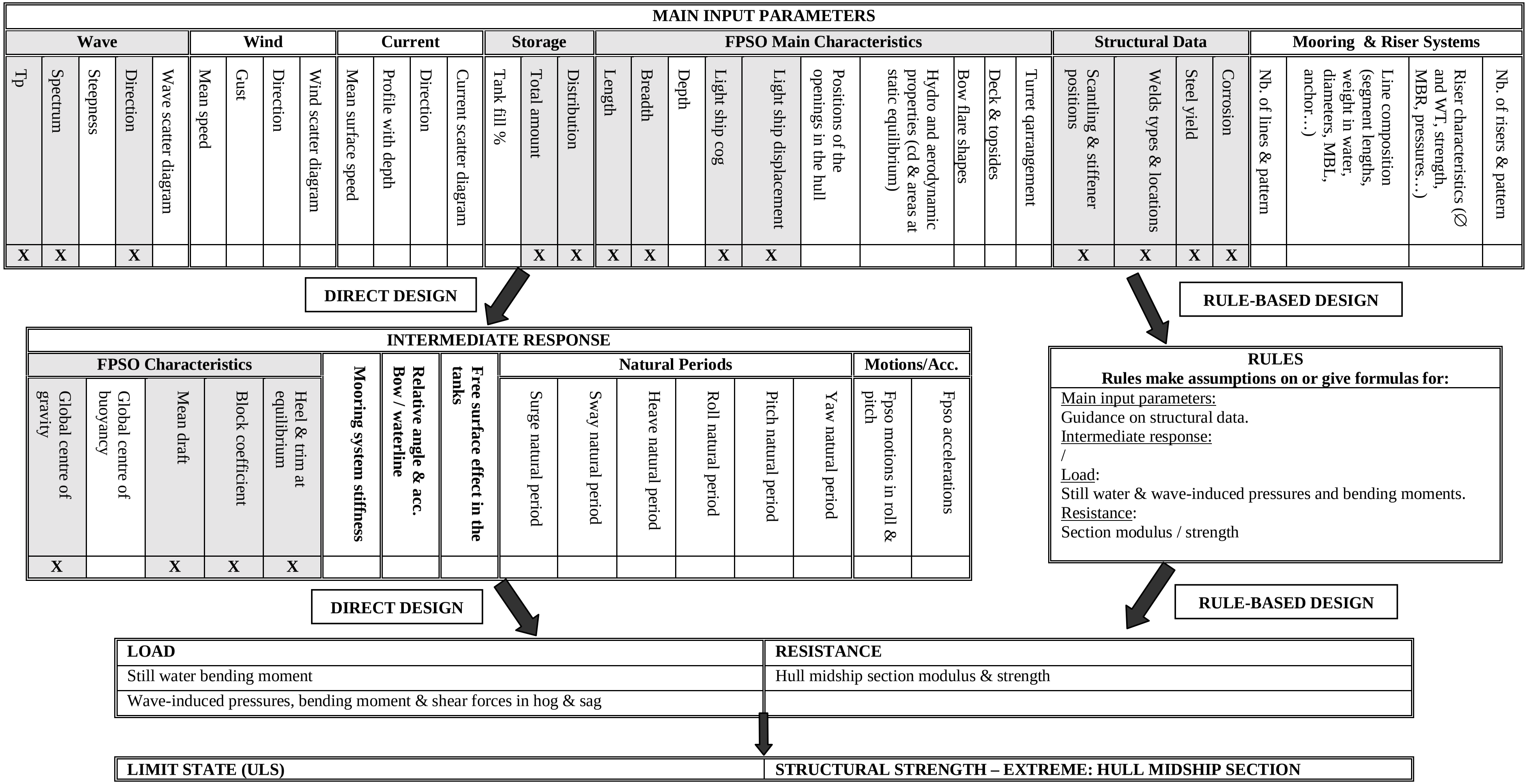



Figure 1: Parameters involved in hull midship section direct design and Rule-based design

## 2.3 STRUCTURAL STRENGTH – EXTREME: BOW STRUCTURE / SLAMMING (ULS)

The floating production system specific Rule LRS FOIFL Pt 4, Ch 4, 4.5 refers to LRS Ship Pt3 Ch 5. It requires the evaluation of the equivalent hydrostatic head due to slamming using an empirical formula. Ship service speed is included in this formula. LRS FOIFL advises the use of a nominal speed of 15 knots for the calculation purposes, which is not related to the true wave induced low and high frequency motions of the FPSO relative to the wave. LRS also recommends a formula for oversizing the wall thickness in the most exposed part of the bow region – the forward most 5 % of the length of the ship.

DNV MOU refers to DNV Ships (Pt 3, Ch 1, Se 7, E 303), which also proposes an empirical formula for the design to resist bow impact pressure, again with an assumed 15 knot velocity. Again overdesign in the bow area is emphasised for the forward most 10% of the length of the ship.

Both DNV and LRS recommend model tests and direct calculations (FEA) for units with unconventional forward ends or when the loadings are in excess of the nominal Rule pressure loads due to impact loading.

However, it has to be noticed that LRS and DNV use different formulae to evaluate the design bow slamming pressure. DNV's formula is more conservative and tends to predict higher pressure loads.

In addition, the definitions of the bow region extent for the design of bottom plating at the bow are not the same: 0.3L for LRS Ships (Pt 3, Ch 5.1) and given by a formula relating the block coefficient and length for DNV Ships (Pt 3, Ch 1, Sec 7).

According to BV OU, "slamming loads are to be considered for horizontal members located in the splash zone and for ship shaped units with particular forward structural configuration. The loads are to be estimated using experimental data or techniques acceptable to the Society". BV OU also refers to the BV Rules for Ships when no accurate information is provided for the Surface Unit.

Whilst ship design codes do not adequately address the potential for bow slamming on permanently moored FPSOs, the estimation of such loads are common place in offshore design practice. Simple momentum theory methods are used, which give the design slam force as a function of the water density, the projected area exposed to slamming, a slam coefficient depending on the surface shape, and the characteristic slam velocity that can be estimated by simplified wave theory or breaking wave theory.

This widespread practice tends to be more conservative than both DNV and LRS. However, it may happen that it still under-predicts the slamming pressures that an FPSO can encounter.

Again, simplifications implied by the Rule-based design or by the standard offshore practice compared to direct design procedures are highlighted in Figure 2.

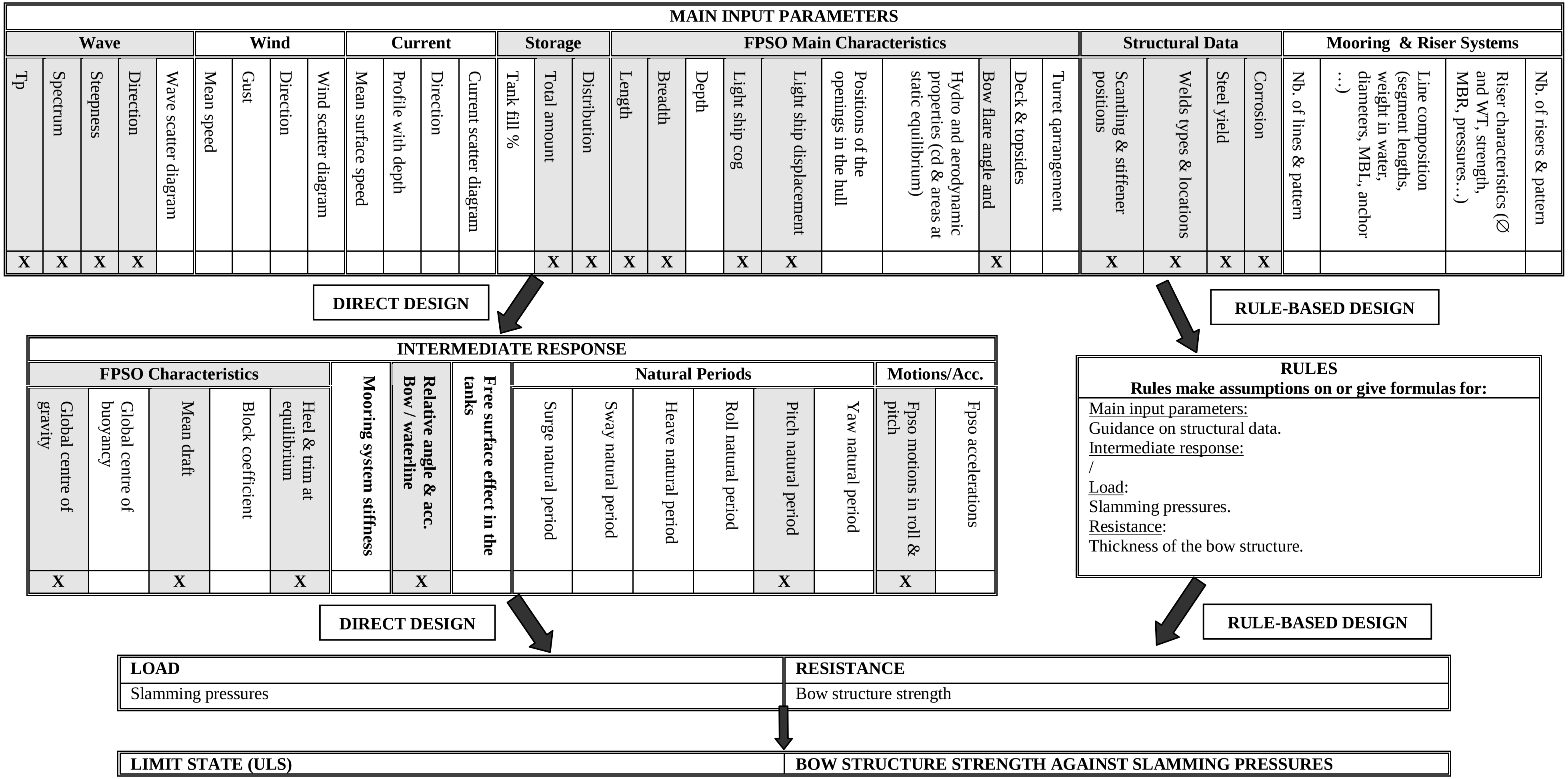



Figure 2: Parameters involved in bow structure direct design against slamming pressures and Rule-based design

## 2.4 STRUCTURAL STRENGTH – EXTREME: CARGO TANK / SLOSHING (ULS)

The Rules account for design requirements associated with cargo tanks and sloshing. LRS Ships (Pt 3, Ch 3, 5.4) deals with critical fill range for a tank. LRS has also edited a Procedure Manual called "Sloshing Loads and Scantling Assessment for Tanks Partially Filled with Liquids". DNV Ships Pt 3, Ch 1, Sec 9 gives the requirements for strengthening against liquid impact pressures in larger tanks and Pt 3, Ch 1, Sec 4 specifies the pressures induced by liquids in tanks. ABS FPSO refers to ABS SV – 5/2 A.3.6.

ABS, DNV and LRS have different views on when tanks should be strengthened against sloshing pressures (Table 2):

| LRS Ships | ABS FPSO / SV | DNV Ships |
|---|---|---|
| When $S_{nr}-5<T_{nr}<S_{nr}+5$<br>Or $S_{np}-3<T_{np}<S_{np}+3$<br>(Natural Rolling (nr) or Pitching (np) periods of the fluid in the tank (T) in the range of the ones of the ship (S).)<br>Unlikely for tanks where stiffening girders or transverses meet certain criteria against the tank fill percentage, thus preventing the resonant motion of the fluid.<br>A formula is given for calculating the critical fill range. | Sloshing has to be analysed when:<br>20% < fill % < 90%<br>The critical fill range is when the fluid natural periods are less than 20% above or below the pitch & roll natural period of the vessel. | Tanks with free sloshing lengths ls>0.13L or breadths bs>0.56B are to be strengthened for the impact sloshing pressure. |

Table 2: Characteristics of the tanks likely to be subject to sloshing pressures.

Once the Rules have identified the risk of sloshing occurrence, they provide the engineer with formulae to evaluate the sloshing pressures, and thus the required tank thickness to hold the pressure. These formulae are not the same for the three classification societies.

The engineer has to cope with a huge amount of cases to be defined and verified: the natural roll and pitch periods of the FPSO and of the fluid inside the several tanks depend on the cargo distribution, which varies continuously and slowly during loading and offloading operations.

However, the Rules enable the engineer to carry out direct design. Thus, using the results from extensive model tests, several programs have been recently developed to help the engineer in better assessing sloshing effects. There seems to be an increasing confidence in the sloshing design. Figure 3 highlights the difference between direct design and strict Rule-based design.

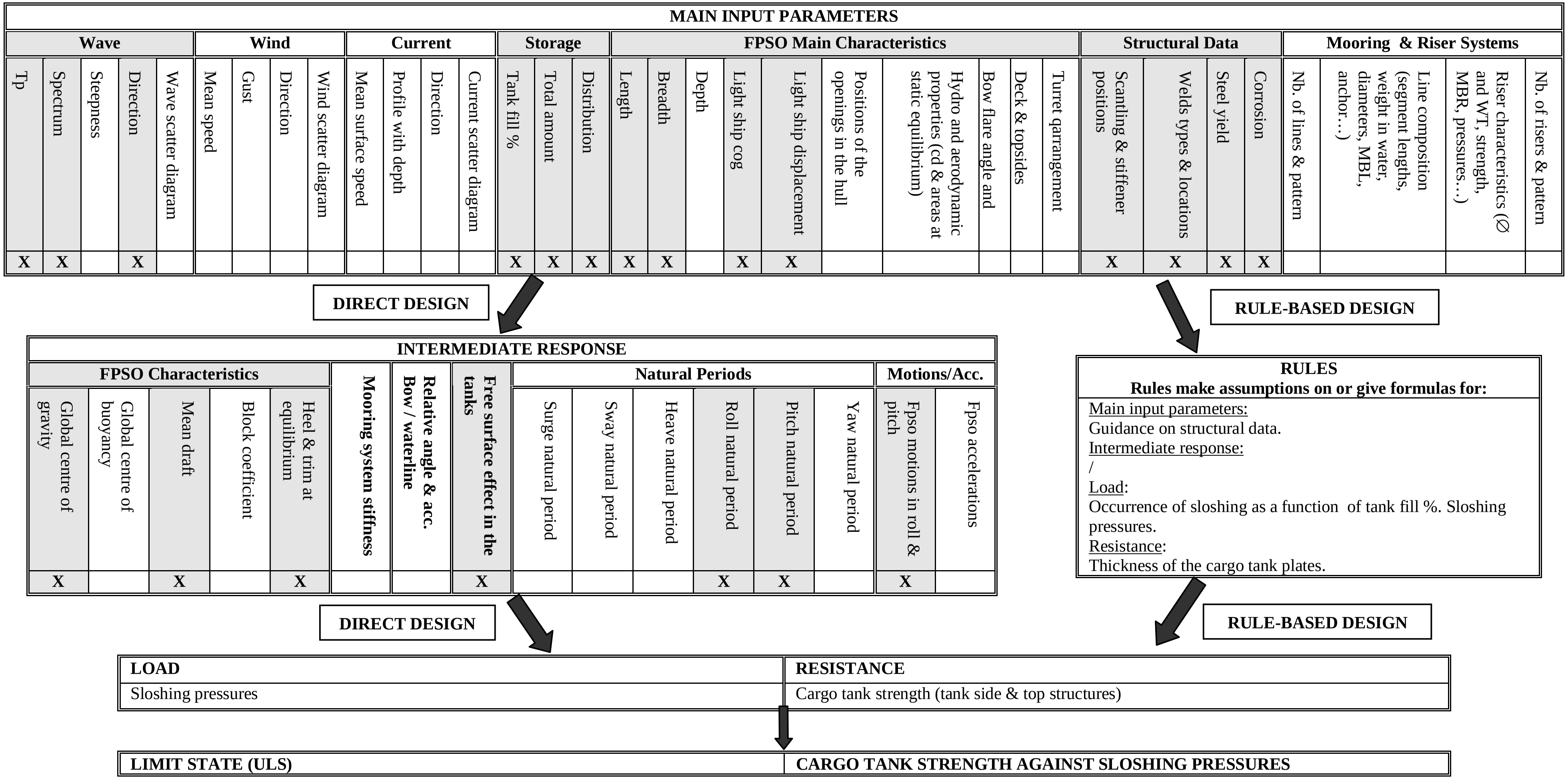



Figure 3: Parameters involved in cargo tank direct design against sloshing pressures and Rule-based design

## 2.5 STRUCTURAL STRENGTH – EXTREME: TURRET (ULS)

Rules rarely refer to turret design. This may be due to the fact that the Rules were originally suited to sea-going Ships, and then adapted to Mobile Offshore Units, neither type of vessel being fitted with a turret. It is only recently that Rules have been adapted to permanently moored floating structures.

LRS FOIFL give general recommendations in Pt 3 Ch 2, Sec 3 and Ch 3, Sec 2. BV OU as well make general design recommendations (Chapter 10-3.3.4). However, no simplified rules have been proposed.

DNV, NMD, and ABS do not offer any simplified rules for turret design.

However, the general offshore practice is reported in the Guide for Design and Analysis for Floating Structures (ref. 2): "Turret structural behaviour is usually confirmed by finite element stress analysis in conjunction with structural strength and fatigue codes of practice. The finite element analysis needs to consider the flexibility and deformations induced by direct loading on the ship hull as well as the turret behaviour itself. The analysis typically includes part of the ship, with suitable boundary loadings or deformations and rigid body hull accelerations taken from global rigid body and ship structural analyses. The turret has important local loading from the mooring system, accelerations of the ship hull and hydrostatic and dynamic pressure loads. Slam may be an important design case for turrets mounted near the bow. A single analysis cannot be expected to provide local hot spot stresses (around notched penetrations for stiffeners etc.) so additional finite element models of local details in the turret would also normally be expected."

Therefore, since the Rules do not give many recommendations on turret design, the current trend is to use direct design with appropriate 3D-FEA program. Provided these programs are accurately checked and validated, this should lead to a rather good level of reliability.

Figure 4 identifies most of the parameters that are involved in turret design.

The turret limit state design is related to station keeping and riser systems design and this link is discussed further in Chapter 5.

**MAIN INPUT PARAMETERS**

| | | |
|---|---|---|
| Wave | Tp | X |
| Wave | Spectrum | X |
| Wave | Steepness | |
| Wave | Direction | X |
| Wave | Wave scatter diagram | |
| Wind | Mean speed | |
| Wind | Gust | |
| Wind | Direction | |
| Wind | Wind scatter diagram | |
| Current | Mean surface speed | |
| Current | Profile with depth | |
| Current | Direction | |
| Current | Current scatter diagram | |
| Storage | Tank fill % | |
| Storage | Total amount | |
| Storage | Distribution | |
| FPSO Main Characteristics | Length | |
| FPSO Main Characteristics | Breadth | |
| FPSO Main Characteristics | Depth | |
| FPSO Main Characteristics | Light ship cog | |
| FPSO Main Characteristics | Light ship displacement | |
| FPSO Main Characteristics | Positions of the openings in the hull | |
| FPSO Main Characteristics | Hydro and aerodynamic properties (cd & areas at static equilibrium) | |
| FPSO Main Characteristics | Bow flare shape | |
| FPSO Main Characteristics | Deck & topsides | |
| FPSO Main Characteristics | Turret qarrangement | |
| Structural Data | Scantling & stiffener positions | |
| Structural Data | Welds types & locations | |
| Structural Data | Steel yield | |
| Structural Data | Corrosion | |
| Mooring & Riser Systems | Nb. of lines & pattern | X |
| Mooring & Riser Systems | Line composition (segment lengths, weight in water, diameters, MBL, anchor…) | X |
| Mooring & Riser Systems | Riser characteristics (∅ and WT, strength, MBR, pressures…) | X |
| Mooring & Riser Systems | Nb. of risers & pattern | X |

**DIRECT DESIGN** | **RULE-BASED DESIGN**

**INTERMEDIATE RESPONSE**

| | | |
|---|---|---|
| FPSO Characteristics | Global centre of gravity | |
| FPSO Characteristics | Global centre of buoyancy | |
| FPSO Characteristics | Mean draft | |
| FPSO Characteristics | Block coefficient | |
| FPSO Characteristics | Heel & trim at equilibrium | |
| | **Mooring system stiffness** | |
| | **Relative angle & acc. Bow / waterline** | |
| | **Free surface effect in the tanks** | |
| Natural Periods | Surge natural period | |
| Natural Periods | Sway natural period | |
| Natural Periods | Heave natural period | |
| Natural Periods | Roll natural period | |
| Natural Periods | Pitch natural period | |
| Natural Periods | Yaw natural period | |
| Motions/Acc. | Fpso motions in roll & pitch | X |
| Motions/Acc. | Fpso accelerations | X |

**RULES**
**Rules make assumptions on or give formulas for:**

**ONLY DIRECT DESIGN IS RECOMMENDED**

**RULE-BASED DESIGN**

**DIRECT DESIGN**

| **LOAD** | **RESISTANCE** |
|---|---|
| Mooring loads (static + dynamic – extreme) | Strength of all turret components |
| Riser loads (static + dynamic – extreme) | |
| Hydrostatic & hydrodynamic pressures on turret structure (including slamming) | |

| **LIMIT STATE (ULS)** | **STRUCTURAL STRENGTH – EXTREME: TURRET** |
|---|---|

Figure 4: Parameters involved in turret direct design and Rule-based design

## 2.6 STATION KEEPING – EXTREME (ULS)

For the final design of a mooring system, most rules require a dynamic analysis.

The Rules comparison has been based on ref. 14. Table 3 shows the current range of safety factors, which are being applied by the industry in the design of mooring systems. The general level of safety factors comes from drilling rig practice. Increasingly sophisticated analysis (dynamic versus quasi-static) and different consequences of mooring system failure between drilling rigs and floating production systems have led to the application of a whole range of safety factors. As a result, different FPSOs for application offshore Europe are being design to safety factors (in the intact case) as low as 1.5 and as high as 2.5 without rational justification for the selection of any particular value.

The Rules have also been compared to the results of the JIP conducted by Noble Denton on Integrated Mooring and Riser Design (ref. 15). The safety factors are presented for a target reliability $2x10^{-4}$ in the event of a failure of a single mooring line, and for a target reliability $2x10^{-3}$ in the event of a failure of second mooring line given one line removed.

Finally, Figure 5 identifies the main parameters involved in the mooring system direct design, and shows the simplifications brought by the Rules.

The rules applicable for synthetic mooring components design are excluded from this study as a result of their relative novelty.

| | | LRS FOIFL | DNV POSMOOR | NMD (appendix to DNV Posmoor) | NPD (appendix to DNV Posmoor) | API RP2SK | ABS FPSO | BV | Mooring & Riser JIP |
|---|---|---|---|---|---|---|---|---|---|
| Design environment | 100-yr Wa + 100-yr Wi +10-yr Cu<br>10-yr Wa + 10-yr Wi +100-yr Cu | X | X | X | X | | | | |
| | 100-yr design env, e.g.:<br>100-yr Wa + associated Wi/Cu<br>100-yr Wi + associated Wa/Cu | | | | | X | X | X | |
| | 100-yr (Hs,Tp) contour<br>100-yr Wa + 100-yr Wi +10-yr Cu<br>10-yr Wa + 10-yr Wi +100-yr Cu | | | | | | | | X |
| Analysis (final design) | Dynamic | X | X | X | X | X | X | | X |
| | Quasi-dynamic (no line dyn.) | | | | | | | X | |
| Factor of Safety (dynamic or quasi-dynamic analysis only) | | | | | | | | | |
| | Intact | 1.67 | 1.50 | 1.65 | 2 | 1.67 | 1.67 | 1.75 | 1.25<br>1.7 |
| | Damage | 1.25 | 1.10 | 1.25 | 1.4 | 1.25 | - | - | 1.1<br>1.65 |
| | Transient | - | 1.00 | 1 | 1 | 1.05 | 1.33 | 1.25 | - |
| | Riser Condition | (5) | (1) | (3) | (6) | (0) | (0) | (0) | (5,8) |
| | Intact | | 2.3 | 2.5 | 3 | | | | |
| | Damage | | 1.5 | 1.65 | 2 | | | | |
| | Transient | | 1.2 | 1.2 | 1.4 | | | | |
| | Condition | | (2) | (4) | (7) | | | | |
| | Intact | | | 2.3 | | | | | |
| | Damage | | | 1.5 | | | | | |
| | Transient | | | 1.2 | | | | | |
| | Condition | | | (5) | | | | | |

Table 3: Station keeping Rule-based design

N.B.: according to HSE Guidance Notes, Section 32, the severe storm condition should be at least as severe as the 50 year return period storm.

(0): not specific.

(1): limited to production through one flexible riser or if production riser system is not critical.

(2): production through rigid or flexible risers where failure is critical.

(3): when risers are disconnected.

(4): risers connected and production in progress or risers under pressure.

(5): risers connected but production shutdown.

(6): for minor failure consequences.

(7): for major failure consequences.

(8): Safety factors applicable to static and dynamic components respectively.

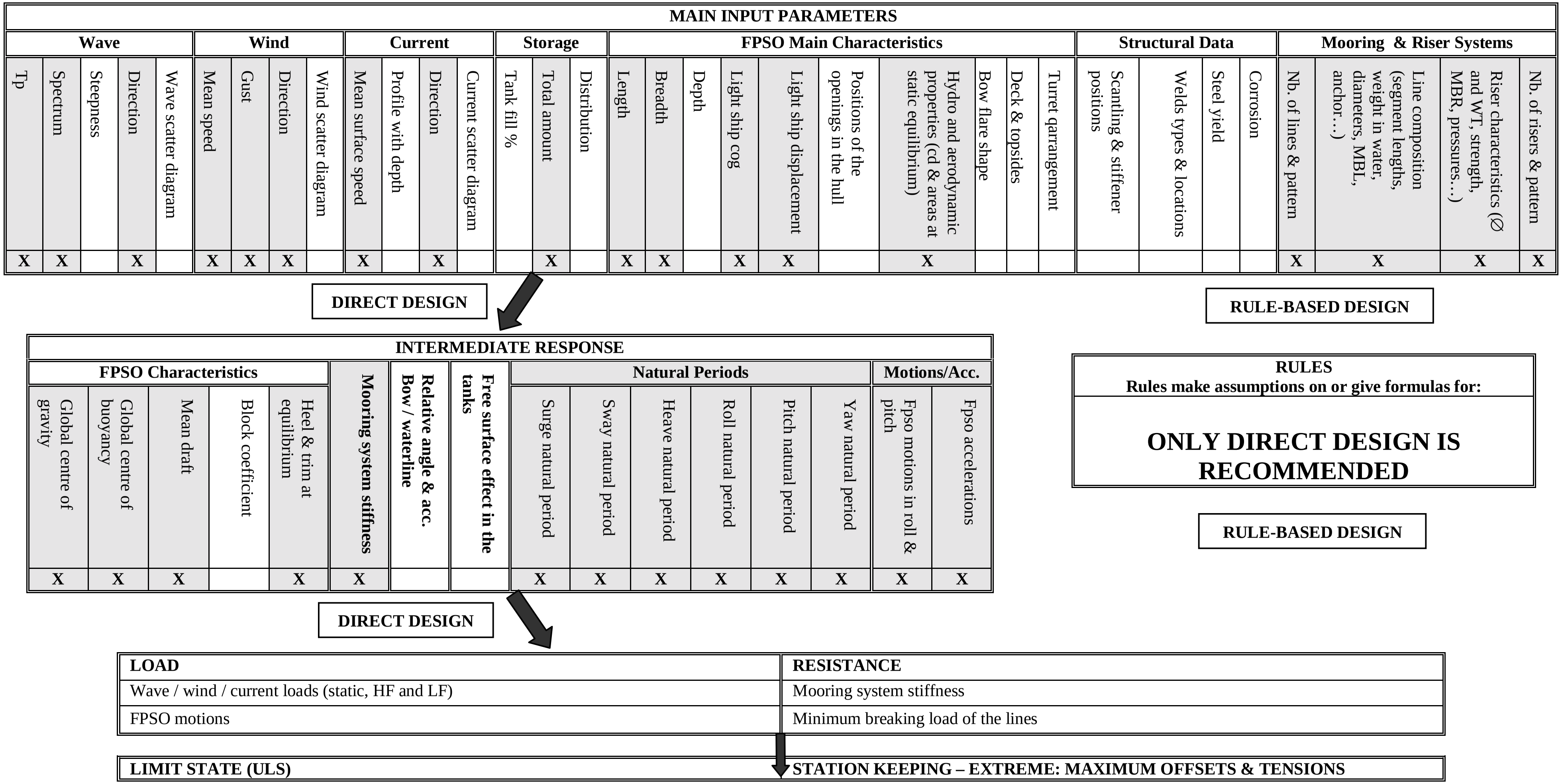



Figure 5: Parameters involved in station keeping – extreme direct design and Rule-based design

## 2.7 FLUID TRANSFER SYSTEM – EXTREME (ULS)

LRS FOIFL recommends that riser design calculations should be in accordance with recognised National or International Standards or Codes of Practice:

- API RP 17B, Spec 17J for Flexible Pipe;
- API RP 2R, 2Q, Bul 2J for Marine Drilling Risers;
- BS 8010 for Pipelines.

DNV MODU (Pt6, Ch6, Sec7) recognises as applicable:

- API RP 17B for flexible pipes;
- DNV, Rules for certification of flexible risers and pipes.
- DNV, Rules for submarine Pipeline Systems.

ABS FPSO recognises as applicable:

- API RP 17B for Flexible Pipe;
- API RP 2R, 2T and 16Q for Rigid Risers.

BV OU recognises as applicable:

- API RP 17B, API SP 17J, and BV Guidance Note NI 364 for non-bonded Flexible Pipe;
- ANSI B 31.4, ANSI B 31.8 and BS 8010 for Rigid Risers.

None of these Rules make reference to the API RP 2RD for steel risers, but this may be due to the fact that this API Recommended Practice was edited very recently, and probably too late to be quoted in other Rules.

However, due to the harsh environment and the shallow water depth in the UKCS, the use of steel risers with FPSOs is not yet a reality. Flexible risers remain the preferred solution for application on turret moored FPSO. Therefore, this review focuses on the Rules used to design flexible risers: API RP 17B and API Spec 17J are the only relevant Codes of Practice for flexible riser design. According to these, the riser has to be designed against crushing collapse, ovalization, buckling, as it is fully described in API RP 17B and API Spec 17J. Their main design criteria are reported in Table 4.

It is worth noticing that the API recommends to analyse the riser under functional, environmental and accidental loads, each category being associated with a specified level of probability of exceedance (ranging from $10^{-2}$ to $10^{-4}$).

These recommendations can be compared to those given by the Integrated Riser and Mooring Design JIP (see)

In addition to this, Figure 6 indicates the main parameters involved in the design of risers. It should be observed that fluid transfer system design is related to station keeping system design as noted in the figure.

| Design external load combinations | | | | | 100-yr wave + 10-yr current<br>10-yr wave + 100-yr current |
|---|---|---|---|---|---|
| Load case | Load condition | Load type | Stress criterion | MBR criterion | Description (example) |
| A | Normal operation | Functional & environment | 0.55 | 1.5 | Operating internal fluid conditions, intact mooring system, and 100-year environmental conditions. |
| B | Normal operation | Functional, environment and accidental | 0.85 | 1.25 | No internal fluid, one mooring line broken, and 100-year environmental conditions. |
| C | Abnormal operation | Functional, environment and accidental | 0.85 | 1.25 | No internal fluid, two mooring lines broken, and 10-year environmental conditions. |

Table 4: Main requirements and design criteria for flexible riser design

| Design external load combinations: Intact Mooring System | | |
|---|---|---|
| Load condition associated to a Pf target / year | Stress criterion | MBR criterion |
| $10^{-3}$ | 0.81 | 1.0 |
| $10^{-4}$ | 0.70 | 1.16 |
| $10^{-5}$ | 0.61 | 1.33 |
| Design external load combinations: Damaged Mooring System | | |
| Load condition associated to a Pf target / quater | Stress criterion | MBR criterion |
| $10^{-3}$ | 0.87 | 1.0 |
| $10^{-4}$ | 0.75 | 1.06 |
| $10^{-5}$ | 0.68 | 1.23 |

Table 5: Recommendations by the Integrated Riser and Mooring Design JIP

**MAIN INPUT PARAMETERS**

| | | |
|---|---|---|
| Wave | Tp | X |
| Wave | Spectrum | X |
| Wave | Steepness | |
| Wave | Direction | X |
| Wave | Wave scatter diagram | |
| Wind | Mean speed | |
| Wind | Gust | |
| Wind | Direction | |
| Wind | Wind scatter diagram | |
| Current | Mean surface speed | X |
| Current | Profile with depth | X |
| Current | Direction | X |
| Current | Current scatter diagram | |
| Storage | Tank fill % | |
| Storage | Total amount | |
| Storage | Distribution | |
| FPSO Main Characteristics | Length | |
| FPSO Main Characteristics | Breadth | |
| FPSO Main Characteristics | Depth | |
| FPSO Main Characteristics | Light ship cog | |
| FPSO Main Characteristics | Light ship displacement | |
| FPSO Main Characteristics | Positions of the openings in the hull | |
| FPSO Main Characteristics | Hydro and aerodynamic properties (cd & areas at static equilibrium) | |
| FPSO Main Characteristics | Bow flare shape | |
| FPSO Main Characteristics | Deck & topsides | |
| FPSO Main Characteristics | Turret qarrangement | |
| Structural Data | Scantling & stiffener positions | |
| Structural Data | Welds types & locations | |
| Structural Data | Steel yield | |
| Structural Data | Corrosion | |
| Mooring & Riser Systems | Nb. of lines & pattern | |
| Mooring & Riser Systems | Line composition (segment lengths, weight in water, diameters, MBL, anchor…) | |
| Mooring & Riser Systems | Riser characteristics (∅ and WT, strength, MBR, pressures…) | X |
| Mooring & Riser Systems | Nb. of risers & pattern | X |

**DIRECT DESIGN**

**RULE-BASED DESIGN**

**INTERMEDIATE RESPONSE**

| | | |
|---|---|---|
| FPSO Characteristics | Global centre of gravity | |
| FPSO Characteristics | Global centre of buoyancy | |
| FPSO Characteristics | Mean draft | |
| FPSO Characteristics | Block coefficient | |
| FPSO Characteristics | Heel & trim at equilibrium | |
| | **Mooring system stiffness** | |
| | **Relative angle & acc. Bow / waterline** | |
| | **Free surface effect in the tanks** | |
| Natural Periods | Surge natural period | X |
| Natural Periods | Sway natural period | X |
| Natural Periods | Heave natural period | X |
| Natural Periods | Roll natural period | X |
| Natural Periods | Pitch natural period | X |
| Natural Periods | Yaw natural period | X |
| Motions/Acc. | Fpso motions in roll & pitch | X |
| Motions/Acc. | Fpso accelerations | X |

| RULES<br>Rules make assumptions on or give formulas for: |
|---|
| **ONLY DIRECT DESIGN IS RECOMMENDED** |

**RULE-BASED DESIGN**

**DIRECT DESIGN**

| LOAD | RESISTANCE |
|---|---|
| Wave / wind / current loads (static, HF and LF), internal & external pressures | Riser strength |
| FPSO motions, and maximum excursion (allowed by the mooring system) | |

| LIMIT STATE (ULS) | FLUID TRANSFER SYSTEM – EXTREME |
|---|---|

Figure 6: Parameters involved in fluid transfer system – extreme direct design and Rule-based design

## 2.8 DECK CLEARANCE / GREENWATER / DECK & TOPSIDE DESIGN (ULS)

To assess deck clearance, most rules comply with the International Convention on Load Lines 1966 (ICLL, as reported in DNV Ships Pt 3, Ch 5), which advises a minimum freeboard depending on the vessel size. This is certainly based on past experience; nevertheless it has not prevented the occurrence of water on deck for several FPSO nor would it have been expected to prevent water on deck.

When “deck clearance against green water” (exceedance of the freeboard) occurs, this will result in impact loads from the water on topsides placed on deck. Thus the ultimate limit state is whether the design loads from the greenwater can be accommodated by the topsides.

The Rules rarely give any guidance concerning the event of green seas, and remain rather qualitative. This is also the conclusion drawn in ref. 22.

Nevertheless, LRS FOIFL (Pt4, Ch4, 4.8.2) give some advice:

“For units with unconventional forward ends and units which may be subjected to high deck loading in excess of the minimum rule heads due to loading from green seas, adequate protection by means of bulwarks and break water structure are to be provided at the forward end and the scantlings of the structure and its under deck supports are to be specially considered. Where necessary the loadings are to be determined by model tests.”

BV OU as well recommend to take into consideration “increased loads due to green waters, that may result from the severity of the environment, or unusual location of the considered construction.” “Providing suitable breakwaters” may help minimising the effect of green waters.

Figure 7 indicates the parameters involved in deck and topsides design against green water and shows that the scarcity of recommendations by the Rules leaves room for direct design.

**MAIN INPUT PARAMETERS**

| | | |
|---|---|---|
| Wave | Tp | X |
| Wave | Spectrum | X |
| Wave | Steepness | |
| Wave | Direction | X |
| Wave | Wave scatter diagram | |
| Wind | Mean speed | |
| Wind | Gust | |
| Wind | Direction | |
| Wind | Wind scatter diagram | |
| Current | Mean surface speed | |
| Current | Profile with depth | |
| Current | Direction | |
| Current | Current scatter diagram | |
| Storage | Tank fill % | |
| Storage | Total amount | |
| Storage | Distribution | |
| FPSO Main Characteristics | Length | |
| FPSO Main Characteristics | Breadth | |
| FPSO Main Characteristics | Depth | |
| FPSO Main Characteristics | Light ship cog | |
| FPSO Main Characteristics | Light ship displacement | |
| FPSO Main Characteristics | Positions of the openings in the hull | |
| FPSO Main Characteristics | Hydro and aerodynamic properties (cd & areas at static equilibrium) | |
| FPSO Main Characteristics | Bow flare shape | |
| FPSO Main Characteristics | Deck & topsides | X |
| FPSO Main Characteristics | Turret qarrangement | |
| Structural Data | Scantling & stiffener positions | X |
| Structural Data | Welds types & locations | X |
| Structural Data | Steel yield | X |
| Structural Data | Corrosion | X |
| Mooring & Riser Systems | Nb. of lines & pattern | |
| Mooring & Riser Systems | Line composition (segment lengths, weight in water, diameters, MBL, anchor…) | |
| Mooring & Riser Systems | Riser characteristics (∅ and WT, strength, MBR, pressures…) | |
| Mooring & Riser Systems | Nb. of risers & pattern | |

**DIRECT DESIGN**

**RULE-BASED DESIGN**

**INTERMEDIATE RESPONSE**

| | | |
|---|---|---|
| FPSO Characteristics | Global centre of gravity | |
| FPSO Characteristics | Global centre of buoyancy | |
| FPSO Characteristics | Mean draft | |
| FPSO Characteristics | Block coefficient | |
| FPSO Characteristics | Heel & trim at equilibrium | |
| | **Mooring system stiffness** | |
| | **Relative angle & acc. Bow / waterline** | |
| | **Free surface effect in the tanks** | |
| Natural Periods | Surge natural period | |
| Natural Periods | Sway natural period | |
| Natural Periods | Heave natural period | |
| Natural Periods | Roll natural period | |
| Natural Periods | Pitch natural period | |
| Natural Periods | Yaw natural period | |
| Motions/Acc. | Fpso motions in roll & pitch | X |
| Motions/Acc. | Fpso accelerations | X |

| RULES<br>Rules make assumptions on or give formulas for: |
|---|
| **ONLY DIRECT DESIGN IS RECOMMENDED** |

**RULE-BASED DESIGN**

**DIRECT DESIGN**

| **LOAD** | **RESISTANCE** |
|---|---|
| Dynamic pressures induced by the flow on deck | Deck & topsides strength |

| | |
|---|---|
| **LIMIT STATE (ULS)** | **DECK & TOPSIDES DESIGN AGAINST GREENWATER** |

Figure 7: Parameters involved in deck and topsides direct design against green water and Rule-based design

## 2.9 STABILITY – INTACT (ULS OR SLS)

This review has been based on previous research reported in ref. 2 and 3.

In DNV MOU, a Guidance note warns "Regarding stability requirements for surface units with ship- or barge-displacement hull, reference is made to DNV Rules for Classifications of Ships." Then, in DNV Ships, the requirements are in compliance with IMO Intact Stability Code (IMO Res. A.749 (18)) and relevant regulations of SOLAS Ch. II-1. In addition, for Oil Production Vessel, the stability design requirements for both intact and damaged conditions have to follow IMO MODU 89. A Weather Criterion is also proposed.

Most Rules quote IMO MARPOL and IMO SOLAS as applicable for Stability requirements, as a minimum.

In the IMO general criteria, usually followed by all Rules, the following aspects are covered:

- Area under the GZ curve up to 30 degrees to be at least 0.055 m-radian;
- Area under the GZ curve to minimum (40 degrees ; down flooding angle) ≥ 0.09 m-radian;
- Area under the GZ curve between 30 degrees and the minimum (40 degrees ; down flooding angle) ≥ 0.03 m-radian;
- GZ to be at least 0.2 m at an angle of ≥ 30 degrees;
- Maximum GZ at least at 25 degrees heel;
- Initial GM to be at least 0.15 m.

For Intact Stability, the wind-heeling curve is constructed at:

- 36 m/s (70 knots) for the transit and operating conditions,
- 51.5 m/s (100 knots) or the survival condition.
- 25.8 m/s (50 knots) for restricted operations.

For Damaged Stability, the wind-heeling curve is constructed at:

- 25.8 m/s (50 knots) for all operations.

Then, the wind overturning moment has to be calculated. It depends on:

- The drag coefficients $C_d$ (composed of shape $C_s$ and height $C_h$ coefficients),
- The exposed areas of topsides and hull, considering or not the variation of the exposed area as the FPSO heels,
- The location of the point where the load is applied.

With regard to the screen area and the lever calculation, the rules may differ. Some consider that both the wind-exposed plate area and the point of application of the wind load (thus the lever) vary with the heel angle, others consider that it remains constant.

For intact stability, all rules agree about the area ratio requirement that states the following: the area under the righting moment curve to the second intercept or downflooding angle, whichever is less, should be not less than 40 % in excess of the area under the wind heeling moment curve to the same limiting angle: $A \geq 1.4 \times B$.

Most rules state that HSE 4th Ed. Guidance Notes apply in the UK.

Only HSE and NMD have additional requirements, which are reported in Table 6. One can notice that there is some disagreement between them.

Figure 8 indicates the parameters involved in intact stability design and highlights the assumptions made by the Rules. Again, it seems that the present rule based design procedure is a rule of thumb based on past experience.

More direct design methods based upon accounting for the roll motion of the vessels have been researched by class societies, industry and academia, but have not been permitted in the design process.

| **Intact Requirements** | **HSE Guidelines** | **NMD** |
|---|---|---|
| **Range of positive stability** | ≥ 30° | ≥ 30° |
| **Steady heel (with wind)** | ≤ 15° | ≤ 17° |
| **Min. Initial GM** | 0.3 m | 0.5 m |
| **Angle of heel at 2nd intercept** | ≥ 30° | |
| **Other** | Min GZ > 0.5 x $GM_{min}$sin(heel angle) where the heel angle is the lowest of downflooding angle, angle of maximum righting lever and 15° | |

Table 6: Intact stability: HSE & DNV additional requirements to IMO.

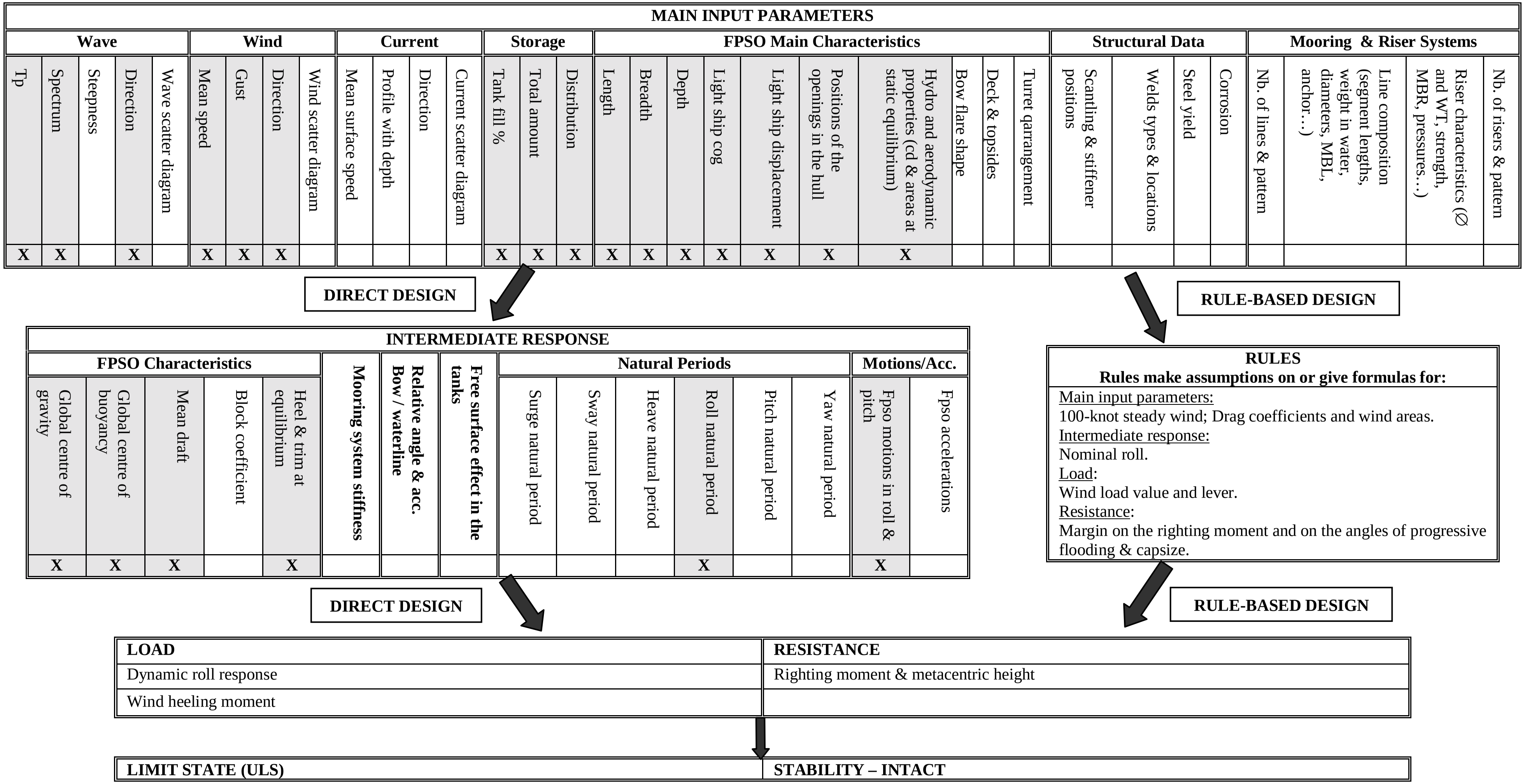



Figure 8: Parameters involved in intact stability direct design and Rule-based design

## 2.10 HULL STRUCTURAL STRENGTH – FATIGUE (FLS)

LRS FOIFL refers to it in Pt 4, Ch 4.3: "The fatigue assessment of the hull structure of ships and barge-type units is to be verified in accordance with LR's ShipRight Fatigue Design Assessment (FDA) Procedure as applicable to oil tankers or another acceptable standard." Pt 4, Ch 5.5 gives general requirements for fatigue.

Interestingly, LRS and DNV propose fatigue life factors depending on the consequence of failure in addition to the possibility of inspection and repair. This is also advised by HSE Guidance Notes (Section 21.2.10)

Apparently, ABS FPSO does not have clear requirements for fatigue ("designed for a 20-year life"; "need to use additional safety factor in non-inspectable or critical areas").

The main Rule requirements are reported in Table 7. LRS, DNV (referring to NPD) and BV do not completely agree on fatigue life factors.

| | | | LRS | DNV (Safety factors from NPD) | BV OU |
|---|---|---|---|---|---|
| Method | Deterministic fatigue analysis | | X | | X (when appropriate) |
| | Spectral fatigue analysis | | X | | X (in general, but time domain analysis may be preferred in some cases) |
| Minimum design fatigue life | ≥ 20 years | | X | X | X (at least twice) |
| Miner's summation | | | X | X | X |
| S-N curves | | | X | X Based on a 95% confidence limit | X |
| Fatigue Life Factors | Non-substantial consequence of failure | Inspectable & dry repair | 1 | 1 | - |
| | | Inspectable & wet repair | 2 | 2 | - |
| | | Not inspectable nor repairable | 5 | 3 | - |
| | Substantial consequence of failure | Inspectable & dry repair | 2 | 2 | - |
| | | Inspectable & wet repair | 4 | 3 | - |
| | | Not inspectable nor repairable | 10 | 10 | - |

Table 7: main Rule requirements for hull structural fatigue

The slamming (decaying, oscillatory) response of the hull should normally be included in the fatigue assessment: this is not explicitly recommended in the Rules.

Figure 9 shows the simplifications made by the Rules compared to a direct design that would take into account all parameters involved in the hull structural fatigue assessment.

**MAIN INPUT PARAMETERS**

| Wave | | | | | Wind | | | | Current | | | | Storage | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tp | Spectrum | Steepness | Direction | Wave scatter diagram | Mean speed | Gust | Direction | Wind scatter diagram | Mean surface speed | Profile with depth | Direction | Current scatter diagram | Tank fill % | Total amount | Distribution |
| X | X | | X | X | | | | | | | | | | X | X |

| FPSO Main Characteristics | | | | | | | | | | Structural Data | | | | Mooring & Riser Systems | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Length | Breadth | Depth | Light ship cog | Light ship displacement | Positions of the openings in the hull | Hydro and aerodynamic properties (cd & areas at static equilibrium) | Bow flare shape | Deck & topsides | Turret qarrangement | Scantling & stiffener positions | Welds types & locations | Steel yield | Corrosion | Nb. of lines & pattern | Line composition (segment lengths, weight in water, diameters, MBL, anchor…) | Riser characteristics (∅ and WT, strength, MBR, pressures…) | Nb. of risers & pattern |
| X | X | | X | X | | | | | | X | X | X | X | | | | |

**DIRECT DESIGN**

**RULE-BASED DESIGN**

**INTERMEDIATE RESPONSE**

| FPSO Characteristics | | | | | | | | Natural Periods | | | | | | Motions/Acc. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Global centre of gravity | Global centre of buoyancy | Mean draft | Block coefficient | Heel & trim at equilibrium | **Mooring system stiffness** | **Relative angle & acc. Bow / waterline** | **Free surface effect in the tanks** | Surge natural period | Sway natural period | Heave natural period | Roll natural period | Pitch natural period | Yaw natural period | Fpso motions in roll & pitch | Fpso accelerations |
| X | | X | X | X | | | | | | | | | | | |

**RULES**
**Rules make assumptions on or give formulas for:**

<u>Main input parameters:</u>
Guidance on structural data.
<u>Intermediate response:</u>
/
<u>Load</u>:
Still water & wave-induced pressures and bending moments.
S/N Curves & Miner's rule for stresses accumulation.
<u>Resistance</u>:
Section modulus / strength

**DIRECT DESIGN**

**RULE-BASED DESIGN**

| **LOAD** | **RESISTANCE** |
|---|---|
| Still water bending moment varying with time | Hull midship section modulus & strength |
| Wave-induced pressures, bending moment & shear forces in hog & sag varying with time | Welds & plates strength |
| Oscillations induced by slamming varying with time | |

| **LIMIT STATE (ULS)** | **STRUCTURAL STRENGTH – FATIGUE: HULL MIDSHIP SECTION** |
|---|---|

<u>Figure 9: Parameters involved in hull structural fatigue direct design and Rule-based design</u>

## 2.11 STATION KEEPING – FATIGUE (FLS)

Both LRS FOIFL and DNV POSMOOR recommend that fatigue life calculations are to be in accordance with API RP 2SK. ABS FPSO mainly refers to API RP 2FP1 which has the same fatigue analysis procedure as API RP 2SK.

If no fatigue test data is available, API RP 2SK proposes typical T-N curves which can be used for calculating nominal tension fatigue lives of wire ropes, chain and connecting links.

The Rules have also been compared to the results of the JIP conducted by Noble Denton on Integrated Mooring and Riser Design (ref. 15). A safety factor on design life of 6 has been selected, based upon the proposed component reliability requirement in the final year of operation $10^{-3}$.

The fatigue life safety factors recommended by the Rules and the JIP have been reported in Table 8. The Rules are in a rather poor agreement.

<table>
<tr><th></th><th></th><th>LRS FOIFL</th><th>DNV</th><th>API RP 2SK</th><th>ABS FPSO</th><th>BV</th><th>Mooring & risers JIP</th></tr>
<tr><td rowspan="3">Fatigue Life Factors</td><td>Inspectable & dry repair</td><td>3</td><td rowspan="2">3</td><td rowspan="3">3</td><td rowspan="2">3</td><td rowspan="3">5</td><td rowspan="3">6</td></tr>
<tr><td>Inspectable & wet repair</td><td>5</td></tr>
<tr><td>Not inspectable nor repairable</td><td>10</td><td>10</td><td>10</td></tr>
</table>

Table 8: Fatigue life factor for mooring systems

Figure 10 identifies the main parameters involved in the mooring system fatigue direct design, and shows the simplifications brought by the Rules. It is fairly similar to Figure 5 for station keeping – extreme.

In the assessment of mooring fatigue, it seems that the uncertainty associated with to the choice of fatigue life safety factors and the simplifications brought by T/N curves and Miner's Rule is added to the uncertainty related to environmental loads.

**MAIN INPUT PARAMETERS**

| | | |
|---|---|---|
| Wave | Tp | X |
| Wave | Spectrum | X |
| Wave | Steepness | |
| Wave | Direction | X |
| Wave | Wave scatter diagram | X |
| Wind | Mean speed | X |
| Wind | Gust | X |
| Wind | Direction | X |
| Wind | Wind scatter diagram | X |
| Current | Mean surface speed | X |
| Current | Profile with depth | |
| Current | Direction | X |
| Current | Current scatter diagram | X |
| Storage | Tank fill % | |
| Storage | Total amount | X |
| Storage | Distribution | |
| FPSO Main Characteristics | Length | X |
| FPSO Main Characteristics | Breadth | X |
| FPSO Main Characteristics | Depth | |
| FPSO Main Characteristics | Light ship cog | X |
| FPSO Main Characteristics | Light ship displacement | X |
| FPSO Main Characteristics | Positions of the openings in the hull | |
| FPSO Main Characteristics | Hydro and aerodynamic properties (cd & areas at static equilibrium) | X |
| FPSO Main Characteristics | Bow flare shape | |
| FPSO Main Characteristics | Deck & topsides | |
| FPSO Main Characteristics | Turret qarrangement | |
| Structural Data | Scantling & stiffener positions | |
| Structural Data | Welds types & locations | |
| Structural Data | Steel yield | |
| Structural Data | Corrosion | |
| Mooring & Riser Systems | Nb. of lines & pattern | X |
| Mooring & Riser Systems | Line composition (segment lengths, weight in water, diameters, MBL, anchor…) | X |
| Mooring & Riser Systems | Riser characteristics (∅ and WT, strength, MBR, pressures…) | X |
| Mooring & Riser Systems | Nb. of risers & pattern | X |

**DIRECT DESIGN** ↓ (to Intermediate Response) **RULE-BASED DESIGN** ↓ (to Rules)

**INTERMEDIATE RESPONSE**

| | | |
|---|---|---|
| FPSO Characteristics | Global centre of gravity | X |
| FPSO Characteristics | Global centre of buoyancy | X |
| FPSO Characteristics | Mean draft | X |
| FPSO Characteristics | Block coefficient | |
| FPSO Characteristics | Heel & trim at equilibrium | X |
| | **Mooring system stiffness** | X |
| | **Relative angle & acc. Bow / waterline** | |
| | **Free surface effect in the tanks** | |
| Natural Periods | Surge natural period | X |
| Natural Periods | Sway natural period | X |
| Natural Periods | Heave natural period | X |
| Natural Periods | Roll natural period | X |
| Natural Periods | Pitch natural period | X |
| Natural Periods | Yaw natural period | X |
| Motions/Acc. | Fpso motions in roll & pitch | X |
| Motions/Acc. | Fpso accelerations | X |

**RULES**
**Rules make assumptions on or give formulas for:**

<u>Main input parameters:</u>
Environmental load combination.
<u>Intermediate response:</u>
/
<u>Load</u>:
Summation of static, HF, and LF components.
T/N Curves & Miner's rule for tensions accumulation.
<u>Resistance</u>:
Safety factor on MBL.

**DIRECT DESIGN** ↓ **RULE-BASED DESIGN** ↓

| **LOAD** | **RESISTANCE** |
|---|---|
| Wave / wind / current loads (static, HF and LF) varying with time | Mooring system stiffness |
| FPSO motions varying with time | Minimum breaking load of the lines |

↓

| **LIMIT STATE (ULS)** | **STATION KEEPING – FATIGUE** |
|---|---|

Figure 10: Parameters involved in station keeping system fatigue direct design and Rule-based design

## 2.12 FLUID TRANSFER SYSTEM – FATIGUE (FLS)

As noted in chapter 2.7, ABS FPSO, LRS FOIFL and DNV MODU state API RP 17B and API Spec 17J as applicable for flexible riser design.

Table 9 reports the fatigue life safety factors recommended by the Rules.

| | | LRS FOIFL | API RP 17B Spec 17J |
|---|---|---|---|
| Fatigue Life Factors | Inspectable & dry repair | 2 | 10 |
| | Inspectable & wet repair | 4 | |
| | Not inspectable nor repairable | 10 | |

Table 9: Fatigue life factors for fluid transfer system.

Figure 11 identifies the main parameters involved in the fluid transfer system fatigue direct design, and shows the simplifications brought by the Rules. It is fairly similar to Figure 6 for fluid transfer system – extreme.

As for mooring system design, in the assessment of riser fatigue, it seems that the uncertainty associated with to the choice of fatigue life safety factors and the simplifications brought by T/N curves and Miner’s Rule is added to the uncertainty related to environmental loads.

Note that fluid transfer system design is influenced by station keeping system design (Figure 10).

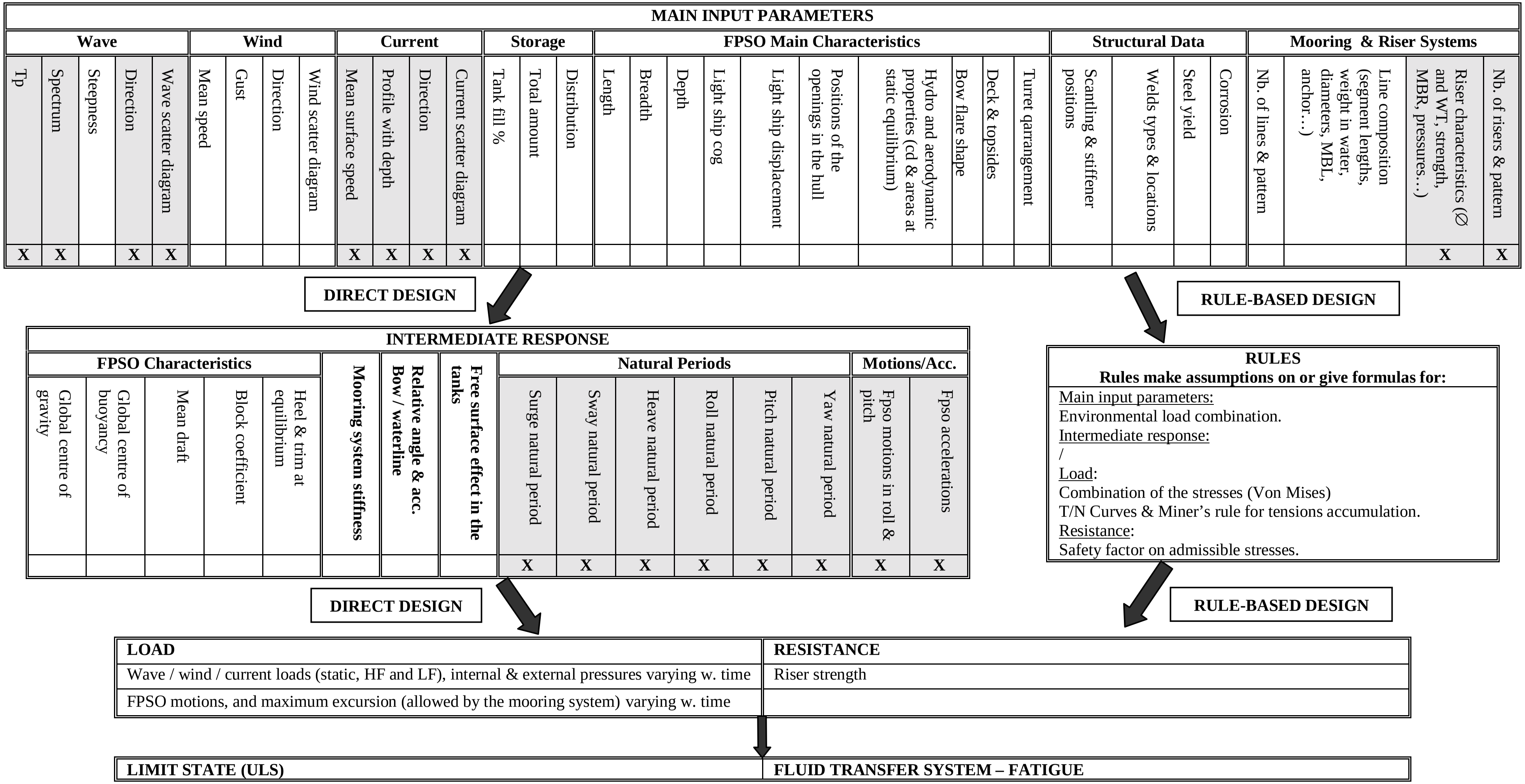



Figure 11: Parameters involved in fluid transfer system fatigue direct design and Rule-based design

## 2.13 STABILITY – DAMAGE (ALS)

The parameters involved in the assessment of damage stability are rather similar to the ones involved in intact stability (see Figure 8), with additional dependence on the **number of compartments that are damaged and their location**.

The damage may be caused by progressive flooding, ship collision, dropped objects, hydrocarbon explosion, ballast system failure or hull structural failure (cracks due to fatigue, exceedance of the hull girder strength, side collapse, etc.), which have their own probabilities of occurrence.

The discrepancy in the criteria highlighted in the review of the Rules dealing with intact stability (see 2.9) is even larger for damage stability, as it can be seen in Table 10 and in Table 11.

Note: BV Rules for Offshore Units comply with MARPOL requirements.

| Extent of Damage | | ICLL (type A) | IMO MODU | HSE | NMD | MARPOL | SOLAS | DNV | LRS | ABS (FPSO refers to MODU) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Longitudinal extent and location** | Only below waterline, adjacent to the sea or connected to the sea | | | | X | | | | | X |
| | Min [$0.333L^{0.667}$;14.5] anywhere between bulkheads unless spaced < $0.333L^{0.667}$ or 14.5 | X | | | | | | | | |
| | Min [$0.333L^{0.667}$;14.5] including bulkheads | | | | | X | | | | |
| | 3 m anywhere between bulkheads (unless spaced < 3 m) | | X | X | | | | X | X | |
| | 3 m including bulkheads | | | | X | | | | | |
| | Probabilistic up to 48/L but not more than 0.24 | | | | | | X | | | |
| **Horizontal penetration** | Min[B/5;11.5] | X | | | | X | | | | |
| | 1.5 m | | X | X | X | | | X | X | X |
| | Probabilistic up to B/2 | | | | | | X | | | |
| **Vertical extent** | Bottom upwards | X | X | X | X | X | | X | X | X |
| | Probabilistic, but:<br><d+7 for L>250;<br>< d+0.056Ls(1-Ls/500) for L≤250 | | | | | | X | | | |

Table 10: Rule assumptions on the damage extent

| Damage requirements | | ICLL (type A) | IMO MODU | HSE | NMD | MARPOL | SOLAS | DNV | LRS | ABS (FPSO refers to MODU) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Heel angle** (angle at equilibrium after damage) | ≤ 15° | X | | | | | | | | |
| | ≤ 15° (without wind) | | | X | | | | | | |
| | ≤ 17° (incl. static wind) | | | | X | | | X | | |
| | ≤ 25° (30° if deck edge not immersed) | | | | | X | | | | |
| | ≤ 30° | | | | | | X | | | |
| **Sinkage limit** | Progressive flooding | X | X | | X | X | X | | | |
| | Progressive flooding allowing 4 m for wind & waves | | | X | | | | X | | |
| **GZ** | “sufficient reserve against capsizing” | | X | | | | | | | |
| | 0.1 m | | | | | X | | | | |
| | ≥ 0 | | | | | | X | | | |
| **Range of stability** | To withstand 50 knot wind heel and no downflooding before 1st intercept | | X | X | X | | | X | X | X |
| | 20° | | | | | X | | | | |
| | ≥ 0 | | | | | | X | | | |
| **Area ratio** | ≥ 1 (50 knot wind) | | | X | X | | | X | | |

Table 11: Rule requirements for damage stability.

## 2.14 SHIP IMPACT (ALS)

The main collision scenarios according to North Sea experience are:

- Passing vessel collisions (low frequency and high consequence)
- Visiting supply vessels (high frequency with the majority resulting in low consequence)
- Offloading shuttle tankers (medium frequency with potential high consequence)

Causes may be high speed (dangerous manoeuvre), failure of control (mechanical failure), and extreme fishtailing (hydro)…

HSE Guidance Notes (Section 15), DNV and LRS agree on a ship impact based on the following minimum assumptions:

Kinetic energy: ≥ 14 MJ for sideway collision
≥ 11 MJ for bow or stern collision

This more or less corresponds to the kinetic energy of a 5000-ton displacement supply boat, with a 2 m/s speed.

Therefore, there seems to be little correlation between the nominal ship impact proposed by the Rules and the more likely impact that is associated with FPSO operations – collision with shuttle tanker.

# 3 STATE-OF-THE-ART REVIEW: PRESENT RELIABILITY LEVELS

## 3.1 INTRODUCTION

This analysis has been carried out after a review of Noble Denton experience, conference proceedings as well as of publications in technical journals.

This review enables the evaluation of the reliability levels to which the designers believe they are designing. For the limit states that are not well documented in literature, the previous analysis of the Rules with their inherent sources of uncertainty can help to estimate the reliability levels they achieve.

However, it is important to emphasise that these reliability levels are mainly rough estimates with an accuracy no better than ±1 order of magnitude.

## 3.2 STRUCTURAL STRENGTH – EXTREME: HULL MIDSHIP SECTION (ULS)

DNV Rules for Ships state the following: "The ship motions and accelerations are given as extreme values, with an associated probability of failure of $10^{-8}$. Design pressures caused by sea, liquid cargoes, dry cargoes, ballast and bunker are based on extreme conditions, but are modified to equivalent values corresponding to the stress levels stipulated in the rules. Normally, this involves a reduction of the extreme [stress] values to a $10^{-4}$ probability level." Impact pressure due to slamming or green water is not taken into account in this probability level.

The above paragraph illustrates the danger in comparing reliability levels. At first sight, the probability level of $10^{-8}$ appears to be conservative, But, when properly interpreted, it merely requires the designer to compute approximately 20-year return motions and accelerations for design purposes. Thus, it is only safety factors which are employed together with these design motions and accelerations which can reduce the probability of failure to acceptable levels.

According to the document HSE OTO 98164 (ref. 4) though IACS (international Association of Classification Society) Unified Standard aims to unify the Rules' requirements, there is still a large diversity in the design wave-induced bending loads and in their interpreted reliability (see OTO 98164 / § 1.2.2.2 p17). In that document, 8 rules have been compared. For a given probability of exceedance $P_e$, say $10^{-8}$/wave, the ratio of the highest calculated design wave-induced moment Mw to the lowest is 1.8. In addition, for a given Mw, $P_e$ varies by 4 orders of magnitude in sag and 3 orders in hog.

However, the Rules have provided a good level of operating safety, since very few (tanker) accidents are due to exceedance of longitudinal ultimate strength but rather to fatigue cracking, corrosion or human errors during loading.

A review of a wide quantity of reasonably maintained **tanker ships** quoted in the report OTO 98164 led to the following **structural probabilities of failure: Pf = $7.2 \times 10^{-5}$ to ≈ $2 \times 10^{-7}$ per year and Pf = $1.35 \times 10^{-3}$ to $3.4 \times 10^{-6}$ for a 20-year life**.

Are these probabilities of failure adaptable to an FPSO? How would the design load for an FPSO compare to the design load for a Ship? Ref.4 proposes to decrease the design extreme load for Ships by a factor of 0.9. Indeed, even if the FPSO has a preferred heading facing the waves, the environment at a fixed location in the North Sea and the zero forward speed – inducing **less slamming** – tend to **reduce the maximum loads**.

This is in agreement with Kaminski (ref. 5) who analysed the **FPSO unit "Uisge Gorm"** moored at the Fife field location. This vessel is a ten year old converted tanker from MT Dirch Maersk, which had the LR Class for an unrestricted service, and which apparently was not strengthened for the

purpose of its new mission. Kaminski quotes a calculated reliability index β for the hull girder of the FPSO against its ductile collapse of **3.91 per year (Pf = $4.71 \times 10^{-5}$), and 3.5 (Pf = $2.3 \times 10^{-4}$) after 20 years of service.** The analysis presented in this paper takes into consideration uncertainties in material properties, geometrical properties, imperfections, still-water loading, bending moment corrections, strength predictions and average wave period.

The above values are not too dissimilar in order of magnitude terms as published historical data on tankers for this failure mode. Hu and Davidson (ref. 25) stated that the probability of loss of ship due to hull/machinery failure is $4.7 \times 10^{-4}$ per ship year. As “hull/machinery failure” encompasses a variety of serious failure modes the actual probability of hull midship section failure is undoubtably less than this value. If, for example, it was assumed that 1 in 10 hull/machinery failures were due to miship section failure, the annual probability, based on historical data, of experiencing a hull midship structural failure can considered as being $4.7 \times 10^{-5}$.

If one refers to the chart given in § 3.1, and to the description of the Rules Statements given in § 3.2, the Rules make assumptions on the Wave Induced Actions, Still Water Bending, Hull Midship Section Modulus, Scantling and Corrosion. It appears that they do not really make allowances for uncertainties related to waves, storage, deck loads, and FPSO motion. These uncertainties are included in the probabilities of failure quoted here above.

Thus it may be concluded that the ***annual probability of failure*** of an FPSO due to hull structural failure is of the **order of $5 \times 10^{-5}$**. The accuracy of this result is approximately a factor of 10 on either side depending upon the specific case.

### 3.3 STRUCTURAL STRENGTH – EXTREME: BOW STRUCTURE / SLAMMING (ULS)

The structural extreme design of the bow structure depends mainly on the slamming pressures. Slamming, like sloshing and green water, is a complicated issue in hydrodynamics.

Marintek recently proposed a JIP called "Design loads and integrity assessment for wave impact on Bow and Deck structures". The objective of the project is "to develop practical engineering tools for prediction of:

- Probabilities of bow slamming, water on deck or water hitting platform deck in a random sea.
- Slamming loads,
- Assessment of structural integrity."

Their work will be based upon an extensive experimental database.

In addition, Marin are also proposing a JIP called FLOW for Floater Loading by Waves, related to bow impact and green water loadings. In their publication at OMAE 2000 (Buchner, ref. 6), they come to the conclusion that there is a quadratic relation between the impact loads on structures at the deck and the freeboard exceedance. The factor between the pressure and the freeboard exceedance squared depends on the bow flare angle and can be evaluated experimentally with 95% reliability in irregular waves.

Therefore, one can be confident that many improvements are carried out to better assess the slamming loads on the bow structure.

Quite obviously, conducting model tests helps to achieve a better understanding of the vessel's behaviour to be achieved which will enable better reliability to be achieved than only meeting the Rule requirements (DNV being apparently more conservative than LRS) or following the more refined standard offshore design practice.

However, even if model tests are carried out, one cannot be sure that all possible waves have been considered. A detailed review of the problem shows that no absolute conclusion can be drawn concerning the probability of exceedance of any given slamming pressure, because of the insufficient data on wave steepness and local wave profile.

Therefore, the probability of exceedance of the bow structural strength against slamming loads has to be evaluated with extreme care. Nevertheless, if the parameters involved in the bow structure design

against slamming pressures are compared to the ones involved in the hull midship section design, one can point out that:

- They seem to be rather similar, except that the uncertainty lying in the wave definition is emphasised, due to the lack of data on wave steepness. Furthermore, in slamming calculations the detailed structural response at very high frequencies are important but introduce additional uncertainties.

- If the engineer sticks to the Rules rather than using the refined standard offshore design practice, he will probably increase the uncertainty lying in his design. However, even with the more refined standard practice, there is a large variability included in slam coefficient values.

Noble Denton has carried out independent reliability analysis to estimate the sensitivity of the probabilities of failure to increase in the COV of the bending strength. Given the increased uncertainties in load effects due to slamming when compared to tradition midship structure bending moment calculations, a doubling of the COV was assumed in the calculation. This increased the probability of failure to $1x10^{-3}$/annum.

Based on the previous remarks, and by comparison to the reliability level stated for hull midship section structural strength, **one could *estimate, recognising the increased uncertainty,* that the annual reliability level for bow structure design against slamming pressure is in the order of $10^{-3}$/annum. Again, an uncertainty of ±1 order of magnitude is likely.**

## 3.4 STRUCTURAL STRENGTH – EXTREME: CARGO TANK / SLOSHING (ULS)

Many efforts have been made to better understand and model sloshing. Several publications report model tests and theoretical developments that are currently taking place.

Although the hydrodynamic phenomenon remains complicated to model, the way the Rules estimate the sloshing pressures may be conservative anyway, because these are usually validated by model tests and apparently consider dynamic pressures occurring at resonance, i.e. typically when the vessel is submitted to a regular wave. This is true provided that the thickness of the tank plates is duly calculated to hold the estimated sloshing pressures, and not arbitrarily taken to be equal to the Rule minimum requirement.

Meanwhile, the engineer needs to keep in mind that the Rules were originally written for sea-going ships. An FPSO – whose tanks are slowly filled and emptied at sea – may be more subject to sloshing than a tanker ship that usually travels with either full tanks or empty tanks.

In addition to this, one can note that the parameters involved in cargo tank design against sloshing pressures are rather similar to the ones involved in the hull midship section structural design, with a strong dependence on wave-induced motions.

Based on these remarks and by comparison to the reliability level assumed for hull midship section strength, **one could *estimate* that the annual reliability level for cargo tank design against sloshing pressures is in the same order as for the hull midship section, that is to say in the order of $10^{-5}$.**

## 3.5 STRUCTURAL STRENGTH – EXTREME: TURRET (ULS)

It is clear from the review of design procedures, that turret structural design is calculated using direct design methods. Thus it may be concluded that extreme design loads will be derived and applied to detailed structural models together with well accepted safety factors (1.25 to 1.35 on loads and 0.8 to 0.85 on strength) thus resulting in structural integrity which is **normally in excess of $10^{-4}$/annum**.

### 3.6 STATION KEEPING – EXTREME (ULS)

Noble Denton and MCS recently managed an industry funded JIP, which sought to address the reliability levels achieved by mooring and riser systems.

The major JIP results are reported in ref. 7, where the hypotheses of the reliability analysis are well documented. Assuming certain distributions of the wave height, wind and current speeds and of the mooring line components strength, the probability of exceedance of critical mooring line tension has been evaluated, for the intact and damaged mooring system conditions. The results are reported in Table 12 for an FPSO in the West of Shetlands (WoS) and another one in the Central North Sea (CNS). One can notice that the range in the probability of exceedance of mooring line tension is large.

| Probability of exceedance per annum | Intact mooring system (1 year exposure period) | Damaged mooring system (3 month exposure period x 4) |
|---|---|---|
| WoS | $6.4x10^{-9}$ | $3.0x10^{-8}$ |
| CNS | $2.3x10^{-5}$ | $2.7x10^{-3}$ |

Table 12: Mooring line tension – reliability

In addition to this, the total mooring system probability of exceedance has been evaluated, as the combination of the three following limit state modes:

- When one mooring line has failed due to extreme loading
- When two mooring lines in the same cluster / windward sector are in the failed state; first line exceedance of limit state due to non-extreme loading, second line exceedance of limit state due to extreme loading.
- When two mooring lines in the same cluster / windward sector are in the failed state; both line exceedance of limit states due to non-extreme loading.

N.B.: **fatigue (see chapter 3.11)** and unexpected mooring line probabilities of exceedance are termed as exceedance under non-extreme conditions.

Table 13 reports the mooring system reliabilities that have been evaluated for the two typical turret-moored FPSOs in the West of Shetlands and in the Central North Sea:

| Probability of exceedance | 1st year | Final year |
|---|---|---|
| WoS | **$3.0x10^{-4}$** | **$1.9x10^{-2}$** (high fatigue) |
| CNS | **$1.8x10^{-4}$** | **$1.8x10^{-4}$** |

Table 13: Total mooring system reliability – 1st year and final year.

Additional work has been carried out by BP Amoco and Noble Denton on reliability of polyester mooring systems (see ref. 8). The main result of this study was that polyester mooring system may have an even better reliability than steel mooring system.

Thus, the mooring ***system*** reliability accounting for all effects appears **to range between $2x10^{-2}$ and $2x10^{-4}$ per annum**. However, the high probability of failure in the final year is dominated by fatigue reliability and future designs that properly account for this effect will improve the system reliability to be nearer to $2x10^{-4}$. Indeed, the JIP proposed target reliabilities of the order of $5x10^{-4}$/annum.

## 3.7 FLUID TRANSFER SYSTEM – EXTREME (ULS)

Again, as a result of the JIP recently managed by Noble Denton and MCS on integrated mooring and riser design (ref. 7), the riser system reliability has been evaluated for typical FPSOs that are turret-moored in the West of Shetlands or in the Northern North Sea.

Assuming certain distributions of the wave height, wind and current speeds and of the riser mean curvature capacity and tension capacity, the probabilities of exceedance of the critical risers' tension and curvature limit states have been evaluated, for the intact and damaged mooring system conditions. The results are reported in Table 14 and in Table 15, for an FPSO in the West of Shetlands (WoS) and another one in the Central North Sea (CNS).

| Probability of exceedance per annum | Intact mooring system (1 year exposure period) | Damaged mooring system (3 month exposure period x 4) |
|---|---|---|
| WoS | $5.6x10^{-17}$ | $2.2x10^{-16}$ |
| CNS | 0 | $4.9x10^{-15}$ |

Table 14: Riser tension reliability

| Probability of exceedance per annum | Intact mooring system (1 year exposure period) | Damaged mooring system (3 month exposure period x 4) |
|---|---|---|
| WoS | $5.2x10^{-7}$ | $4.5x10^{-7}$ |
| CNS | $2.7x10^{-4}$ | $3.5x10^{-4}$ |

Table 15: Riser curvature reliability

Then, the definition of the mooring & riser system failure has been considered as being the event of riser failure. This however does not represent a permanent shut down of the system. It instead represents the event of the system reaching an undesirable state. This state resulting in temporary loss of production, until the riser is then repaired. By this definition, it is therefore possible for more than one system failure to occur during the service life of the structure, and even during the period of the year. As a result, the system failure events are not mutually exclusive over the system's lifetime.

The total riser system probability of exceedance has been evaluated as the combination of the five following limit states:

- When all mooring lines are intact.
- When one mooring line has failed due to extreme loading.
- When one mooring line has failed under non-extreme loading conditions.
- When two mooring lines in the same cluster / windward sector are in the failed state; first line exceedance of limit state due to non-extreme loading, second line exceedance of limit state due to extreme loading.
- When two mooring lines in the same cluster / windward sector are in the failed state; both line exceedance of limit states due to non-extreme loading.

N.B.: **fatigue (see chapter 3.11)** and unexpected mooring line probabilities of exceedance are termed as exceedance under non-extreme conditions. **Riser fatigue (see chapter 3.12)** probability of exceedance has also been considered in the following calculation.

Table 16 reports the riser system reliabilities that have been evaluated for the two typical turret-moored FPSOs in the West of Shetlands and in the Central North Sea:

| Probability of exceedance | 1st year | Final year |
|---|---|---|
| WoS | **$3.0x10^{-4}$** | **$1.9x10^{-2}$**<br>(high mooring fatigue) |
| CNS | **$6.9x10^{-4}$** | **$6.9x10^{-4}$** |

Table 16: Total riser system reliability – 1st year and final year.

Thus, the riser ***system*** reliability accounting for all effects appears **to range between $2x10^{-2}$ and $7x10^{-4}$ per annum**. However, the high probability of failure in the final year is dominated by fatigue reliability of mooring lines and future designs that properly account for this effect will improve the system reliability to be nearer to $7x10^{-4}$. Indeed, the JIP proposed target reliabilities of the order of $5x10^{-4}$/annum.

### 3.8 DECK CLEARANCE / GREENWATER / DECK & TOPSIDE DESIGN (ULS)

The general design approach in recent years is to carry out model tests. Model tests can help to define the choice of the hull shape, the bow flare angle, as well as the design of topsides that are submitted to the green water pressures and the safety escape routes that may be submerged by the flow. In addition, international JIPs like those conducted by Marintek or Marin also aim at calculating the probability of exceedance of freeboard using the relative motions between the FPSO and the water surface.

In their publication at OMAE 2000 (ref. 9), Marin come to the conclusion that there is a quadratic relation between the impact loads on structures at the deck and the freeboard exceedance. The factor between the pressure and the freeboard exceedance squared depends on the bow flare angle and can be evaluated experimentally with 95% reliability in irregular waves. Undeniably, many improvements are currently carried out to better assess the effects of Green Water.

Deck and topside design against greenwater has several similarities with bow structure design against slamming pressures. If the parameters involved in both designs are compared to each other, one can point out that:

- For both designs, there is a major uncertainty lying in the wave definition, which seems to be more critical than for hull midship section strength design.

- As for bow structure design against slamming pressures, topside design also depends on structural strength parameters.

Therefore, one could argue that this limit state has a relatively similar reliability level when compared to bow structure design against slamming pressure.

As a conclusion, and based on the previous assumptions, **one could *estimate* that the annual reliability levels for deck / topsides design against green water is in the order of $10^{-3}$/annum. The accuracy of the result is unlikely to be better than ±1 order of magnitude.**

## 3.9 STABILITY – INTACT (ULS OR SLS)

The current approach is to check against an area ratio with a “safety factor” of 1.4. This approach does not take account of roll motions or any directly relevant site-specific wind speeds on the beam.

Thus the criteria for stability seem even more arbitrary than the Rules for hull midship section design. However, this does not necessarily mean that these are any less conservative.

On the contrary, according to historical database, it appears that intact stability failure is less likely to occur than structural failure.

Unlike sea-going ships, an FPSO weathervanes. As a consequence, it is rather seldom that beam seas occur together with beam winds. This could justify a better reliability level for FPSOs than for Ships.

Based on the previous remarks, and by comparison to the reliability level of the hull midship section design, **the reliability level of the intact stability *might be estimated* to fall in the range of $5x10^{-6}$ to $1x10^{-8}$**. This would be about one order of magnitude better than the reliability level achieved for the hull midship section design. Furthermore, given that moorings and risers will be present in the FPSO, it would be very surprising to see the capsize of a turret moored FPSO.

## 3.10 STRUCTURAL STRENGTH – FATIGUE (FLS)

As pointed out in the document HSE OTO 98164 (ref. 4), the FPSO spends all its life on site, unlike a tanker that is normally able to avoid bad storms and sea-states, and that spends a significant part of its life in port. Therefore, **the structural fatigue should be worse for an FPSO than for a traditional Ship.**

However, FPSO are offshore installations with potential high risks and are therefore likely to be inspected more often than bulk carriers and oil tanker.

Two sister JIPs will probably give the industry a better knowledge of the fatigue loads and resistance on FPSOs, and help developing requirements more adapted than the ones originally written for merchant ships or oil tankers. These are the FPSO Integrity JIP (Bultema Marine, Marin, Bluewater) and the FPSO Fatigue Capacity JIP (DNV).

Some references can be found in literature:

- Ref. 11: For evaluating the fatigue damage of ship structures, uncertainties related to fatigue property of members and inspection ability are necessary.

  "Fatigue reliability analysis under repeated inspections is carried out for the six structural members of bulk carriers. Crack initiation and propagation properties of the members, probability of crack detection by the visual inspection and target failure probabilities of the members, etc., which are essential information to the reliability analysis, are collected by the [questionnaire] asked to naval engineers. In this study, *crack length exceeding 200 mm was defined as [fatigue] failure event*. Additionally, from the viewpoint of covering almost entire cracks detected in real inspection, another critical crack length of 500 mm was selected as failure event."

  At present, Pf(200) = $2x10^{-1}$ and Pf(500) = $7x10^{-2}$ for a member during 20 years' service. Target reliability = 1/8 = $13x10^{-2}$ and 1/16 = $6x10^{-2}$ respectively, by reducing the inspection intervals. Again, it is noticed that the failure event is defined as an exceedance of the crack length. It does not mean necessarily that this will lead to a major structural failure.

- Ref. 12: This paper contains a general description and the results of the reliability analysis made for fatigue sensitive joints in the FPSO Uisge Gorm. The *annual risk of fracture failure of the hull girder due to fatigue* is calculated, and the inspections and repair strategy are accounted for. It is concluded that up to the 6th year, the fracture risk is at an acceptable level (annual probability failure progressively increasing from **$5x10^{-7}$ to $10^{-4}$**). If no inspection is carried out, the annual probability of failure can reach a level of **$2x10^{-3}$** on the 20th year. However, it is expected that an inspection programme will keep an acceptable level (Pf < $10^{4}$) for the rest of the life of the FPSO.

When the parameters involved in the design of hull midship section (extreme) are compared to the ones involved in the design of the hull fatigue (see § 4), it appears that they are rather similar. Nevertheless, fatigue design includes an additional uncertainty coming from environmental scatter diagram, load distribution on the hull welded joints, and accumulation process with time. Therefore, it seems relevant to consider a decreased reliability level for fatigue design compared to extreme structural design, as well as a large scatter depending on inspection frequency.

Based on the previous remarks and references, and by comparison with the reliability level stated or estimated for hull midship section, **one could *estimate* the annual probability level for hull structural fatigue failure (provided regular inspection is carried out) to be in the range of $10^{-4}$ to $5x10^{-7}$.**

## 3.11 STATION KEEPING – FATIGUE (FLS)

As a result of the JIP recently managed by Noble Denton and MCS on integrated mooring and riser design (ref. 7), the mooring line reliability against fatigue loading has been evaluated for typical FPSOs that are turret-moored in the West of Shetlands or in the Northern North Sea.

The probability of mooring fatigue limit state exceedance has been calculated by assuming certain distributions for the fatigue strength of chain and model uncertainty, and by neglecting the wire fatigue limit state's probability of exceedance (fatigue lives of wire are much larger than for chain).

Table 17 reports the mooring fatigue limit state's probabilities of exceedance that have been calculated for an FPSO in the West of Shetlands and another one in Northern North Sea. The significant difference between them is a reflection of the size of the safety factor on fatigue that had been selected for the design (3.25 and 42.9 respectively!).

| Probability of exceedance | Design life (years) | Design life Pf |
|---|---|---|
| WoS | 20 | **$7.8 \times 10^{-2}$** |
| CNS | 10 | **$2.0 \times 10^{-11}$** |

Table 17: Mooring fatigue probability of exceedance.

This probability of exceedance of fatigue limit state has been taken into account in the calculation of the mooring system reliability (see chapter 3.6).

## 3.12 FLUID TRANSFER SYSTEM – FATIGUE (FLS)

The JIP recently managed by Noble Denton and MCS on integrated mooring and riser design (ref. 7) also addressed the issue of riser tension reliability against fatigue loading.

The probability of riser fatigue limit state exceedance has been calculated by assuming certain distributions for the fatigue strength of flexible riser and load model uncertainty, and by taking into account loading due to vessel motions. It was performed for two turret-moored FPSOs in West of Shetlands and in Central North Sea.

**The evaluation of the probability of exceedance by fatigue of the flexible riser layers was found to be negligible**.

## 3.13 STABILITY – DAMAGE (ALS)

Unlike for intact stability, for which IMO requirements seem to be adopted by the majority of the Rules, a large discrepancy between the Rules has been highlighted for damage stability. They agree neither on the criteria to meet in order to ensure damage stability, nor on the number / location of the compartments that have to be damaged before checking those criteria.

Damage may be caused by intact stability failure (progressive flooding due to excessive heel angle or to greenwater), by a ship collision, or by the hull structural failure (cracks due to fatigue, exceedance of the hull girder strength, side collapse, etc.). Each of these causes has its own probability of occurrence.

As damage stability calculations are normally performed and checked against an area ratio of 1 (i.e. no safety factor) using a wind overturning arm computed from a wind speed of about 50 knots (more or less equivalent to a 10-year return wind speed), the exceedance of this limit state may be estimated to be about 0.05/annum. However, the probability of first compartment damage is unknown but given the widespread acceptance of one compartment damage calculations, this probability is not negligible and could be in the range 0.01-0.001.

Nothing has been found in literature dealing with the reliability level of damage stability. However, since it is dependent on other limit states failure such as topside design overload due to green water, hull structure failure due to extreme loads or most probably to fatigue, its reliability level cannot be easily determined. **Thus more detailed analysis is necessary before the reliability against capsize after the failure of a compartment may be determined with even ±1 order of magnitude accuracy**.

### 3.14 SHIP IMPACT (ALS)

According to ref. 13, “Most offshore installations are designed to withstand collisions from supply boats at moderate speed. They are unlikely to withstand collision from large merchant ship at full speed or from large support vessels such as flotels if they come adrift in severe weather. Such events have been extremely rare, but the results may be total collapse of the installation, making them a significant risk.”

Still quoting ref. 13: “the Rules are based on J.P. Kenny (1988), “Study on Offshore Installations Protection against impact”, Department of Energy Offshore Technology Information Report OTI 88 535.” This report considered the impact energy to have an exceedance probability of $10^{-3}$ per platform year.” This implies that the damaging energy probability is better than $10^{-3}$/annum because of the use of conventional >1 safety factors. As the probability of any sort of impact is of the order of 0.1 (based upon historical data which suggests 491 impacts in 23 years of 201 installations in the UKCS (Ref.19)), severe impact damage can be estimated to be $<10^{-4}$/annum.

In a study conducted by Dovre Safetec (Ref. 19) they conclude that world-wide only 9 collision incidents involving offshore installations have resulted in total loss. Based upon the historical data presented in that reference, it has been derived that the probability of severe consequence from ship collision with an offshore installation is in the region of $4x10^{-3}$/annum.

Considering the uncertainty lying in these calculations, it is suggested that **the annual reliability level of the FPSO design against ship impact is between $4x10^{-3}$ and $4x10^{-5}$**.

## 3.15 SUMMARY

The reliability levels obtained previously by calculation or estimation are summarised in Figure 12.

The calculated reliability levels for extreme design of fluid transfer and station keeping systems take into account the probability of failure due to fatigue (final year). Thus, the reliability levels for fatigue of fluid transfer and station keeping systems have not been reported independently in this summary.

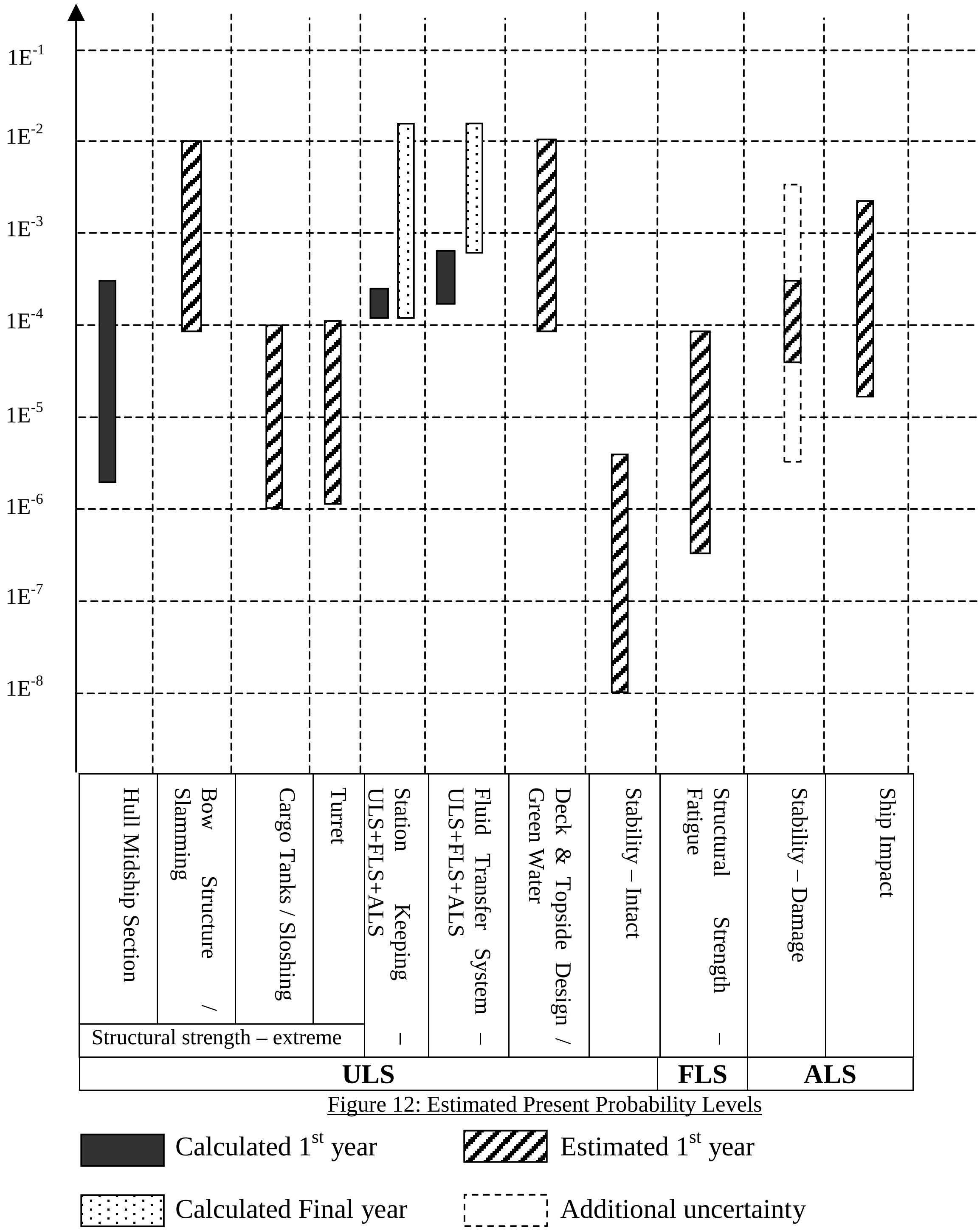



Figure 12: Estimated Present Probability Levels

# 4 CONSEQUENCES OF EACH LIMIT STATE EXCEEDANCE

## 4.1 INTRODUCTION

Once the current individual reliability levels of each key limit state have been evaluated, it becomes necessary to assess the relevance of their relative levels. Indeed, although commensurate reliability levels are desired in FPSO design, equal reliability levels for different limit states are not.

Therefore, this Chapter examines the consequences of different limit state exceedances so that the probability levels can be put in context. The consequences of failure will be categorised into potential loss of life, containment and production. Their probability of occurrence can be ranked in Low, Medium, or High, as well as their financial consequences.

In the following discussion, “High” consequence is considered to be one in which fatalities in excess of 10 could occur and/or oil spill in excess of 10000-100000 bbls could occur and/or production loss/delay of about $100 million could occur. “Low” consequence may be defined as no fatalities and/or negligible oil spill and/or less than $1 million worth of production loss/delay.

## 4.2 STRUCTURAL STRENGTH – EXTREME: HULL MIDSHIP SECTION (ULS)

A structural failure can cause plate deformations and deflections, but also stiffener distortions and detachments, which can even lead to large tears. Depending on the severity of the failure and on the ability to repair on site, different consequences can occur.

Loss of Production is very likely to happen: even if the damage is not too serious, production may be stopped temporarily during the repairs for safety reasons. It is even more probable if a compartment is damaged, thus endangering the FPSO stability. Since the damage can weaken the whole FPSO structure, it may be preferable to stop completely the loading procedure, thus the production. Therefore, the financial consequence can be rather high.

Loss of Containment can happen if the damage causes an opening in the tanks. The amount of oil spill will depend on the location of the damage. However, it is likely to be rather serious if the FPSO breaks its back.

Loss of Life might happen if a loss of containment causes an explosion. More likely, loss of life could happen if the structural failure involves the flooding of one or more compartments and if in turn **damage stability failure** occurs, thus making the FPSO capsize. In that case, there might be a large number of fatalities.

Therefore, hull midship section failure can have very serious consequences.

| **Hull Midship Section Failure Probability of Occurrence / annum** | **Loss of Life Consequence** | **Loss of Containment Consequence** | **Loss of Production Consequence** |
|---|---|---|---|
| $5x10^{-6}$ - $5x10^{-4}$ | High | High | High |

## 4.3 STRUCTURAL STRENGTH – EXTREME: BOW STRUCTURE / SLAMMING (ULS)

Damage of the Bow Structure due to excessive slamming pressures can induce plate deformations and deflections, but also stiffener distortions and detachments, which can even lead to large tears.

Loss of Production and Loss of Containment can happen for the same reasons as for hull midship section failure. However, since the damage is more localised, the consequences may be lower. Indeed, only the fore tanks are concerned by a potential loss of containment. In addition, the local damage should not prevent from restarting production quite quickly, by using the other tanks for loading the oil produced. However, it should be noticed that the main production issue could be loss of key utilities or damaged process items.

Loss of Life seems unlikely to happen, except if some of the fore spaces are manned. Still, it might well be due to an explosion caused by a release of products from a damaged tank.

Therefore, the bow structure failure due to slamming pressures seems to have lower consequences than hull midship section failure.

| Bow Structure Failure / Slamming Probability of Occurrence / annum | Loss of Life Consequence | Loss of Containment Consequence | Loss of Production Consequence |
|---|---|---|---|
| $10^{-4}$ - $10^{-2}$ | Medium | Medium | Medium |

## 4.4 STRUCTURAL STRENGTH – EXTREME: CARGO TANK / SLOSHING (ULS)

If the pressures induced by sloshing exceed an admissible level, the tank side and top plates may suffer from damage ranging from deflections to more serious tears.

Since the damage is directly located in a storage tank, Loss of Containment is very likely to occur, all the more so if there is no double skin hull. The amount of oil spill may be equal to the whole content of one single tank. Thus, the oil spill may be rather high, but is nevertheless expected to remain smaller than in the event of a hull midship section failure.

Loss of Production may occur for the same reasons as for Bow Structure failure due to Slamming. The occurrence of this event would induce repair works requiring access to the tanks, thus leading to down time.

A for Bow Structure failure due to Slamming, Loss of Life seems quite unlikely to happen.

| **Cargo Tank Failure / Sloshing Probability of Occurrence / annum** | **Loss of Life Consequence** | **Loss of Containment Consequence** | **Loss of Production Consequence** |
|---|---|---|---|
| $10^{-6}$ - $10^{-4}$ | Low | Medium | Medium |

## 4.5 STRUCTURAL STRENGTH – EXTREME: TURRET (ULS)

The FPSO turret is a “hot spot” because it is a complicated structural piece, ensuring the connection of mooring lines and risers to the FPSO.
**Turret Failure may lead to Station Keeping Failure or to Fluid Transfer System Failure.**

Loss of Containment may be due to a damage to one of the compartments surrounding the turret, or to the fluid swivels and / or piping. The turret is therefore a very sensitive part of the hull, but the consequences remain quite low. Indeed, the amount of oil spill is limited to the content of the surrounding compartments (that are normally protected by double sides), or only to the content of the damaged riser / piping.

In case of turret failure, it seems difficult to avoid Loss of Production, because of the proximity between the damage and the fluid transfer system. Depending on the extent of the failure, from none to all risers need to be shut down. In addition, if a mooring line attachment is damaged and if the FPSO moves beyond its admissible offset, the fluid transfer system may be endangered, so disconnection or shut down may be required. It also seems difficult to restart production before completion of repairs: given the relative complexity of the turret arrangement, this could last quite a long time. Therefore, both the risk and the consequence of Loss of Production due to turret failure are predicted to be high.

In major cases, Loss of Life is likely to happen only if the damage to the turret causes leakage and explosion.

| Turret Failure Probability of Occurrence / annum | Loss of Life Consequence | Loss of Containment Consequence | Loss of Production Consequence |
|---|---|---|---|
| $10^{-6}$ - $10^{-4}$ | Medium | Low | High |

## 4.6 STATION KEEPING (ULS+ALS+FLS)

Since the main function of the mooring system is to keep the FPSO in station, so that it can produce safely, the major consequence of a station keeping failure would be to endanger the fluid transfer system, through which production is carried out.
**Thus, station-keeping failure can not be studied independently of fluid transfer system failure.**

As a consequence, for station keeping failure as well as for fluid transfer system failure, both Loss of Production and Loss of Containment are very likely to occur with rather high consequences. However, the amount of oil spill should be lower than in the event of hull midship section failure, because riser shut down could normally be performed before the FPSO drifts too far.

Considering that shut down could be performed quickly, station keeping failure normally does not induce Loss of Life.

| Station Keeping Failure Probability of Occurrence / annum | Loss of Life Consequence | Loss of Containment Consequence | Loss of Production Consequence |
|---|---|---|---|
| $2x10^{-4}$ - $2x10^{-2}$ | Low | Low | High |

## 4.7 FLUID TRANSFER SYSTEM – (ULS +FLS+ALS)

See **Station Keeping Failure**.

In case of fluid transfer system failure, both Loss of Production and Loss of Containment are very likely to occur with high consequences. The amount of oil or gas spill may be higher than in the event of station keeping failure, because the damage could happen suddenly, without enabling shut down.

Fluid transfer system failure normally could induce more fatalities than station keeping failure: it could happen that the damage to the riser is not controlled and that it induces an explosion.

| Fluid Transfer Failure Probability of Occurrence / annum | Loss of Life Consequence | Loss of Containment Consequence | Loss of Production Consequence |
|---|---|---|---|
| $7x10^{-4}$ - $2x10^{-2}$ | Medium | Medium | High |

### 4.8 DECK CLEARANCE / GREENWATER / DECK & TOPSIDES DESIGN(ULS)

If the pressures induced by Green Water are too high, the deck and topside designs may be insufficient to support them.

In the event of deck and / or topside failure due to green water, some tanks may be damaged thus inducing Loss of Containment. However, since the damage should be located on the deck, the opening normally remains above the water line, so the amount of oil spill should remain low.

Production could be affected as a result of damage to process equipment. Whilst production may continue, it will be under reduced capacity.

Last, topside failure due to green water may imply fatalities, all the more so if accommodation is damaged.

| Deck & Topside Failure/ Green Water Probability of Occurrence / annum | Loss of Life Consequence | Loss of Containment Consequence | Loss of Production Consequence |
|---|---|---|---|
| $10^{-4}$ - $10^{-2}$ | Medium | Low | Medium |

### 4.9 STABILITY – INTACT (ULS OR SLS)

In the event of intact stability failure, the FPSO may capsize. This event is however unlikely with moorings and risers still connected.

Loss of Production can be permanent if it is not possible to recover a safe equilibrium by ballasting compartments or tensioning the mooring lines. The consequence can be catastrophic if the wellheads have not been kept safe, thus making impossible to restart production later on (possibly with another FPSO, EPS-type).

Loss of Containment is likely to happen, all the more so if the risers are damaged, and if some tank openings are below the water line after capsize. However, since no compartment is damaged, the amount of oil spill should remain controlled (except for risers).

Intact stability failure is an unexpected event. In addition, it modifies and endangers all safety escape routes. Therefore, it can imply many fatalities among the whole crew.

| Intact Stability Failure Probability of Occurrence / annum | Loss of Life Consequence | Loss of Containment Consequence | Loss of Production Consequence |
|---|---|---|---|
| $10^{-8}$ - 5x $10^{-6}$ | High | Medium | High |

## 4.10 STRUCTURAL STRENGTH – FATIGUE (FLS)

See section 5.2 for consequence discussion.

| Structural Fatigue Failure Probability of Occurrence / annum | Loss of Life Consequence | Loss of Containment Consequence | Loss of Production Consequence |
|---|---|---|---|
| $5x10^{-7}$ - $10^{-4}$ | High | High | High |

## 4.11 STABILITY – DAMAGE (ALS)

Damage Stability Failure is rather similar to Intact Stability Failure, except than the risk and consequence of Loss of Containment is even greater, since some compartments are damaged and open to the sea.

| Damage Stability Failure Probability of Occurrence / annum | Loss of Life Consequence | Loss of Containment Consequence | Loss of Production Consequence |
|---|---|---|---|
| *$5x10^{-6}$ – $5x10^{-3}$* ***??*** | High | High | High |

## 4.12 SHIP IMPACT (ALS)

In the event of abnormal ship impact energy, the major likely consequence is a hull damage that may lead to structural failure or even damage stability failure.

One could therefore put the consequences of a ship impact energy exceedance at the same level as the consequences of hull midship section failure and damage stability failure.

| Ship Impact Failure Probability of Occurrence / annum | Loss of Life Consequence | Loss of Containment Consequence | Loss of Production Consequence |
|---|---|---|---|
| $4x10^{-5}$ – $4x10^{-3}$ | High | High | High |

## 4.13 SUMMARY

The estimated levels of present reliability and the consequences of limit state failures can be summarised in the following table.

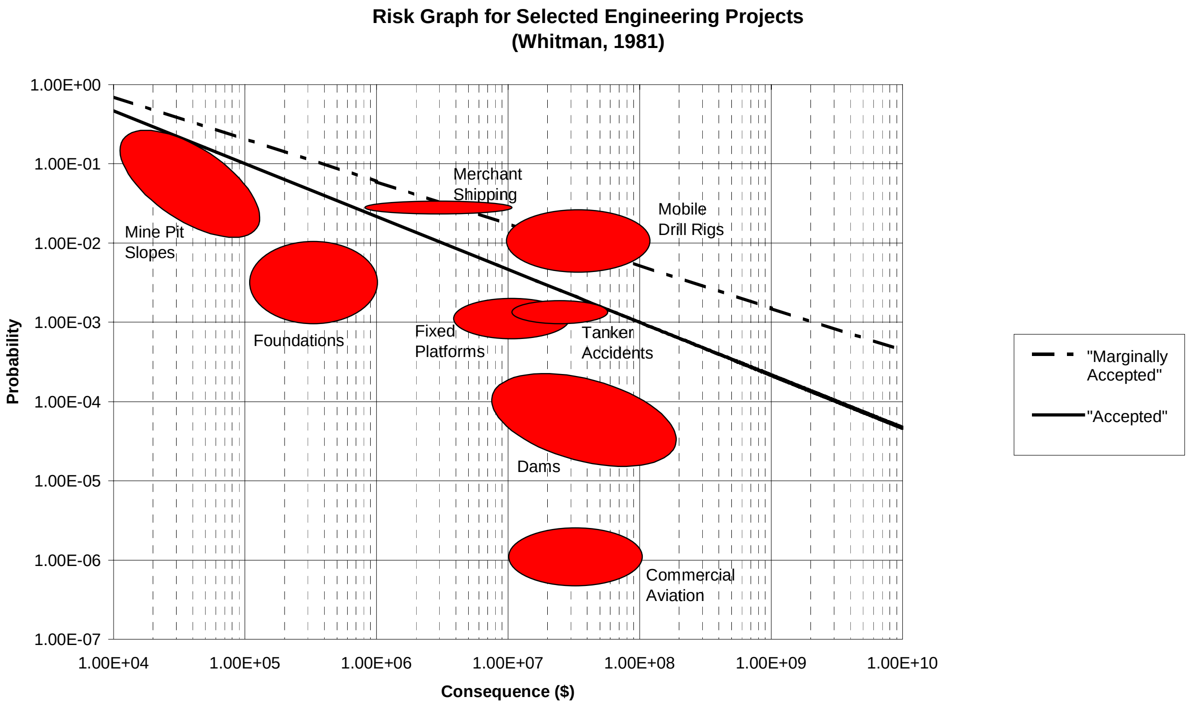
| Failure of Limit State | Probability of Occurrence / annum | Loss of Life Consequence | Loss of Containment Consequence | Loss of Production Consequence |
|---|---|---|---|---|
| **Hull Midship Section** | $5x10^{-6}$ - $5x10^{-4}$ | High | High | High |
| **Bow Structure / Slamming** | $10^{-4}$ - $10^{-2}$ | Medium | Medium | Medium |
| **Cargo Tank / Sloshing** | $10^{-6}$ - $10^{-4}$ | Low | Medium | Medium |
| **Turret** | $10^{-6}$ - $10^{-4}$ | Medium | Low | High |
| **Station Keeping System** | $2x10^{-4}$ - $2x10^{-2}$ | Low | Low | High |
| **Fluid Transfer System** | $7x10^{-4}$ - $2x10^{-2}$ | Medium | Medium | High |
| **Deck & Topside / Green Water** | $10^{-4}$ - $10^{-2}$ | Medium | Low | Medium |
| **Intact Stability** | $10^{-8}$ - $5x\ 10^{-6}$ | High | Medium | High |
| **Structural Fatigue Failure** | $5x10^{-7}$ - $10^{-4}$ | High | High | High |
| **Damage Stability** | *$5x10^{-6}$ – $5x10^{-3}$* ***??*** | High | High | High |
| **Ship Impact** | $4x10^{-5}$ – $4x10^{-3}$ | High | High | High |

Table 18: Summary of probability of occurrence and of consequences of limit state failure

Table 18 may be used to draw risk matrices for Loss of Life (Figure 13), Loss of Containment (Figure 14) and Loss of Production (Figure 15) with a code of colours for each limit state.

Given the range of consequence severity that has been chosen for each category, High/Medium/Low (see § 5.1.3), the Whitman (Ref. 20) "acceptable" risk levels can be superimposed on the risk matrix. Although Whitman's work presented here was carried out in the early eighties, no attempt has been made to account for the effects of inflation since then.

It should be noted that although Whitman's "acceptable" line has been used in this study it is **not** explicitly considered as an indicator of "acceptable" and "unacceptable" risks but ***is used more as a boundary of general reference and a filter to identify the critical issues of concern***. In other words, the level of "acceptable" risk may in truth be lower, but Whitman's work still provides a trend line with a somewhat justifiable and reliable gradient. This enables the assessment of relative risk levels associated with the various limit states, evaluated as much as possible on a common footing, and to assist in pin-pointing the most critical limit states.


Risk Graph for Selected Engineering Projects
(Whitman, 1981)
Probability
Consequence ($)
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E+04
1.00E+05
1.00E+06
1.00E+07
1.00E+08
1.00E+09
1.00E+10
Mine Pit Slopes
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"Marginally Accepted"
"Accepted"

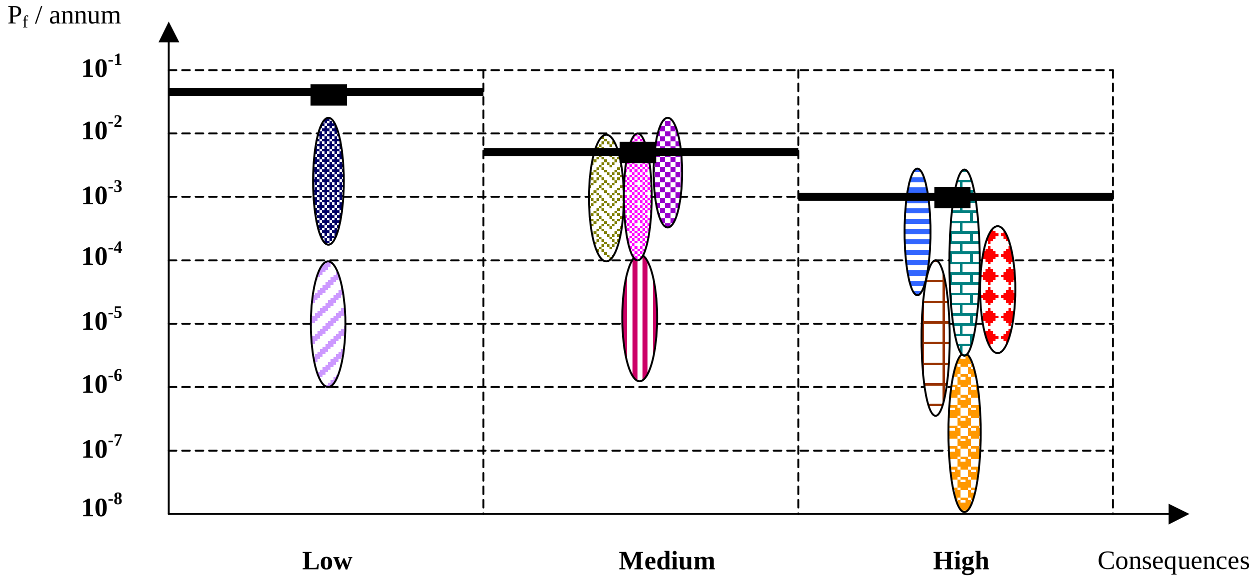
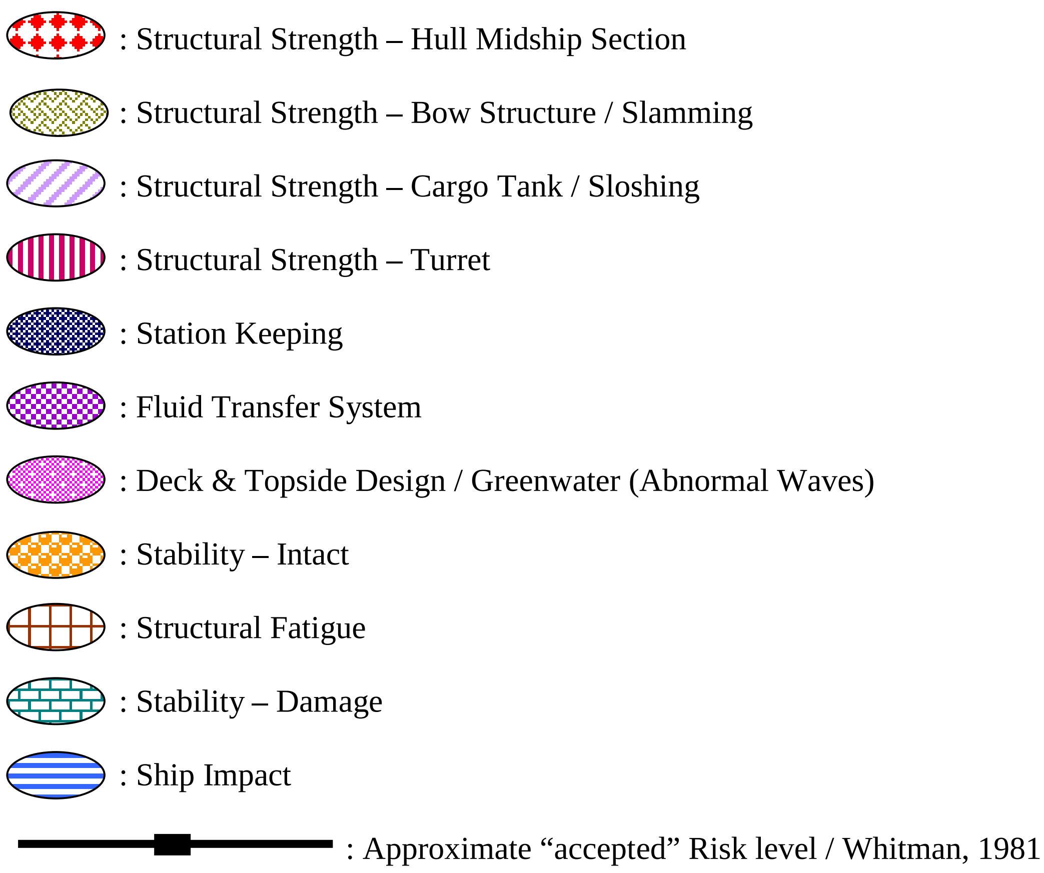



Figure 13: Present Risk Matrix for **Loss of Life**



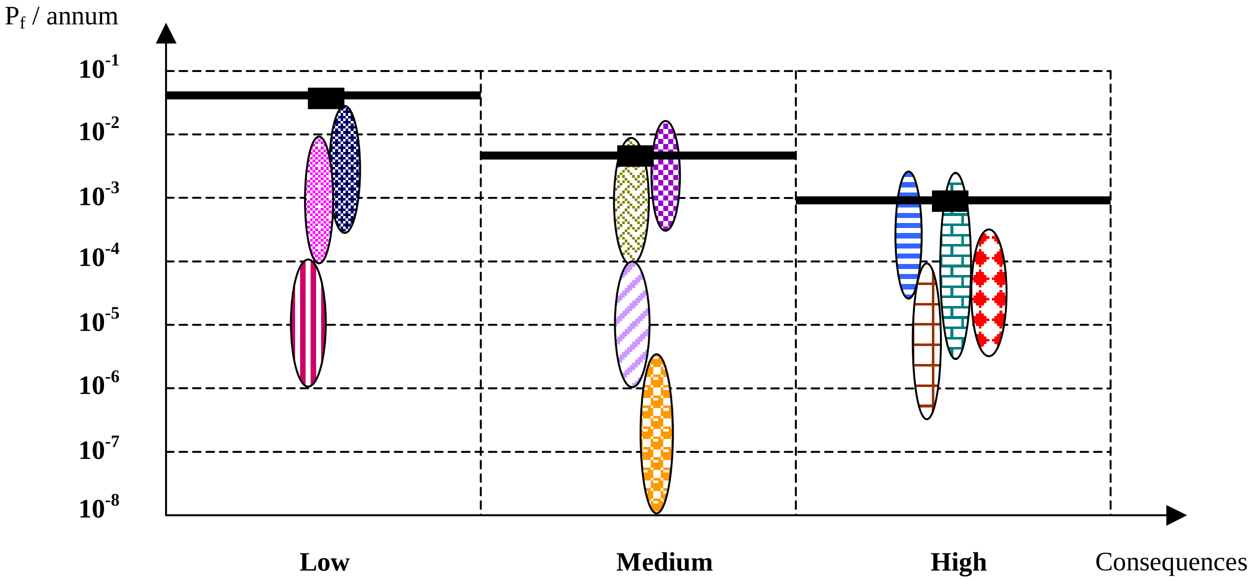
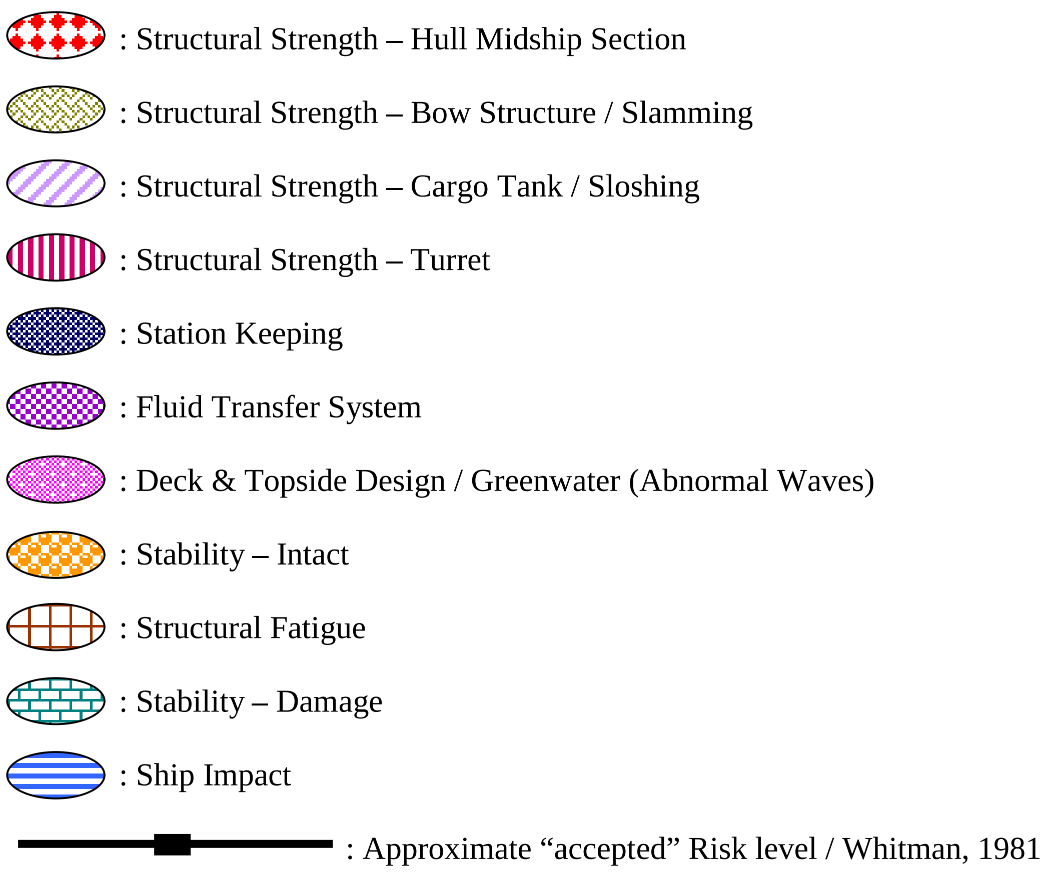



Figure 14: Present Risk Matrix for **Loss of Containment**



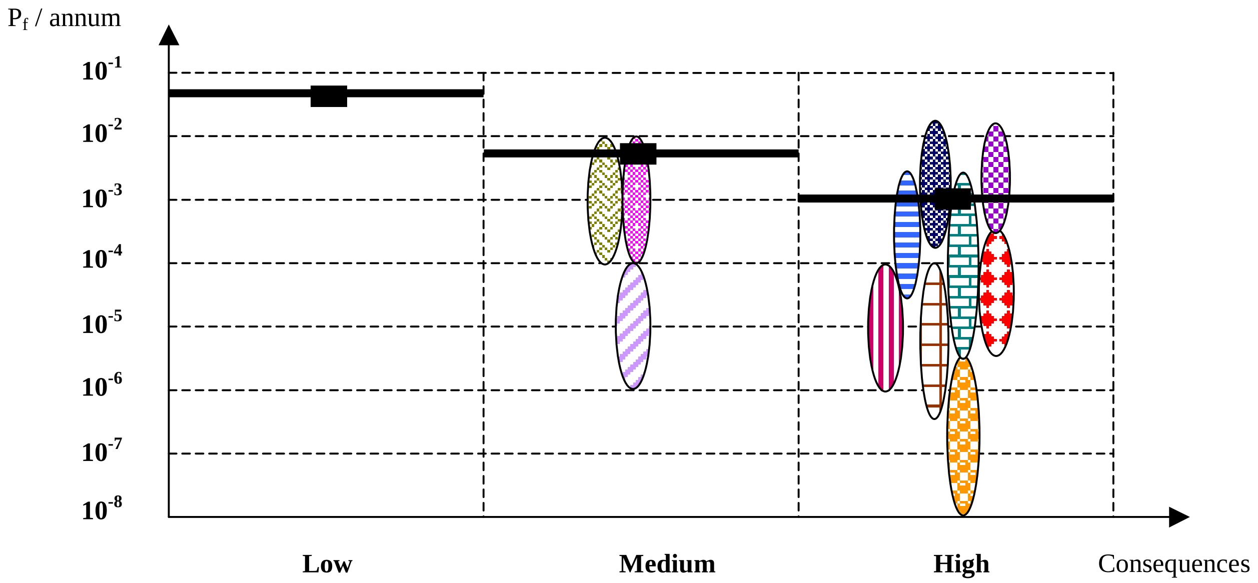
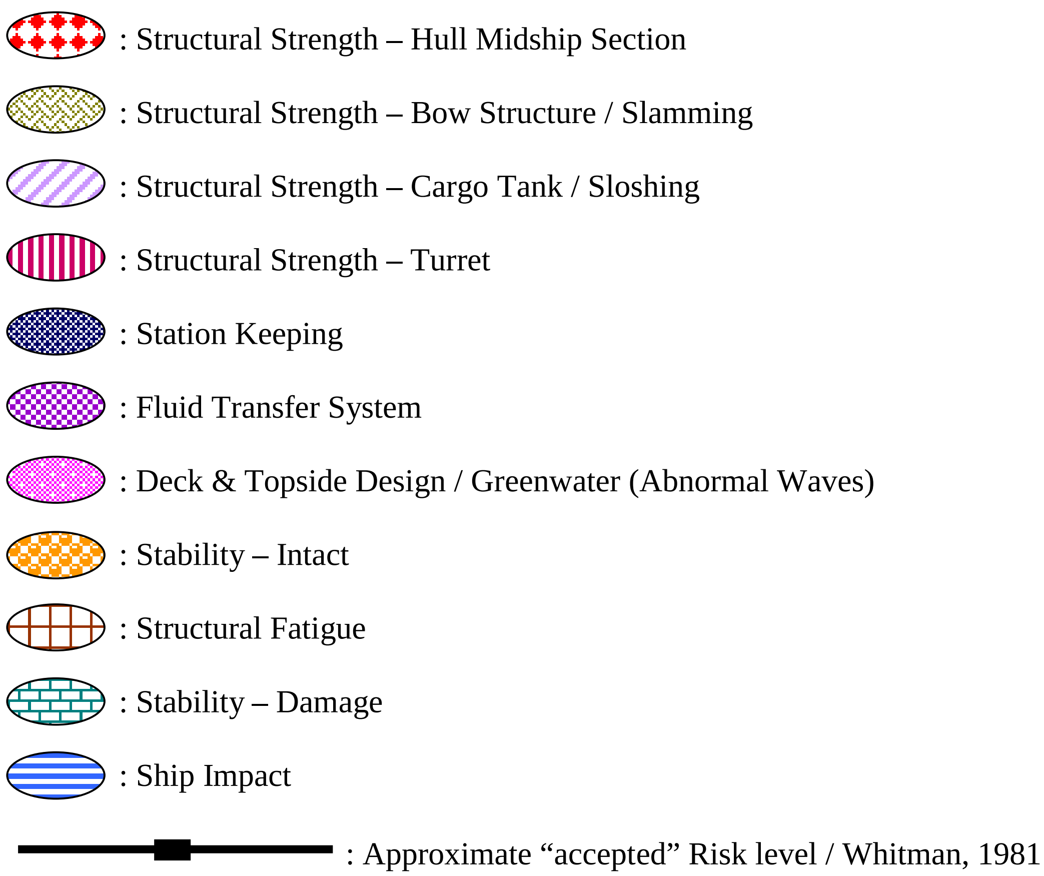



Figure 15: Present Risk Matrix for **Loss of Production**



# 5 DISCUSSION AND RECOMMENDATIONS

## 5.1 INTRODUCTION

Figures 13 to 15 can help towards setting the relative reliability levels of the identified limit states in context. Indeed, some limit states exceed the Whitman "acceptable" risk level line; the engineer should strive to increase the reliability level of those limit states and should aim at setting them down at a tolerable risk level. On the other hand, these figures can also help to identify the limit states where relative over-design / over-conservatism occurs. There may be economical benefits in decreasing the reliability level of some limit states, while maintaining them at an acceptable risk level. Such actions may help towards achieving a risk-consistent design.

However, it should be noticed that the conclusions that may be drawn from these figures should not be taken to be accurate enough to boldly recommend "reductions" in reliability; as stated previously, the present reliability levels have been ***estimated with an accuracy not better than ± 1 order of magnitude.***

## 5.2 DISCUSSION

Assuming that these figures provide a reasonable basis, at least for identifying the "hierarchy of risks", several comments can be made:

- Generally speaking, it seems that a rather good level of safety for both life and environment is currently reached when designing an FPSO. Indeed, no limit state significantly exceeds the acceptable risk level in the risk matrices for Loss of Production and Loss of Life. On the other hand, some improvements may be needed as far as Loss of Production is concerned.

- Looking closely at the figures, there appear to be some similarities between the three issues of concern, loss of life, loss of containment and loss of production. Indeed, some limit states are slightly in excess the acceptable risk levels for the three issues together. All three consequence types (Production, Containment and Life) may be likely with the following limit states:

    - **Bow structure design against slamming** (with consequences of medium severity),
    - **Fluid Transfer System** design (with consequences of medium to high severity),
    - **Ship Impact** and **Damage Stability** (both with consequences of high severity).

- In addition to this, Deck & Topside Design against Green Water turns out to be slightly in excess of the "acceptable risk level" for Loss of Life and Loss of Production (with consequences of medium severity).

- Finally, Station Keeping System design is also in exceedance of the acceptable risk level for Loss of Production (with consequences of high severity).

- All other limit states are maintained at an acceptable risk level. Nevertheless, if one focuses now on over-design and over-conservatism, one could argue that the reliability level obtained for Intact Stability is not consistent (too high) with the ones obtained for the majority of the key limit states that have been studied.

The above conclusions have been drawn on the basis that the reliability levels are accurate to within approximately ±1 order of magnitude. However, it should be noted that an increase (or decrease) in the level of inaccuracy associated with the estimated reliability levels would not dramatically change the conclusions of the study, as the same trends would mainly be observed throughout.

Similarly, there is also uncertainty associated with the ideal position of Whitman's line for this study, if it were to be used as an "acceptable risk" boundary. As detailed earlier the results of Whitman's study is being used here merely as a guidance tool when identifying relative risk levels. As a result, moving the location of Whitman's line wouldn't significantly affect the general findings of the study. For example, lowering the line by decreasing probability levels by one order of magnitude would not modify the main conclusions of the study, although the move would lead to identifying three additional limit states as being "critical";

- Hull midship section ULS,

and to a lesser extent,

- Structural fatigue FLS,
- Turret structural design ULS.

The reason that the identification of the above additional three "critical" limit states does not significantly change the conclusions of the study is that **it is relative criticality which is of most relevance**.

Based on the previous comments, one could now make some recommendations for either design improvement or further work if needed. The following sections aim at developing these recommendations.

## 5.3 BOW STRUCTURE / SLAMMING & DECK & TOPSIDE DESIGN / GREENWATER

It is obvious that further work has to be performed on these subjects. Model tests are highly recommended, and should be taken together with risk assessment in order to deduce practical recommendations.

International JIPs similar to those proposed by Marin and Marintek will most probably lead to a better knowledge on these issues, and might enable an increase of the reliability levels against bow structure slamming loads and response.

## 5.4 STATION KEEPING & FLUID TRANSFER SYSTEMS

First and foremost, it should be remembered that the conclusions that can be drawn from the risk matrices should not be put out of context. Indeed, although the reliability levels achieved for station keeping and fluid transfer systems seem to be more in excess of the acceptable risk level than for any other limit states, this unacceptability is dominated by low reliability against fatigue failure. (c.f. chapters 3.6 and 3.7). Indeed this is the reason why acceptable risk levels are exceeded only for the "economic" risk whilst the "environmental" and safety risks are within allowable levels.

Thus, an FPSO whose mooring system is designed with a larger safety factor on fatigue life should have a much better reliability level for both station keeping and fluid transfer systems. Such a conclusion has already been reached by the NDE/MCS Integrated Mooring and Riser Design JIP and by DNV in their JIP, DEEPMOOR.

It is also worth observing that cost benefit analyses (as given in Ref. 21) could still show that low fatigue safety factors may be acceptable.

## 5.5 INTACT & DAMAGED STABILITY

Computer models for evaluating FPSO dynamics under wave and wind loading would definitely be the best solution to assess the vessel stability. However, as long as these models are not thoroughly validated, they should be treated with caution. Meanwhile, present rules criteria can be improved as proposed in the ref. 16. Their proposal relies on these main principles:

- Provide a more rigorous approach to wind heeling arm making allowances for gusts;
- Calculate roll-back angle based on ship characteristics and sea state (instead of choosing an arbitrary angle);
- Specify a dynamic stability ratio without margin ($A1 = A2$ in place of $A1 \geq 1.4xA2$). This, however, would mean that no safety factor is considered, which may be critical.

In addition, a procedure for development of reliability-based transverse stability criteria should be highly recommended, with the following steps (cf. Ref. 17):

- Analysis of the sources of uncertainties associated with ship characteristics, operation profile, loading, manufacturing, etc., using probabilistic and statistical analysis;
- Development of probabilistic characteristics of basic random variables involved in stability calculations (righting and heeling moments, KB, BM, KG) such as mean / nominal values, COV, and distribution types;
- Determination of limit states for the chosen stability criteria (for instance the one proposed here above);
- Selection of a target reliability level;
- Determination of biases between predicted and measured values of stability variables;
- Computation of partial safety factors to develop a reliability-based code.

As far as damaged stability is concerned, it should be recommended that a risk analysis enabling the evaluation of the probability of location and extent of damage should be carried out.

## 5.6 SHIP IMPACT

It is recommended that a risk analysis taking into account the operations that may occur in the vicinity of the FPSO be carried out to determine the most appropriate design impact energy. This energy level must be linked to some target probability.

## 5.7 OVERALL RELIABILITY

The study clearly demonstrates that FPSO reliability against environmental load effects is dependent upon a number of comparably serious limit states. This is in contrast to a fixed structure, where only one or two limit states such as airgap could be of significance.

This implies that the overall FPSO reliability against environmental overload cannot be simply appreciated by observing individual limit states. Correlation between them and the substantial differences in the consequences make the combinatrion of the reliability levels estimated for each limit state into a single figure appropriate for an FPSO, extremely difficult and unreliable at this stage.

For instance, if one considers the occurrence of each of the failure modes as being non-mutually exclusive independent events, one could estimate the system probability of failure as:

$$Pf_{FPSO} = 1 - \prod_i (1 - Pf_i)$$ where $Pf_i$ if the probability of failure of the limit state "i".

That calculation would lead to an overall probability of failure of about $1x10^{-3}$ to $7x10^{-2}$.

On the contrary, if one considers that all limit states are completely correlated, then the probability of failure of the overall system is the highest probability of failure of the individual limit states, that is to say about $1x10^{-4}$ to $1x10^{-2}$.

Discrepancy between these figures shows that they should not be taken for granted at this stage, and that it is not possible to draw a serious conclusion about the overall system reliability without further work.

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