
OFFSHORE STANDARD
DNV-OS-F201
DYNAMIC RISERS

2001

*Since issued in print (2001), this booklet has been amended, latest in October 2003.
See the reference to “Amendments and Corrections”.*

DET NORSKE VERITAS

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All changes affecting DNV Offshore Codes that have not been reprinted, are published separately in the current *Amendments and Corrections*, issued as a printable (pdf) file.



OFFSHORE STANDARD DNV-OS-F201

DYNAMIC RISERS

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FOREWORD

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DNV offshore publications consist of a three level hierarchy of documents:

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- *Recommended Practices*. Provide proven technology and sound engineering practice as well as guidance for the higher level Offshore Service Specifications and Offshore Standards.

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- A) Quality and Safety Methodology
- B) Materials Technology
- C) Structures
- D) Systems
- E) Special Facilities
- F) Pipelines and Risers
- G) Asset Operation

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In addition to the feedback from the JIP steering committee the Standard has been circulated on extensive internal and external hearing. The following organisations have made contributions to the standard.

Coflexip Stena Offshore	Norsk Hydro	Stolt Offshore
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ELF	Phillips Petroleum	Stress Engineering
Europipe	Saga Petroleum	Shell
Exxon Prod. Research Company	SeaFlex	Statoil
MCS Norway		

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SECTION 1 GENERAL

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A. General

A 100 Introduction

101 This standard gives criteria, requirements and guidance on structural design and analysis of riser systems exposed to static and dynamic loading for use in the offshore petroleum and natural gas industries.

102 The major benefits in using this standard comprise:

- provision of riser solutions with consistent safety level based on flexible limit state design principles;
- application of safety class methodology linking acceptance criteria to consequence of failure;
- provision of state-of-the-art limit state functions in a Load and Resistance Factor Design (LRFD) format with reliability-based calibration of partial safety factors. As an alternative, a simple conservative Working Stress Design (WSD) format is also given;
- guidance and requirements for efficient global analyses and introduce a consistent link between design checks (failure modes), load conditions and load effect assessment in the course of the global analyses;
- allowance for the use of innovative techniques and procedures, such as reliability-based design methods.

103 The basic design principles and functional requirements are in compliance with state-of-the-art industry practice.

A 200 Objectives

201 The main objectives of this standard are to:

- provide an international standard of safety for steel risers utilised for drilling, completion/ workover, production/injection, or transportation of hydrocarbons (import/export) in the petroleum and gas industries;
- serve as a technical reference document in contractual matters; and
- reflect the state-of-the-art and consensus on accepted industry practice and serve as a guideline for riser design and analysis.

A 300 Scope and Application

301 This standard applies to all new built riser systems and may also be applied to modification, operation and upgrading of existing risers.

302 The scope covers design, materials, fabrication, testing, operation, maintenance and re-assessment of riser systems. Aspects relating to documentation, verification and quality control are also addressed. The main purpose is to cover design and analysis of top tensioned and compliant steel riser systems operated from floaters and fixed platforms. The standard applies for permanent operation (e.g. production and export/import of hydrocarbons and injection of fluids), as well as for temporary operation (e.g. drilling and completion/workover activities).

303 This standard is applicable to structural design of all pressure containing components that comprise the riser system, with special emphasis on:

- single pipes with a ratio of outside diameter to wall thickness less than 45;
- riser connectors and other riser components such as tension joints and stress joints.

Guidance note:

This standard may also be applied to design of single steel pipes used as components in more complex composite cross-sections (e.g. umbilical) if the loading on the pipe can be adequately predicted.

Multitube cross-sections (i.e. pipes inside pipes) are not considered explicitly. However, this standard may be applied for design of each individual tubular of such cross-sections provided a realistic (conservative) distribution of the loading on each individual tubular are assumed. Boundary conditions of the pipes, temperature and local contact loads should be considered in particular.

- end - of - Guidance - note -

304 There are, in principle, no limitations regarding floater type, water depth, riser application and configuration. However, for novel applications where experience is limited, special attention shall be given to identify possible new failure mechanisms, validity/adequacy of analysis methodology and new loads and load combinations.

Guidance note:

For application of this standard to new riser types/concepts (e.g. novel hybrid systems, complex riser bundles etc) it shall be documented that the global load effects can be predicted with same precision as for conventional riser systems. This may typically involve validation of computational methodology by physical testing.

As an alternative an appropriate conservatism in design should be documented.

- end - of - Guidance - note -

305 Examples of typical floater and riser configurations are shown schematically in Figure 1-2. Examples of some typical components/important areas included in typical riser systems are illustrated in Figure 1-3.

A 400 Other Codes

401 In case of conflict between requirements of this standard and a reference document, the requirements of this standard shall prevail.

402 Where reference is made to codes other than DNV documents, the valid revision shall be taken as the revision that was current at the date of issue of this standard, unless otherwise noted, see B 700.

403 The framework within DNV Riser standards and RP's is illustrated in Figure 1-1.

404 This standard provides the design philosophy, loads and global analysis aspects valid for all riser materials. Specific acceptance criteria for steel are given in this standard while titanium and composite materials are currently under development in associated recommended practices. These Recommend Practice (RP) documents subscribe, for consistency, to the safety philosophy and analyses methodology set forward by this standard.

405 This standard is compatible with the DNV Offshore Standard for Submarine Pipeline Systems DNV-OS-F101. DNV-OS-F101 forms the primary reference for materials, testing and fabrication for riser pipes. Strain limits and acceptance criteria for displacement controlled conditions of pipes (e.g. for reeling) shall comply with DNV-OS-F101. The limit state design checks for this standard and DNV-OS-F101 is similar but due to difference in the governing failure modes and prevailing uncertainties some difference in safety factors exist. This is discussed in more details in Section 5.

Guidance note:

The major differences/conflicts in design principles compared to current industry practice reflected by API (RP2RD and RP1111) are:

- in the ASME and API codes the hydrostatic pressure test is fundamental and often drives the design of pipelines and export risers. The limit state based DNV-OS aim to design for the actual modes of failure and the safety margin is ensured by a combination of material requirements, and testing;
- the API codes (RP2RD and RP1111) implicitly assumes displacement controlled riser configuration with secondary bending stress for ULS design checks. The DNV-OS a priori assumes that important riser locations (top- and

touch-down point) are load controlled unless otherwise argued and documented. This implies that the fatigue criterion in API is used as an implicit control of excessive bending rather than explicit ULS design checks where relevant as in this standard.

- end - of - Guidance - note -

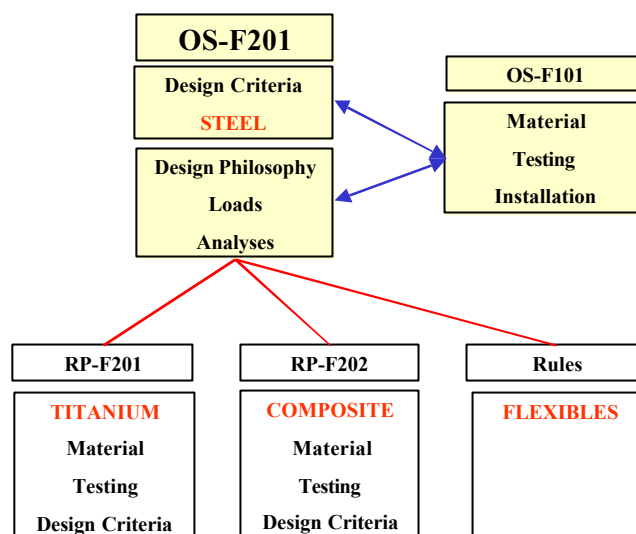


Figure 1-1 Framework for DNV Riser Standards and RP's

A 500 Structure of Standard

501 This standard consist of two parts:

1. a main part providing minimum requirements in terms of explicit criteria where relevant and functional requirements elsewhere;
2. appendices containing practical guidance and background information on topical issues.

In addition a number of supporting documents may be required as listed in section B.

502 The main part is organised as follows:

Section 1 contains the objectives and scope of the standard. It further introduces essential concepts, definitions and abbreviations.

Section 2 contains the fundamental design philosophy and design principles. It introduces the safety class methodology and normal classification of safety classes.

Section 3 contains a classification of loads into pressure loads, functional loads and environmental loads. Important internal pressure definitions are given.

Section 4 contains the framework for global analysis methodology. It provides a consistent link between design checks for combined loading, global analysis, load effect assessment and load cases. The section is supported by

- appendix A providing additional information on global analyses;
- appendix B on fatigue analyses;
- appendix C on assessment of extreme load effect for combined loading;
- appendix D on verification of global analysis model,

— section 5 on acceptance criteria for combined loading

Section 5 contains acceptance criteria for the riser pipe for ULS, SLS, ALS and FLS. This includes a definition of resistance and load effects and safety factors for explicit limit states.

Section 6 contains the fundamental functional requirements for connectors and riser components.

Section 7 contains requirements for materials, manufacture, fabrication and documentation of riser pipe and components where the principles and requirements in OS-F101 is adhered. If other codes are applied additional evaluations is required.

Section 8 contains requirements for documentation and verification of the riser system. Appendix F provides additional information.

Section 9 contains basic requirements for operation and in-service operations.

B. Normative References

The latest revision of the following documents applies:

Guidance note:

Explicit reference to paragraphs in DNV-OS-F101 should relate to January 2000 version.

- end - of - Guidance - note -

B 100 Offshore Service Specifications

DNV-OSS-301 *Certification and Verification of Pipelines*

B 200 Offshore Standards

DNV-OS-F101 *Submarine Pipeline Systems*

DNV-OS-C105 *Structural Design of TLPs by the LRFD Method*

DNV-OS-C106 *Structural Design of Deep Draught Floating Units*

B 300 Recommended Practices

DNV RP B401 *Cathodic Protection Design*

DNV RP-C203 *Fatigue Strength*

DNV RP-F101 *Corroded Pipelines*

DNV RP-F104 *Mechanical Pipeline Couplings*

DNV RP-F105 *Free Spanning Pipelines*

DNV RP-F106 *Factory applied Pipeline Coatings for Corrosion Control*

DNV RP-F108 *Fracture Control for Reeling of Pipelines*

DNV RP-F201 *Titanium Risers*

DNV RP-F202 *Composite Risers*

DNV RP O501 *Erosive Wear in Piping Systems*

B 400 Rules

DNV Rules for Certification of Flexible Risers and Pipes

DNV Rules for Planning and Execution of Marine operations

DNV Rules for Classification of Fixed Offshore Installations

B 500 Certification notes and Classification notes

DNV CN 1.2 *Conformity Certification Services, Type Approval*

DNV CN 1.5 *Conformity Certification Services, Approval of Manufacturers, Metallic Materials*

DNV CN 7 *Ultrasonic Inspection of Weld Connections*

DNV CN 30.2 *Fatigue Strength Analysis for Mobile Offshore Units*

DNV CN 30.4 *Foundations*

DNV CN 30.5 *Environmental Conditions and Environmental Loads*

DNV CN 30.6 *Structural Reliability Analysis of Marine Structures*

B 600 Guidelines

DNV *Guidelines for Flexible Pipes*

B 700 Other references

BS 7910 *Guide on methods for assessing the acceptability of flaws in fusion welded structures*

API RP1111 *Design, Construction, Operation, and Maintenance of Offshore Hydrocarbon Pipelines (Limit State Design)*

API RP2RD *Design of Risers for Floating Production Systems (FPSs) and Tension-Leg Platforms (TLPs)*

EUROCODE 3 *Design of steel structures - Part 1.1: General rules and rules for building.*

ISO/FDIS 2394 *General Principles on Reliability for Structures*

ISO/CD 13628-7 *Petroleum and natural gas industries - Design and operation of subsea production systems - Part 7: Completion/workover riser systems*

Guidance note:

The latest revision of the DNV documents may be found in the publication list at the DNV website www.dnv.com.

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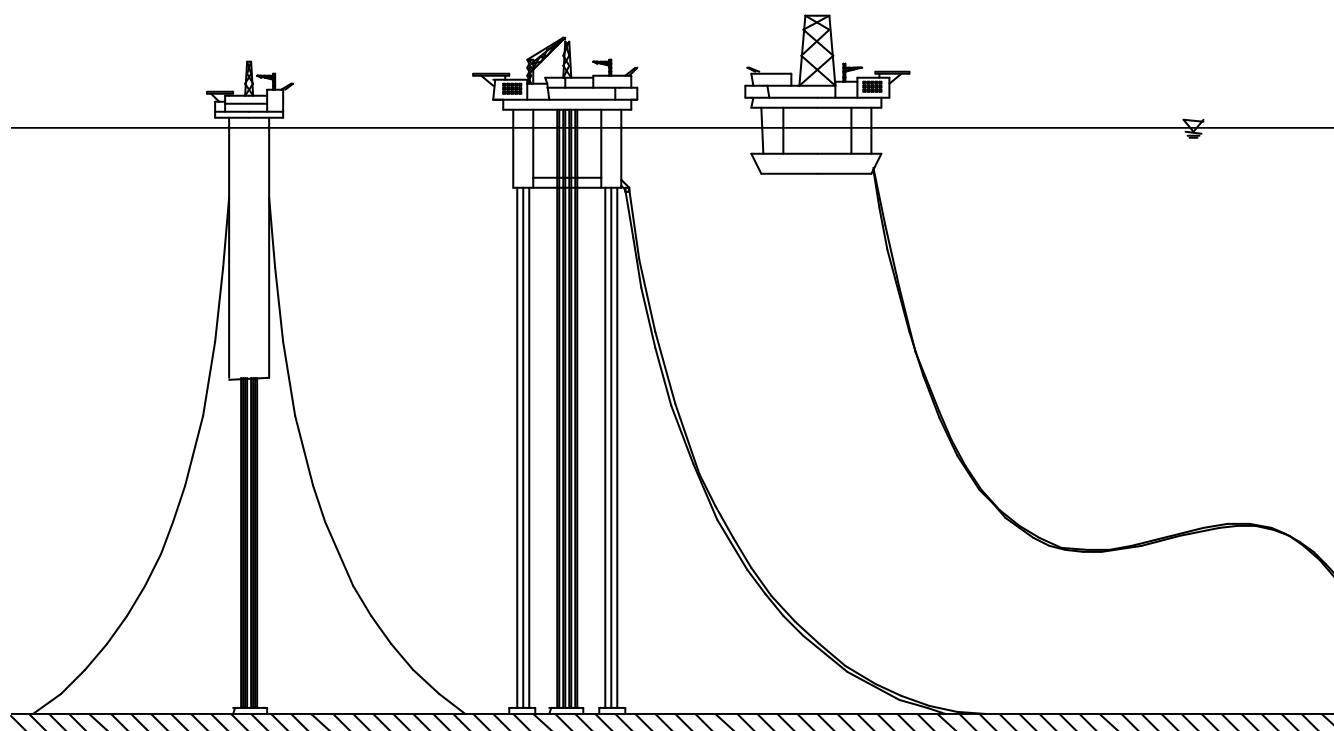
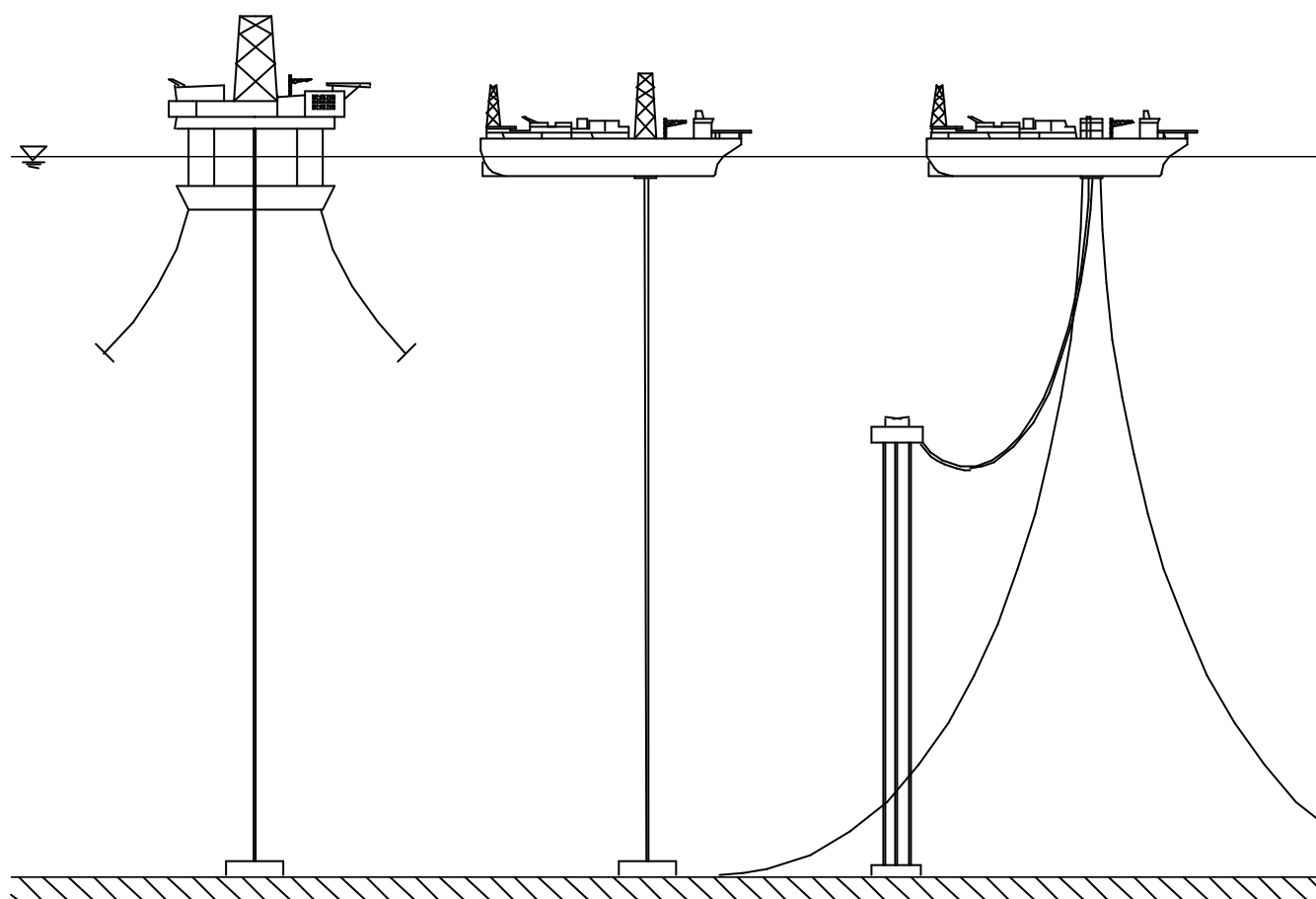


Figure 1-2 Examples of metallic riser configurations and floaters

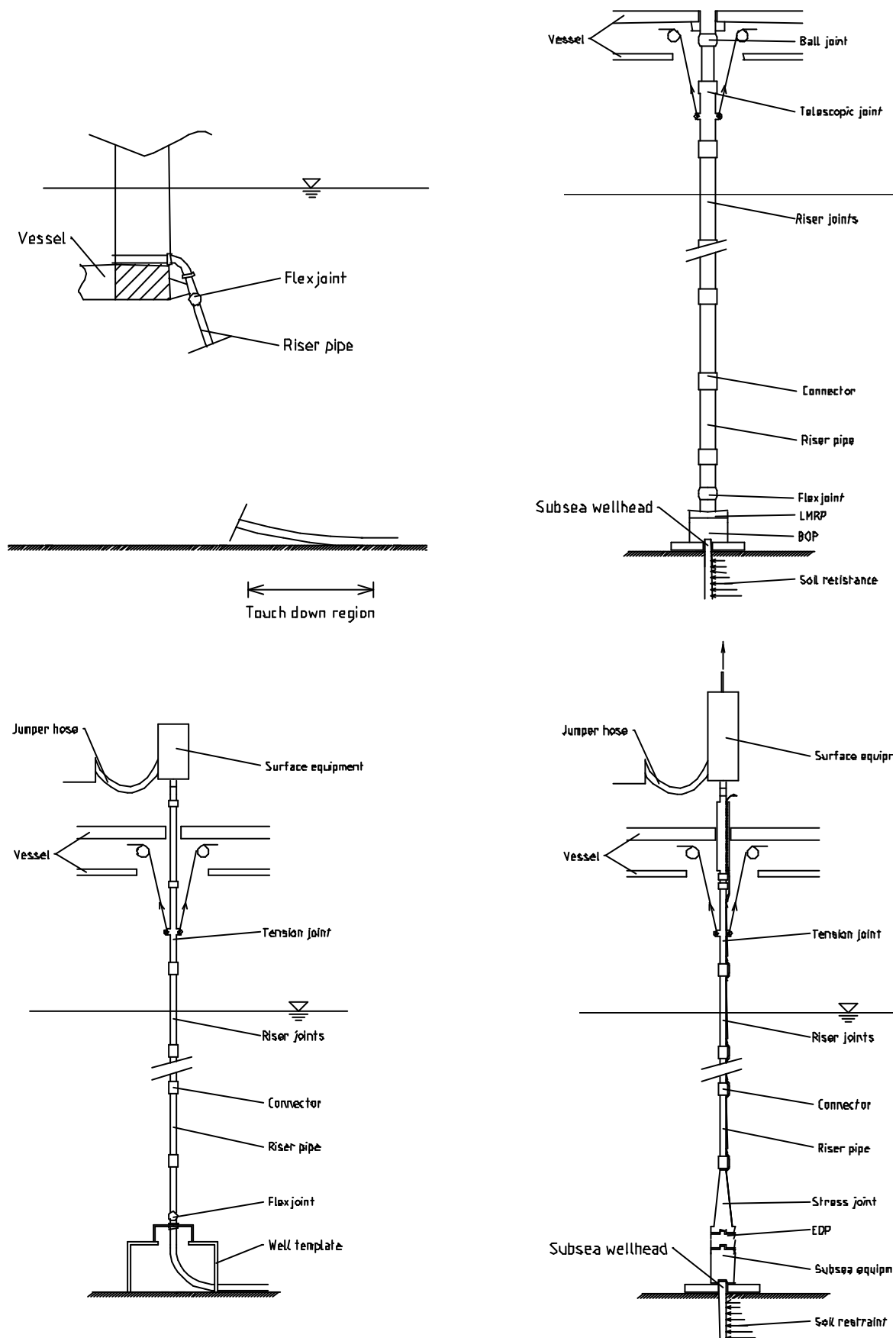


Figure 1-3 Examples of riser components

C. Definitions

C 100 Verbal forms

101 “*Shall*”: Indicates requirements strictly to be followed in order to conform to this standard and from which no deviation is permitted.

102 “*Should*”: Indicates that among several possibilities, one is recommended as particularly suitable, without mentioning or excluding others, or that a certain course of action is preferred but not necessarily required. Other possibilities may be applied subject to agreement.

103 “*May*”: Verbal form used to indicate a course of action permissible within the limits of the standard.

104 “*Agreement*”, “*by agreement*”: Unless otherwise indicated, this means agreed in writing between Manufacturer/ Contractor and Purchaser.

C 200 Definitions

201 *Accidental loads*: Loads acting on the riser system, because of a sudden, unintended and undesirable event. Typical accidental event has an annual probability of occurrence less than 10^{-2} .

202 *Auxiliary line*: A conduit (excluding choke and kill lines) attached to the outside of the riser main pipe such as hydraulic supply line, buoyancy control line and mud boost line.

203 *Buckling, global*: This is usually referred to as elastic Euler buckling or bar buckling.

204 *Buckling, local*: Buckling mode implying deformations of the cross section. This can e.g. be due to external pressure (hoop buckling) and moment (wrinkling) or a combination thereof.

205 *Buoyancy modules*: Structure of light weight material, usually foamed polymers, strapped or clamped to the exterior of riser joints, to reduce the submerged weight of the riser.

206 *Collapse capacity*: Resistance against external overpressures, i.e. hoop buckling failure (collapse).

207 *Completion/Workover riser (C/WO riser)*: Temporary riser used for completion or workover operations and includes any equipment between the subsea tree/tubing hanger and the workover floaters tensioning system.

208 *Connector or coupling*: A mechanical device use to connect adjacent components in the riser system, e.g. connecting two joints of riser pipe end-to-end.

209 *Corrosion allowance*: The amount of wall thickness added to the pipe or component to allow for corrosion/erosion/wear.

210 *Design checks*: Design checks are investigations of the structural safety of the riser under the influence of load effects (design load cases) with respect to specified limit

states, representing one or more failure modes, in terms of resistance of relevant structural models obtained in accordance with specified principles.

211 *Design load*: The combination of load effects, multiplied by their respective load effect factors.

212 *Design resistance*: The resistance divided by the appropriate resistance factor(s).

213 *Drilling riser*: A riser utilised during drilling and workover operations and isolates any wellbore fluids from the environment. The major functions of drilling riser systems are to provide fluid transportation to and from the well; support auxiliary lines, guide tools, and drilling strings; serve as a running and retrieving string for the BOP. Drilling risers may also be used for well completion and testing.

214 *Dynamic Positioning (DP, automatic station keeping)*: A computerised means of maintaining a floater on location by selectively driving thrusters.

215 *Effective tension*: The axial wall force (axial pipe wall stress times area) adjusted for the contributions from external and internal pressure.

216 *Environmental loads*: Loads due to the environment, such as waves, current, wind, ice and earthquake.

217 *Export/import riser*: Export/import risers transfer the processed fluids from/to the floater/structure to/from another facility, which may include an another platform/floater or pipeline.

218 *Failure*: An event causing an undesirable condition, e.g. loss of component or system function, or deterioration of functional capability to such an extent that the safety of the unit, personnel or environment is significantly reduced.

219 *Fatigue*: Cyclic loading causing degradation of the material.

220 *Fail safe*: Term applied to equipment or a system so designed that, in the event of failure or malfunction of any part of the system, devices are automatically activated to stabilise or secure the safety of the operation.

221 *Flex joint*: A laminated metal and elastomer assembly, having a central through-passage equal to or greater in diameter than the interfacing pipe or tubing bore, that is positioned in the riser string to reduce the local bending stresses.

222 *Floater*: Buoyant installation, which is floating or fixed to the sea bottom by mooring systems in temporary or permanent phases, e.g. TLP, Ship, Semi, Spar, Deep Draft Floater etc.

223 *Floater offset*: The total offset of the floater, taking into account the floater mean offset, wave frequency motions and low frequency wind and wave motions.

224 *Floater mean offset*: The offset created by steady forces from current, wind and waves.

225 Floater wave frequency motions: The motions that are a direct consequence of first order wave forces acting on the floater, causing the platform to move at periods typically between 3 – 25 seconds, and termed the wave frequency (WF) regime.

226 Flowline: Any pipeline connecting to the subsea tree assembly.

227 Fracture analysis: Analysis where critical initial defect sizes under design loads are identified to determine the crack growth life to failure, i.e. leak or unstable fracture.

228 Functional loads: Loads caused by the physical existence of the riser system and by the operation and handling of the system, excluding pressure loads.

229 Global analysis: Analysis of the complete riser system.

230 Hang-off: Riser when disconnected from seabed.

231 Installation: The operation related to installing the riser system, such as running of riser joints, landing and connecting or such as laying, tie-in, etc. for a catenary riser.

232 Interface loads and displacements: Loads and displacements at a particular boundary between two systems.

233 Limit state: The state beyond which the riser or part of the riser no longer satisfies the requirements laid down to its performance or operation. Examples are structural failure (rupture, local buckling) or operational limitations (stroke or clearance).

234 Load: The term load refers to physical influences which cause stress, strain, deformation, displacement, motion, etc. in the riser.

235 Load effect: Response or effect of a single load or combination of loads on the structure, such as bending moment, effective tension, stress, strain, deformation, etc.

236 Load effect factor: Partial safety factor by which the load effect is multiplied to obtain the design load (effect).

237 Location class: A geographic area classified according to the distance from locations with regular human activities.

238 Load and Resistance Factor Design (LRFD): Design format based upon a Limit State and Partial Safety Factor methodology. The partial safety factor methodology is an approach where separate factors are applied for each load effect (response) and resistance term.

239 Low Frequency (LF) motion: Motion response at frequencies below wave frequencies at, or near surge, sway and yaw eigenperiods for the floater. LF motions typically have periods ranging from 30 to 300 seconds.

240 Material resistance factor: Partial safety factor transforming a resistance to a lower fractile resistance.

241 Maximum operating condition: Maximum condition in which the normal operations are carried out.

242 Mode of operation: The riser mode of operation includes typically running, landing and connecting, overpull testing, pressure testing, well-kill, connected production (well access), connected shut-in, disconnecting, emergency disconnect, hang-off (disconnected).

243 Nominal value: Specified value.

244 Operating envelope: Limited range of parameters in which operations will result in safe and acceptable equipment performance.

245 Operation, Normal Operation: Conditions that are part of routine (normal) operation of the riser system. This should include steady flow conditions over the full range of flow rates as well as possible packing and shut-in conditions where these occur as part of routine operation.

246 Operation, Incidental Operation: Conditions that are not part of normal operation of the system. Such conditions may lead to incidental pressures. Such conditions may for example be surges due to bullheading, sudden closing of valves, or failure of the pressure regulating system and activation of the pressure safety system.

247 Out of roundness: The deviation of the perimeter from a circle. This can be an ovalisation, i.e. an elliptic cross section, or a local out of roundness, e.g. flattening. The numerical definition of out of roundness and ovalisation is the same.

248 Ovalisation: The deviation of the perimeter from a circle. This has the form as an elliptic cross section. The numerical definition of out of roundness and ovalisation is the same.

249 Permanent riser: A riser, which will be in continuous operation for a long time period, irrespective of environmental conditions.

250 Pressure definitions

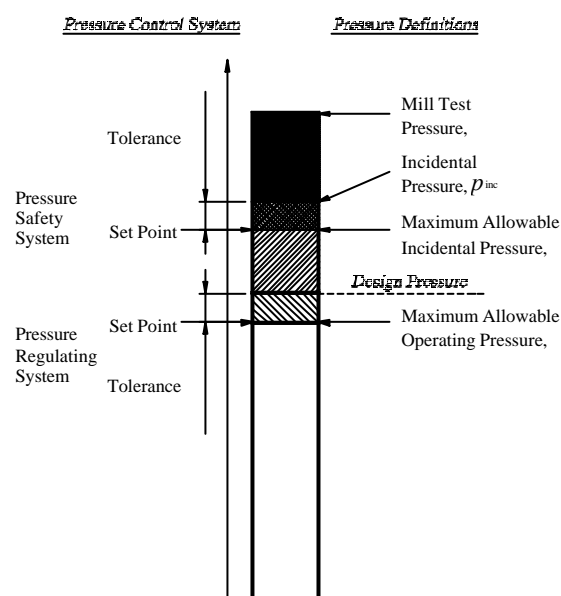


Figure 1-4 Pressure definitions

251 *Pressure, design* is the maximum internal pressure during normal operations. The design pressure must take account of steady flow conditions over the full range of flow conditions as well as possible packing and shut-in conditions.

252 *Pressure, local*: The internal pressure at any point in the riser for the corresponding design pressure, incidental pressure or test pressure, i.e., the pressure at the reference height plus the static head of the transported/test medium due to the difference between the reference height and the height of the section being considered.

253 *Pressure, incidental*: The maximum internal pressure that is unlikely to be exceeded during the duration/life of the riser or the maximum permitted internal pressure due to incidental operation of the riser. Incidental pressure is referred to the same reference height as the design pressure and includes the situations where the riser is subject to surge pressure, unintended shut-in pressure, bullheading (water-hammer) or any temporary incidental condition.

254 *Pressure, initiation*: External overpressure required to initiate a propagating buckle from an existing local buckle or dent.

255 *Pressure, Maximum Allowable Incidental (MAIP)*: The maximum pressure at which the riser/pipeline system shall be operated during incidental (i.e. transient) operation. The maximum allowable incidental pressure is defined as the maximum incidental pressure less the positive tolerance of the pressure safety system.

256 *Pressure, Maximum Allowable Operating (MAOP)*: The maximum pressure at which the riser/pipeline system shall be operated during normal operation. The maximum allowable operating pressure is defined as the design pressure less the positive tolerance of the pressure regulating system.

257 *Pressure, minimum*: The local minimum internal pressure in the riser. This is equal to the minimum pressure at the reference height plus the static head of the fluid. A conservative estimate is to assume zero.

258 *Pressure, propagating*: The lowest pressure required for a propagating buckle to continue to propagate.

259 *Pressure regulating system*: For export risers and in relation to pipelines, this is the system which ensures that, irrespective of the upstream pressure, a set pressure is maintained at a given reference point.

260 *Pressure safety system*: The system which, independent of the pressure regulating system, ensures that the allowable incidental pressure is not exceeded.

261 *Pressure, surge*: The pressure produced by sudden changes in the velocity of fluids inside the riser.

262 *Pressure, System test*: The surface internal pressure or local internal test overpressure applied to the riser or riser section during testing after completion of the installation work to test the riser system for tightness. (normally performed as hydrostatic testing).

263 *Process shut-down*: A controlled sequence of events that ensures that the well is secured against accidental release of hydrocarbons to the environment.

264 *Production/injection riser*: Production risers transport fluids produced from the reservoir. Injection risers transport fluids to the producing reservoir or a convenient disposal or storage formation. The production riser may be used for well workovers, injection, completion and other purposes.

265 *Ratcheting*: Accumulated plastic deformation during cyclic loading.

266 *Resistance*: Capability of a structure or part of a structure to resist load effects also noted strength or load carrying capacity.

267 *Resistance, characteristic*: The nominal value of a strength parameter to be used in determination of design resistance. The (characteristic) resistance is normally based on a defined fractile in the lower end of the distribution function for the resistance.

268 *Riser component*: Any part of the riser system that may be subjected to pressure by the internal fluid. This includes items such as flanges, connectors, stress joints, tension joints, flex-joints, ball joints, telescopic joints, slick joints, tees, bends, reducers and valves.

269 *Riser disconnect*: The operation of unlatching of a riser connector.

270 *Riser joint*: A riser joint consists of a pipe member mid section, with riser connectors at each end. Riser joints are typically provided in 30 ft. to 50 ft. (9,14m to 15,24m) lengths. Shorter joints, "pup joints", may also be provided to ensure proper space-out.

271 *Riser pipe (riser tube)*: The pipe, which forms the principal conduit of the riser joint. For example, the riser pipe is the conduit for containing the production fluid flow from the well into the surface tree.

272 *Riser system*: A riser system is considered to comprise the riser, all integrated riser components and corrosion protection system.

273 *Riser tensioner stroke*: The total upward and downward vertical movements of the riser relative to the floater.

274 *Riser tensioner system*: A device that applies a tension to the riser string while compensating for the relative vertical motion (stroke) between the floater and riser. Tension variations are controlled by the stiffness of the unit.

275 *Risk analysis*: Analysis including a systematic identification and categorisation of risk to people, the environment and to assets and financial interests.

276 *Safety class*: The concept adopted herein to classify the criticality of the riser system.

277 *Safety class resistance factor*: Partial safety factor multiplied on the resistance reflecting the safety class.

278 Serviceability: A condition in which a structure is considered to perform its design function satisfactorily.

279 Service life: The length of time assumed in design that a component will be in service.

280 S-N fatigue curve: Stress range versus number of cycles to failure.

281 Specified Minimum Tensile Strength (SMTS): The minimum tensile strength (stress) at room temperature prescribed by the specification or standard under which the material is purchased.

282 Specified Minimum Yield Stress (SMYS): The minimum yield strength (stress) at room temperature prescribed by the specification or standard under which the material is purchased. The tensile stress at 0.5 % elongation of the specimen gauge length.

283 Specified weather window: Limits to environmental conditions specified in operation manual.

284 Splash zone: The external region of the riser that is periodically in and out of the water. The determination of the splash zone includes evaluations of all relevant effects including wave height, wave diffraction effects, tidal variations, settlements, subsidence and vertical motions of the riser in the splash zone.

285 Stress Concentration Factor (SCF): Equal to the local peak alternating principal stress in a component (including welds) divided by the nominal alternating principal stress near the location of the component. This factor is used to account for the increase in the stresses caused by geometric stress amplifiers, which occur in the riser component.

286 Stress joint: A specialised riser joint designed with a tapered cross section, to control curvature and reduce local bending stresses.

287 Submerged weight: Weight minus buoyancy (commonly referred to as weight in water, wet weight, net lift, submerged weight or effective weight). Also named apparent weight.

288 System Effects: System effects are relevant in cases where many riser pipe sections are subjected to similar loading conditions, and potential structural failure may occur in connection with the lowest structural resistance among riser pipe sections.

289 Temporary riser: A riser which is used intermittently for tasks of limited duration, and which can be retrieved in severe environmental conditions, essentially marine/drilling risers and completion/workover risers.

290 Tensioned riser: A riser, which is essentially kept straight and tensioned in all parts, by applying a top tension to it.

291 Tubing: Pipe used in wells to conduct fluid from the well's producing formation into the subsea tree or to the surface tree.

292 Water Level. The tidal range is defined as the range between the highest astronomical tide (HAT) and lowest

astronomical tide (LAT). The mean water level (MWL) is defined as the mean level between HAT and LAT. The design maximum still water level (SWL) is to include astronomical tidal influences, wind and pressure induced storm surge and settlements and subsidence if relevant.

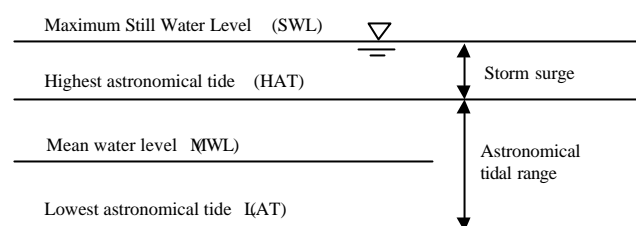


Figure 1-5 Definition of water levels

293 Wave Frequency (WF) motion: Motion of the floater at the frequencies of incident waves.

294 Wellbore annulus: Annular space between the production tubing and the well casing.

295 Working Stress Design (WSD): Design method where the structural safety margin is expressed by one central safety factor for each limit state. The central safety factor is the ratio between a resistance and the load effect.

D. Abbreviations and Symbols

D 100 Abbreviations

ALS	Accidental Limit State
BOP	Blow Out Preventer
C-Mn	Carbon Manganese steel
CRA	Corrosion Resistant Alloys
CTOD	Crack Tip Opening Displacement
DDF	Deep Draft Floater
DFF	Design Fatigue Factor
DFCGF	Design Fatigue Crack Growth Factor
DFI	Design, Fabrication and Installation
DP	Dynamic Positioning
ECA	Engineering Criticality Assessment
FAT	Factory Acceptance Tests
FD	Frequency Domain
FLS	Fatigue Limit State
FMEA	Failure Mode Effect Analysis
FPS	Floating Production System
HAZ	Heat Affected Zone
HAZOP	Hazard and Operational Analysis
HIPC	Hydrogen Induced Pressure Cracking
HIPPS	High Integrity Pressure Protection System
HSE	Health, Safety and Environment

IM	Installation Manual	f_0	Ovality, $\frac{D_{\max} - D_{\min}}{D}$
LF	Low Frequency	f_y	Yield strength to be used in design
LRFD	Load and Resistance Factor Design	f_u	Tensile strength to be used in design
MQL	Material Quality Level	f_k	Material strength
MWL	Mean water level	g	Gravity acceleration
NDT	Non Destructive Testing	$g(t)$	Generalised load effect
RFC	Rain Flow Counting	h	Height from the riser section to the reference point for design pressure
SCR	Steel Catenary Riser	H_s	Significant wave height
QA	Quality Assurance	M	Bending moment
QC	Quality Control	M_A	Bending moment from Accidental loads
QL	Material Quality Level	M_d	Design bending moment
QRA	Quantitative Risk Analysis	M_d^{\max}	Maximum design bending moment, e.g. in short term sea state
SCF	Stress Concentration Factor	M_E	Bending moment from Environmental loads
SLS	Serviceability Limit State	M_F	Bending moment from Functional loads
SML	Seamless Pipe	M_k	Plastic bending moment resistance
SMTS	Specified Minimum Tensile Strength	N	Axial force in pipe wall ("true" force) (tension is positive)
SMYS	Specified Minimum Yield Stress	n_i	Number of stress blocks
SRA	Structural Reliability Analysis	N_i	Number of stress cycles to failure at constant amplitude
SWL	Still Water Level	O	Out of roundness, $D_{\max} - D_{\min}$
TD	Time Domain	p_b	Burst resistance pressure
TRB	Three Roll Bending	p_c	Collapse pressure
TLP	Tension Leg Platform	p_d	Design pressure at reference point
ULS	Ultimate Limit State	p_e	External pressure
UO	Pipe fabrication process for welded pipes	p_{el}	Elastic collapse pressure
UOE	Pipe fabrication process for welded pipes, expanded	p_i	Internal pressure
VIV	Vortex Induced Vibrations	p_{inc}	Incidental pressure
WF	Wave Frequency	p_{ld}	Local internal design pressure
WSD	Working Stress Design	p_{li}	Local incidental pressure
		p_{min}	Local minimum internal pressure taken as the most unfavourable internal pressure plus static head of the internal fluid.
		p_p	Plastic collapse pressure
		p_{pr}	Propagating pressure
		R_k	Vector of resistances
		t	time
		t_1, t_2, t_3	Pipe wall thickness, see section 5
		t_{corr}	Internal and external corrosion allowance
		t_{fab}	Absolute value of the negative tolerance taken from the material standard/specification of the pipe
		t_{nom}	Nominal wall thickness of pipe (uncorroded), as specified on the drawing/specification
		$T_{e,A}$	Effective tension from Accidental loads
		$T_{e,E}$	Effective tension from Environmental loads
		$T_{e,F}$	Effective tension from Functional loads

D 200 Symbols

A	Cross section area
A_i	Internal fluid area $\frac{\pi}{4}(D - 2 \cdot t)^2$
A_e	External cross sectional area $\frac{\pi}{4}D^2$
A_s	$p(D - t) \cdot t$ Pipe steel cross section area
D	Nominal outside diameter.
D_{fat}	Accumulated fatigue damage or Miner sum
D_i	$D - 2t_{nom}$ = Nominal internal diameter
D_{\max}	Greatest measured inside or outside diameter
D_{\min}	Smallest measured inside or outside diameter
E	Young's Modulus

T_e	Effective tension (axial force) (Tension is positive), wave period or calculation (operating, design) temperature	α_U	Material quality factor
T_{ed}^{\max}	Maximum design effective tension, e.g. in short term sea state	γ_A	Load factor for accidental loads
T_{ed}	Design effective tension (force)	γ_c	Condition factor
T_k	Plastic axial force resistance	γ_E	Load effect factor for environmental loads
T_p	Wave peak period	γ_F	Load effect factor for functional loads
T_w	True wall tension	γ_m	Resistance factor to take into account uncertainties in material properties
T_z	Wave zero-upcrossing period	γ_{SC}	Resistance factor dependent on safety class (consequence of failure)
D 300 Greek Characters		ν	Poisson's ratio for pipe wall material
α_c	Flow stress parameter accounting for strain hardening	η	usage factor
α_{fab}	Manufacturing process reduction factor	ρ_e	Density of external fluid (e.g. sea water)
		ρ_i	Density of internal fluid (contents)

SECTION 2 DESIGN PHILOSOPHY AND DESIGN PRINCIPLES

Contents

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B 200	Safety Objective
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C 300	Design by LRFD Method
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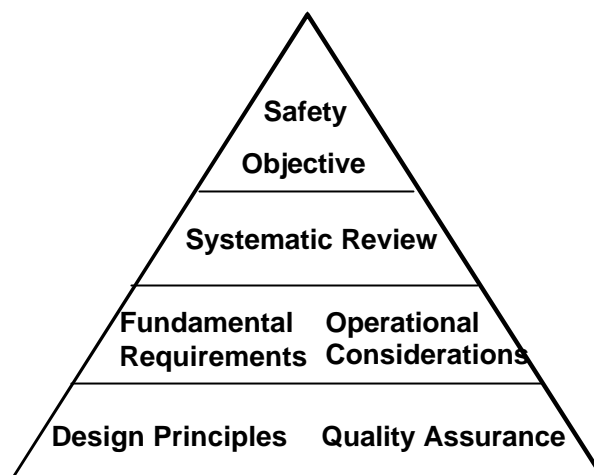


Figure 2-1 Safety hierarchy

B 200 Safety Objective

201 An overall safety objective shall be established, planned and implemented covering all phases from conceptual development until retrieval or abandonment.

Guidance note:

All companies have policy regarding human aspects, environment and financial issues. These are typically on an overall level, but more detailed objectives and requirements in specific areas may follow them. These policies should be used as a basis for defining the Safety Objective for a specific riser system. Typical statements can be:

- all work associated with the transportation, installation/ retrieval, operation and maintenance of the riser system shall be such as to ensure that no single failure will lead to life-threatening situations for any person, or to unacceptable damage to material or the environment;
- the impact on the environment shall be reduced to as low as reasonably possible (ALARP);
- no releases of fluid content will be accepted during operation of the riser and pipeline system;

Statements such as those above may have implications for all or individual phases only. They are typically more relevant for the work execution and specific design solutions. Having defined the Safety Objective, it can be a point of discussion as to whether this is being accomplished in the actual project. It is therefore recommended that the overall Safety Objective be followed up by more specific, measurable requirements.

If no policy is available, or if it is difficult to define the safety objective, one could also start with a risk assessment. The risk assessment could identify all hazards and their consequences, and then enable back-extrapolation to define acceptance criteria and areas that need to be followed up more closely.

In this standard, the structural failure probability is reflected in the choice of safety class. The choice of safety class should also include consideration of the expressed safety objective.

- end - of - Guidance - note -

A. General

A 100 Objective

101 The purpose of this section is to present the safety philosophy and corresponding limit state design format applied in this standard.

A 200 Application

201 This section applies to all risers that are to be built in accordance with this standard. The section also provides guidance for extension of this standard in terms of new criteria etc.

B. Safety Philosophy

B 100 General

101 The objective of this standard is that design, materials, fabrication, installation, commissioning, operation, repair, re-qualification, and abandonment of riser systems are safe and conducted with due regard to public safety and protection of the environment.

102 The integrity of a riser system constructed to this standard is ensured through a safety philosophy integrating the different aspects illustrated in Figure 2-1.

B 300 Systematic review

301 A systematic review or analysis shall be carried out at all phases in order to identify and evaluate the consequences of single failures and series of failures in the riser system, such that necessary remedial measures can be taken. The consequences include consequences of such events for people, for the environment and for assets and financial interests.

302 The Operator shall determine the extent of risk assessments and the risk assessment methods. The extent of the review or analysis shall reflect the criticality of the riser system, the criticality of the planned operation and previous experience with similar systems or operations.

Guidance note:

A methodology for such a systematic review is quantitative risk analysis (QRA). This may provide an estimation of the overall risk to human health and safety, environment and assets and comprises:

- hazard identification,
- assessment of probabilities of failure events,
- accident developments, and
- consequence and risk assessment.

It should be noted that legislation in some countries requires risk analysis to be performed, at least at an overall level to identify critical scenarios that might jeopardise the safety and reliability of a riser system. Other methodologies for identification of potential hazards are Failure Mode and Effect Analysis (FMEA) and Hazard and Operability studies (HAZOP).

- end - of - Guidance - note -

B 400 Fundamental requirements

401 A riser shall be designed, manufactured, fabricated, operated and maintained in such a way that:

- with acceptable probability, it will remain fit for the use for which it is intended, having due regard to its service life and its cost, and
- with appropriate degree of reliability, it will sustain all foreseeable load effects and other influences likely to occur during the service life and have adequate durability in relation to maintenance costs.

402 In order to maintain the required safety level, the following requirements apply:

- the design shall be in compliance with this standard;
- risers shall be designed by appropriately qualified and experienced personnel ;
- the materials and products shall be used as specified in this standard or in the relevant material or product specification ;
- adequate supervision and quality control shall be provided during manufacture and fabrication, on site and during operation ;
- manufacture, fabrication, handling, transportation and operation shall be carried out by personnel having the appropriate skill and experience. Reference is made to recognised standards for personnel qualifications ;

- the riser shall be adequately maintained including inspection and preservation when applicable ;
- the riser shall be operated in accordance with the design basis and the installation and operating manuals;
- relevant information between personnel involved in the design, manufacture, fabrication and operation shall be communicated in an understandable manner to avoid misunderstandings, see e.g. Section 9;
- design reviews shall be carried out where all contributing and affected disciplines (professional sectors) are included to identify and solve any problems;
- verification shall be performed to check compliance with provisions contained herein in addition to national and international regulations. The extent of the verification and the verification method in the various phases, including design and fabrication, shall be assessed, see Section 8.

B 500 Operational considerations

501 Operational requirements are system capabilities needed to meet the functional requirements. Operational considerations include matters which designers should address in order to obtain a design that is safe and efficient to install, operate and maintain. Operational requirements include operational philosophy, floater motions and environmental limits, floater interfaces, riser installation and retrieval, in-service operations, inspection and maintenance philosophy.

502 Safe operation of a riser requires that:

- the designer shall take into account all realistic conditions under which the riser will be operated;
- the operations personnel shall be aware of, and comply with, limits for safe operations.

Guidance note:

Risers generally fit into two main operational types:

- permanent risers; risers installed and left for (many) years until subsequent retrieval, e.g. for production/injection and export/import of fluids and temporary risers for drilling/workover where it is not allowable to disconnect in extreme conditions (e.g. TLP, DDF, Spar), and
- temporary risers; risers run and retrieved many times during their service life, e.g. for drilling and/or workover operations.

Permanent risers are normally designed to stay connected and operate when subjected to the extreme environment. However, operating limits may be introduced for some temporary conditions, e.g. shut down, bullheading etc.

A temporary riser may be designed to be disconnected, retrieved or hung-off when the operating limit for the riser is about to be exceeded. Temporary riser system operational parameters normally are closely monitored at all times to ensure that the riser is being operated within prescribed limits. The operational parameters may include parameters such as internal pressure and density, wave height, relative vertical motions between riser and floater (stroke), floater offset, top tension, flex joint/ball joint angle and stress joint stresses.

Both temporary risers and permanent risers normally have certain operations, such as riser installation including connection, retrieval including disconnection and pressure testing, which are normally limited due to weather conditions.

There are two levels of riser disconnection: normal or planned disconnection and rapid or emergency disconnection. Rapid or emergency disconnection of the riser system may be necessary if floater or well system emergencies occur, the floater station-keeping/tensioning system fails, or the weather suddenly and unpredictably deteriorates beyond the riser's operating threshold. If riser recovery is required following an emergency disconnect event, all subsea valves should be closed before the riser system is removed. All equipment should be designed to be fail-safe to prevent the escape of fluids from the riser/well bore/pipeline to the environment during disconnection.

end - of - Guidance - note -

B 600 Design Principles

601 In this standard, structural safety of the riser is ensured by use of a safety class methodology, see C 200.

602 The riser system including riser pipe and interfaces, details and components, shall be designed according to the following basic principles:

- the riser system shall satisfy functional and operational requirements as given in the design basis.
- the riser system shall be designed such that an unintended event does not escalate into an accident of significantly greater extent than the original event;
- permit simple and reliable installation, retrieval, and be robust with respect to use;
- provide adequate access for inspection, maintenance, replacement and repair;
- the riser joints and components shall be made such that fabrication can be accomplished in accordance with relevant recognised techniques and practice;
- design of structural details and use of materials shall be done with the objective to minimise the effect corrosion, erosion and wear;
- riser mechanical components shall, as far as practicable, be designed "fail safe". Consideration is to be given in the design to possible early detection of failure or redundancy for essential components, which cannot be designed according to this principle;
- the design should facilitate monitoring of its behaviour in terms of tension, stresses, angles, vibrations, fatigue cracks, wear, abrasion, corrosion etc.

B 700 Quality Assurance and Quality System

701 The design format within this standard requires that the possibility of gross errors (human errors) shall be prevented by requirements to the organisation of the work, competence of personnel performing the work and verification activities during the design, manufacture and fabrication phases and quality assurance during all relevant phases.

702 A quality system shall be applied to the design, manufacturing, fabrication, testing, operation and maintenance activities to assist compliance with the requirements of this standard.

Guidance note:

ISO/CD 13628-7 give guidance on the selection and use of quality systems.

end - of - Guidance - note -

C. Design Format

C 100 Basic Considerations

101 The design objective is to keep the failure probability (i.e. probability of exceeding a limit state) below a certain value. All relevant failure modes for the riser shall be identified and it shall be verified that no corresponding limit state is exceeded.

102 The following design methods may be applied:

- Load and Resistance Factor Design (LRFD) method, see C 300
- Working Stress Design (WSD) method, see C 400
- Reliability analysis, see C 500
- Design by testing, see C 600

Guidance note:

The LRFD method separates the influence of uncertainties and variability originating from different causes by means of partial safety factors.

The WSD method adopted herein addresses the same limit states as the LRFD but accounts for the influence of uncertainty in only a single usage factor. The LRFD method allows for a more flexible and optimal design with uniform safety level and is considered superior to the WSD method. The WSD format is included as a more easy-to-use conservative alternative.

Reliability analysis is mainly considered as applicable to unique, special case design problems, for conditions where limited experience exists and for (re-) calibration of safety/usage factors.

As an alternative or supplement, testing (full-scale or model) conducted in accordance with valid experimental methods may be used to determine or verify riser system load effects, structural resistance and resistance against material degradation.

- end - of - Guidance - note -

C 200 Safety Class Methodology

201 This standard gives the possibility to design risers with different safety requirements, depending on the safety class to which the riser belongs. The riser system shall (on a component level if relevant) be classified into one or more safety classes based on the failure consequences. The safety class of a riser depends on:

- the hazard potential of the fluid in the riser, i.e. fluid category;
- the location of the part of the riser that is being designed;
- whether the riser is in operating or temporary state.

202 Fluids in the riser system shall be categorised according to their hazard potential as given in Table 2-1. Contents not specifically identified shall be classified in the category containing substances most similar in hazard potential to those quoted. If the category is not evident, the most hazardous category shall be assumed.

Table 2-1 Classification of fluids	
Category	Description
A	Typical non-flammable water-based fluids.
B	Flammable and/or toxic substances which are liquids at ambient temperature and atmospheric pressure conditions. Typical examples would be oil, petroleum products, toxic liquids and other liquids, which could have an adverse effect on the environment if released.
C	Non-flammable substances which are gases at ambient temperature and atmospheric pressure conditions. Typical examples would be nitrogen, carbon dioxide, argon and air.
D	Non-toxic, single-phase gas which is mainly methane.
E	Flammable and toxic substances, which are gases at ambient temperature and atmospheric pressure conditions and which, are conveyed as gases or liquids. Typical examples would be hydrogen, methane (not otherwise covered under category D), ethane, ethylene, propane, butane, liquefied petroleum gas, natural gas liquids, ammonia, and chlorine.

203 The riser system shall be classified into a location class 1 and 2 as defined in Table 2-2.

Table 2-2 Classification of locations	
Location	Description
1	Area where no frequent human activity is anticipated
2	The part of the riser in the near platform (manned) area or in areas with frequent human activity. The extent of location class 2 should be based on appropriate risk analyses. If no such analyses are performed, a minimum horizontal distance of 500 m may be adopted.

204 Riser design shall be based on potential failure consequences. This is implicit by the concept of safety classes defined in Table 2-3.

Table 2-3 Classification of safety classes	
Safety class	Definition
Low	Where failure implies low risk of human injury and minor environmental and economic consequences.
Normal	For conditions where failure implies risk of human injury, significant environmental pollution or very high economic or political consequences.
High	For operating conditions where failure implies high risk of human injury, significant environmental pollution or very high economic or political consequences.

205 The safety class is a function of the riser status (phase) and location class. For normal riser use, the safety classes in Table 2-4 apply. Other classifications may exist depending on the conditions and criticality of the riser. The operator shall specify the safety class to which the riser shall be designed.

Table 2-4 Normal classification of safety classes ^{3), 4), 5)}						
Riser status (phase)	Riser content					
	Fluid category A,C		Fluid category B		Fluid category D, E	
	Location class		Location class		Location class	
	1	2	1	2	1	2
Testing ¹⁾	Low	Low	Low	Low	NA	NA
Temporary with no pipeline/well access ²⁾	Low	Low	Low	Low	Low	Normal
In-service with pipeline/well access	Low	Normal	Normal	Normal	Normal	High
NOTES 1) Testing like overpull to test connection (e.g. bottom connection) and system pressure test performed with incompressible medium is classified as safety class low. 2) Temporary conditions include handling, transportation, installation, landing, connecting, disconnection, retrieval and hang-off. 3) Riser with non-flammable content but under pressure may require to be classified as safety class Normal. 4) Risers that are pressurised in temporary condition may require to be treated as in-service risers. 5) If deemed necessary, a riser can always be designed to the requirements of a more strict safety class.						

C 300 Design by LRFD Method

301 The fundamental principle of Load and Resistance Factored Design (LRFD) method (also denoted partial safety factor method) is to verify that factorised design load effects do not exceed factored design resistance for any of the considered limit states (i.e., failure modes).

302 In the LRFD approach it is distinguished between:

- pressure load effect (static) ;
- functional load effects (static) ;
- environmental load effects (mainly dynamic) and
- accidental load effects.

Guidance note:

This separation of loads is done in order to cope with sources of uncertainties in a rational way; e.g. uncertainties in the

environmental load effects are typically larger compared to those in pressure or functional load effects implying a higher safety factor

- end - of - Guidance - note -

303 The general LRFD safety format can be expressed as:

$$g(S_P; \gamma_F; S_F; \gamma_E; S_E; \gamma_A; S_A; R_k; \gamma_{SC}; \gamma_m; \gamma_c; t) \leq 1 \quad (2.1)$$

$g(\bullet)$ is the generalised load effect. $g(\bullet) < 1$ implies a safe design and $g(\bullet) > 1$ implies failure. Further,

S_P	=	Pressure loads
S_F	=	Load effect from functional loads (vector or scalar)
S_E	=	Load effect from environmental load (vector or scalar)
S_A	=	Load effect from accidental loads (vector or scalar)
g_F	=	Load effect factor for functional loads(vector or scalar)
g_E	=	Load effect factor for environmental loads
g_A	=	Load effect factor for accidental loads
R_k	=	Generalised resistance (vector or scalar)
γ_{SC}	=	Resistance factor to take into account the safety class (i.e. failure consequence)
γ_m	=	Resistance factor to account for material and resistance uncertainties
γ_c	=	Resistance factor to account for special conditions
t	=	Time

Guidance note:

$g(\bullet)$ is a function of time for systems exposed to time varying excitations. The time-dependent generalised load effect $g(\bullet)$ defined above covers the general case for combined loading. For design criteria where the load effects and resistance can be separated the LRFD format can be written in the more familiar format:

$$S_d(S_P; \gamma_F; S_F; \gamma_E; S_E; \gamma_A; S_A) \leq \frac{R_k}{\gamma_{SC} \cdot \gamma_m \cdot \gamma_c}$$

The generalised load effect $g(\bullet)$ is discussed in more detail in [section 4](#).

- end - of - Guidance - note -

304 The acceptance criteria presented in this standard are calibrated using a reliability-based methodology for the different safety classes. The following comments apply:

- the load effect factors and resistance factors depend on the limit state category
- identical load effect factors will apply to limit states and safety classes;
- the set of resistance factors are adapted to the particular failure mode being considered and safety class;

- an additional safety factor, γ_c is applied where appropriate in order to account for conditions with specific load effects or resistances. (e.g. in case of prevailing system effects where many pipe sections are exposed to the same loading)

Guidance note:

Load effect factors typically account for natural variability in loads and model uncertainties due to incomplete knowledge or models leading to possible inaccurate calculation of load effects.

Resistance factors typically account for variability in strength and basic variables including the effect of dimensional tolerances and model uncertainties due to incomplete resistance model.

- end - of - Guidance - note -

305 The load effects and resistance in this standard are usually given as percentile values (i.e. return period values for load effects) of the respective probability distributions. They shall be based on reliable data, using recognised statistical techniques.

Guidance note:

The characteristic resistances in this standard do not necessarily reflect either mean values or certain percentile values. The resulting design formulas provide design criteria as a totality of model uncertainty, bias loads etc. Hence, care shall be taken when re-calibrating these formulas to ensure this totality.

- end - of - Guidance - note -

C 400 Design by WSD Method

401 The Working (allowable) Stress Design (WSD) method is a design format where the structural safety margin is expressed by one central safety factor or usage factor for each limit state.

402 The WSD method adopted herein applies explicit design checks similar to the LRFD method but accounts for the influence of uncertainty in only a single usage factor.

Guidance note:

The usage factor accounts for the integrated uncertainty and possible bias in load effects and resistance. The usage factor, h , may be interpreted as an inverted weighted product of partial safety factors.

The usage factor is also named Allowable Stress factor or Design Factor in some WSD codes and standards.

- end - of - Guidance - note -

403 The general WSD design format can be expressed as:

$$g(S, R_k, \eta, t) \leq 1 \quad (2.2)$$

404 where S is the total load effect, R_k is the resistance, η is the usage factor and $g(\bullet)$ is the generalised load effect as discussed for the LRFD safety format. It is emphasised that S is the total load effect (scalar or vector), due to combined

action from pressure-, functional-, environmental- and accidental loads as relevant for the actual limit state and load case.

Guidance note:

It should be observed that the generalised load effect for the WSD formulation could be derived as a special case of the generalised load effect for the LRFD formulation.

For design criteria where the load effect and resistance can be separated the WSD format can be expressed in the more familiar format:

$$S_d(S) \leq \eta R_k$$

- end - of - Guidance - note -

C 500 Reliability Based Design

501 As an alternative to the design formats specified in this standard, a probabilistic design approach based on a recognised structural reliability analysis may be applied provided that:

- it is used for calibration of explicit limit states outside the scope of this standard;
- the method complies with DNV Classification Note no. 30.6 or ISO 2394;
- the approach is demonstrated to provide adequate safety for familiar cases, as indicated by this standard.

502 Suitably competent and qualified personnel shall perform the structural reliability analysis, and extension into new areas of application shall be supported by technical verification.

503 As far as possible, target reliability levels shall be calibrated against identical or similar riser designs that are known to have adequate safety based on this standard. If this is not feasible, the target safety level shall be based on the failure type and class as given in Table 2-5. The values are nominal values reflecting structural failure due to normal variability in load and resistance but excluding gross error.

Table 2-5 Acceptable failure probabilities¹⁾ vs. safety class

Limit state	Probability bases ^{2,3)}	Safety classes		
		Low	Normal	High
SLS ⁴⁾	Annual per riser	10 ⁻¹	10 ⁻¹ -10 ⁻²	10 ⁻² -10 ⁻³
ULS	Annual per riser	10 ⁻³	10 ⁻⁴	10 ⁻⁵
FLS ⁵⁾	Annual per riser			
ALS	Annual per riser			

NOTES

- 1) The failure probability from a structural reliability analysis is a nominal value and cannot be interpreted as an expected frequency of failure.
- 2) The probability basis is failures per year for permanent conditions and for the actual period of operation for temporary conditions.
- 3) Per riser imply for the riser in each location class
- 4) The failure probabilities provided for SLS are not mandatory. SLS are used to select operational limitations and can be defined according to the operator's preference. Note that exceedence of a SLS conditions require a subsequent ALS design check.
- 5) The FLS probability basis is failures per year, i.e., often last year of service life or last year before inspection.

C 600 Design by Testing

601 Testing (full-scale or model) conducted in accordance with valid experimental methods may be used to determine or verify riser system load effects, structural resistance and resistance against material degradation. Design by testing or observation of performance shall be supported by analytical design methods.

Guidance note:

Load effect model tests are normally performed to determine the floater responses as wave induced motions and drift motions. In general, load effect model tests should be considered to verify methods for predicting systems load effect (response) for concepts with little or no field experience and cases with high uncertainty in analysis models. These tests may include tests for evaluation of hydrodynamic coefficients, shielding effects, vortex-induced vibrations, interference and soil-structure interaction i.e. for touch down regions.

Certain vital riser components and materials including seals may, due to their specialised and unproven function, require extensive engineering and prototype testing to determine and confirmation of anticipated design performance including fatigue characteristics, fracture characteristics, corrosion characteristics, wear characteristics, mechanical characteristics.

- end - of - Guidance - note -

602 When implementing experimental test results into design, all relevant deviations between the model test and reality shall be considered including:

- scaling effects,
- model/testing simplifications and uncertainties,
- data acquisition and processing simplifications and uncertainties,
- uncertainties with regard to long-term effects and failure modes.

Statistical uncertainties with respect to a limited number of test results are to be included in the determination of model load effects or resistance.

SECTION 3 LOADS

Contents

A. General

- A 100 Objective
- A 200 Application
- A 300 Loads

B. Pressure Loads

- B 100 Definition
- B 200 Determination of Pressure Loads
- B 300 Pressure Control System
- B 400 Pressure Ratings

C. Functional Loads

- C 100 Definition
- C 200 Determination of Functional Loads

D. Environmental Loads

- D 100 Definition
- D 200 Environmental Load Condition
- D 300 Waves
- D 400 Current
- D 500 Floater Motion

A. General

A 100 Objective

101 This section defines the loads to be considered in the design of riser systems. The loads are classified into different load categories.

Guidance note:

The aim of the load classification is to relate the load effect to the different uncertainties and occurrences.

- end - of - Guidance - note -

A 200 Application

201 This section describes the loads to be applied in the adopted LRFD criteria.

A 300 Loads

301 Loads and deformations shall be categorised into four groups as follows:

- pressure (P) loads (section B);
- functional (F) loads, (section C);
- environmental (E) loads, (section D)
- accidental (A) loads, (section 5.F 400)

Table 3-1 gives some examples on how the various loads are categorised.

Table 3-1 Examples of categorisation of loads ¹⁾		
<i>F</i> -loads	<i>E</i> -loads	<i>P</i> -loads ⁷⁾
Weight and buoyancy ⁶⁾ of riser, tubing, coatings ⁶⁾ , marine growth ²⁾ , anodes, buoyancy modules, contents and attachments Weight of internal fluid Applied tension for top-tension risers Installation induced residual loads or pre-stressing Pre-load of connectors Applied displacements and guidance loads, including active positioning of support floater Thermal loads Soil pressure on buried risers Differential settlements Loads from drilling operations Construction loads and loads caused by tools	Waves Internal waves and other effects due to differences in water density. Current Earthquake ⁴⁾ Ice ³⁾ Floater motions induced by wind, waves and current, i.e.: — Mean offset including steady wave drift, wind and current forces — Wave frequency motions — Low frequency motions	External hydrostatic pressure Internal fluid pressure: hydrostatic, static and dynamic ⁵⁾ contributions, as relevant Water Levels
NOTES 1) Accidental loads, both size and frequency, for a specific riser and floater may be defined by a risk analysis. 2) For temporary risers, marine growth can often be neglected due to the limited duration of planned operations. 3) Ice effects shall be taken into account in areas where ice may develop or drift. 4) Earthquake load effects shall be considered in the riser design for regions considered being seismically active. 5) Slugs and pressure surges may introduce global load effects for compliant configurations. 6) Includes also absorbed water. 7) Possible dynamic load effects from P-loads and F-loads shall be treated as E-loads, e.g. slug flow.		

B. Pressure Loads

B 100 Definition

101 Pressure loads, P , are loads that are strictly due to the combined effect of hydrostatic internal and external pressures see Table 3-1. Such loads are often included in the general class of functional loads, however, they are considered separately in this standard.

102 The following internal pressure definitions apply at the surface (top) of the riser, see Table 3-2:

- *Design pressure*, p_d , is the maximum surface pressure during normal operations.
- *Incidental pressure*, p_{inc} , is the surface pressure that is unlikely to be exceeded during the life of the riser.

Table 3-2 Internal pressure definitions at riser surface (top)²⁾

<i>Riser Type</i>	<i>Design pressure, p_d</i>	<i>Incidental pressure, p_{inc}</i>
Drilling riser above subsea BOP stack	Zero	Maximum diverter line back pressure
Drilling riser with surface stack	Zero (or if drilling under-balanced, maximum under –balance pressure)	Design as an extension of the last casing string that will be drilled through. This applies to both outer riser and inner riser, if used.
Drilling riser with both surface and subsea BOP stacks	Zero (or if drilling under-balanced, maximum under-balance pressure)	Surface pressure that will handle most well control situations. Assume subsea BOP will be closed before pressure rises higher.
Production or injection riser used as extension of production casing	Specified maximum annulus pressure ¹⁾ or maximum sustained pressure allowed by regulation or company policy	Pressure caused by near-surface leak of shut-in tubing (maximum).
Outer casing of dual casing production or injection riser with surface tree	No requirement or specified pressure.	Pressure caused by near-surface or near-bottom leak of inner tubing/casing maximum operating pressure.
Tubing (single pipe) riser or flowline from subsea satellite well	Surface shut-in pressure with subsea valves open	Maximum surge pressure or maximum well kill pressure.
Import riser from subsea manifold	Surface shut-in pressure with subsea valves open unless pressure can be reliably limited to a lower value by e.g. a pressure reduction system (HIPPS)	Maximum surface shut-in pressure with subsea valves open unless pressure can be reliably limited to a lower value
Export/import riser from/to pipeline	Maximum export/import pressure during normal operations	Maximum surge pressure defined with low lifetime probability of occurrence. Normally to be taken as $1.1 \cdot p_d$
Other riser type	Highest pressure that will be seen for an extended time	Pressure that is unlikely to be exceeded during life/period of operation of riser

NOTES

1) Annulus refers to the space between the external riser pipe and the tubing/work-string/drill-string in the case of a single-casing production/workover/drilling riser, or the space between the inner casing and the tubing/work string in the case of a dual-casing riser. The content and pressure of the outer annulus for a dual-casing riser can normally be assumed constant and as specified.

2) Internal pressure may also be specified at subsea wellhead.

B 200 Determination of Pressure Loads

201 It is the responsibility of the owner to determine design surface- and incidental surface internal pressures together with internal content density- and temperature based on the guidelines given above and Table 3-2. The owner shall also specify surface operating pressure and minimum surface stresses with corresponding temperature and density. It may be necessary to specify pressure-temperature-density values (p , T , ρ), which determine an envelope of the (p , T , ρ) - regime of the credible extreme values.

202 The local internal design pressure p_{ld} and local incidental pressure p_{li} are determined based on the definitions given in B 100 as follows

$$p_{ld} = p_d + \rho_i \cdot g \cdot h \quad (3.1)$$

$$p_{li} = p_{inc} + \rho_i \cdot g \cdot h$$

where ρ_i is the density of the internal fluid, h is the height difference between the actual location and the internal pressure reference point, and g is the acceleration of gravity.

Guidance note:

Gas mixed with oil in the riser could reduce the hydrostatic internal pressure acting downstream of the closed valve. This should be taken into account when calculating the maximum allowable shut-in pressure for the specific application

- end - of - Guidance - note -

203 The hydrostatic seawater pressure governs the external pressure on pipes directly exposed to seawater (e.g. single pipe risers or outer riser of multi-tube risers). Annual average seawater density and mean sea levels shall be used to establish the external hydrostatic pressure.

Guidance note:

The external pressure should not be taken as higher than the water pressure at the considered location corresponding to low

tide when external pressure increase the resistance and high tide when external pressure decreases the resistance.

- end - of - Guidance - note -

204 The hydrostatic annulus pressure governs the external pressure on the inner riser and tubing in multi-tube risers. The hydrostatic annulus pressure should be defined in terms of the density of the annulus content together with a reference pressure at a given location (i.e., similar to internal pressure).

B 300 Pressure Control System

301 A pressure control system may be used to prevent the internal pressure at any point in the riser system rising to an excessive level. The pressure control system comprises the pressure regulating system, pressure safety system and associated instrumentation and alarm systems, see DNV-OS-F101.

B 400 Pressure Ratings

401 The local differential pressure may form the basis for selection of pressure rated components. Pressure rated components like valves, flanges and other equipment shall have pressure rating not less than the surface pressure or local overpressure of the riser.

Guidance note:

Riser components at any point along the riser should be designed for or selected to withstand the maximum differential pressure between internal and external pressure to which the components will be exposed to during operating conditions.

Pressure-controlling components (such as valve bore sealing mechanism and tubing plugs) may be isolated from the external ambient pressure under certain operating conditions.

In most cases, valves in subsea gas service cannot be used in applications where the shut-in pressure would exceed the maximum rated working pressure stamped on the equipment.

Pressure-controlling components on subsea oil wells may benefit from "external" downstream pressure due to hydrostatic head of the oil column in the riser. In such cases, the equipment could be used at pressures above the marked pressure rating.

- end - of - Guidance - note -

C. Functional Loads

C 100 Definition

101 Functional loads, F, are defined as loads that occur as a consequence of the physical existence of the system and by operating and handling of the system, without environmental or accidental load. Examples of functional loads are listed in Table 3-1.

C 200 Determination of Functional Loads

201 The following apply when the characteristic values of the F-load shall be determined:

- In the case of well-defined functional loads, the expected value of the load shall be used. Examples are accurate data of the riser weight, buoyancy, contents and applied tension;

- In the case of variable functional loads, the most unfavourable with respect to the combined P, F, E loading condition shall be considered. Sensitivity analyses should be performed to quantify criticality. Example is change in weight due to corrosion and effects due to marine growth (weight and effects on hydrodynamic loading);
- In the case of functional load caused by deformation, the extreme value shall be used. Example is intended vessel offset.

Guidance note:

The effect of marine growth on riser shall be considered, taking into account biological and other environmental phenomena relevant for the location. Such biological and environmental factors include water salinity, oxygen content, pH, current and temperature.

The estimation of hydrodynamic load on risers subjected to accumulated marine growth shall account for the increase in effective diameter and surface roughness.

- end - of - Guidance - note -

D. Environmental Loads

D 100 Definition

101 E-loads are loads imposed directly or indirectly by the ocean environment, see Table 3-1. The principal environmental parameters are waves, currents and floater motions.

D 200 Environmental Load Condition

201 Environmental phenomena that are relevant for the particular location and operations in question shall be taken into account; see Table 3-1. The principles and methods as described in DNV CN 30.5 may be used as basis for establishing the environmental load conditions.

D 300 Waves

301 Wind driven surface waves are a major source of dynamic environmental forces on the risers. Such waves are irregular in shape, can vary in length and height, and can approach the riser from one or more directions simultaneously.

302 Wave conditions may be described either by a deterministic design wave or by stochastic methods applying wave spectra.

Guidance note:

Most spectra is described in terms of a few statistical wave parameters such as significant wave height, H_s , spectral peak period, T_p , spectral shape and directionality.

Other parameters of interest, such as the maximum wave height H_{max} and the associated wave period T_{Hmax} can be derived from these.

- end - of - Guidance - note -

303 The selection of appropriate wave theories depends on the actual application and link to assumptions used for adjacent structures e.g. floater motion transfer function

Guidance note:

Normally, linear wave theory combined with Wheeler stretching should be considered in addition to disturbed kinematics if relevant.

For part of the riser below the splash-zone linear wave theory is usually adequate in connection with irregular sea-states. Note however that disturbed kinematics e.g. for semi-submersibles and TLP's may effect the kinematics close to the floater.

- end - of - Guidance - note -

304 Combination of wind driven waves and swell from different directions must be taken into account in design.

Guidance note:

This has relevance e.g. for monohull vessels (FPSO's and Drill Ships) where large roll motions may introduce high bending moments due to beam swell sea in combination with wind driven head sea.

- end - of - Guidance - note -

D 400 Current

401 The design current velocity, profile and direction shall be selected using the best statistics available. The resulting current velocities shall include contributions from tidal current, wind induced current, storm surge current, density induced current, global ocean current, eddies that spin off from a circulating current and other possible current phenomena.

D 500 Floater Motion

501 Floater offset and motions constitute a source of both static and dynamic loading on the riser. The main data regarding floater motions needed for riser designs are:

- static offset - mean offset due to wave, wind and current loads ;
- wave frequency motions - first order wave induced motions ;
- low frequency motions - motions due to wind gust and second order wave forces ;
- pulldown/set down - due to the combined effect of mooring lines/tether constraints and floater offset (e.g. for TLP's);

For further details, reference is made to appendix F.

SECTION 4 ANALYSIS METHODOLOGY

Contents

A. General

- A 100 Objective
- A 200 Application
- A 300 Riser Analysis Procedure

B. Extreme Combined Load Effect Assessment

- B 100 Fundamentals
- B 200 Generalised Load Effect
- B 300 Load Cases
- B 400 Design Based on Environmental Statistics
- B 500 Design Based on Response Statistics

C. Global Analysis

- C 100 General
- C 200 Fatigue Analysis

A. General

A 100 Objective

101 The purpose of this section is to provide requirements for global analysis. Focus is on assessment of global structural load effects in connection with design criteria specified in Section 5.

A 200 Application

201 Combined load effects from pressure, functional and environmental loads are provided below. For accidental load and load effects see also Section 5. F.

202 Section B considers extreme load effect assessment for SLS, ULS and ALS while FLS is discussed in C 200.

A 300 Riser Analysis Procedure

301 An overview of the (ULS)-design approach is shown in Figure 4-1. The design approach may be summarised as:

- identify all relevant design situations and limit states, e.g. by FMEA, HAZOP and design reviews;
- consider all relevant loads defined in Section 3.;
- perform preliminary riser design and static pressure; design checks (bursting, hoop buckling and propagating buckling) specified in Section 5;
- establish loading conditions defined in B 300;
- define generalised load effect for combined design criteria defined in Section 5;
- conduct riser analysis using appropriate analysis models and methods defined in C;
- establish extreme generalised load effect estimate based on environmental statistics B 400, or on response statistics, B 500.
- check that no relevant limit state is exceeded.

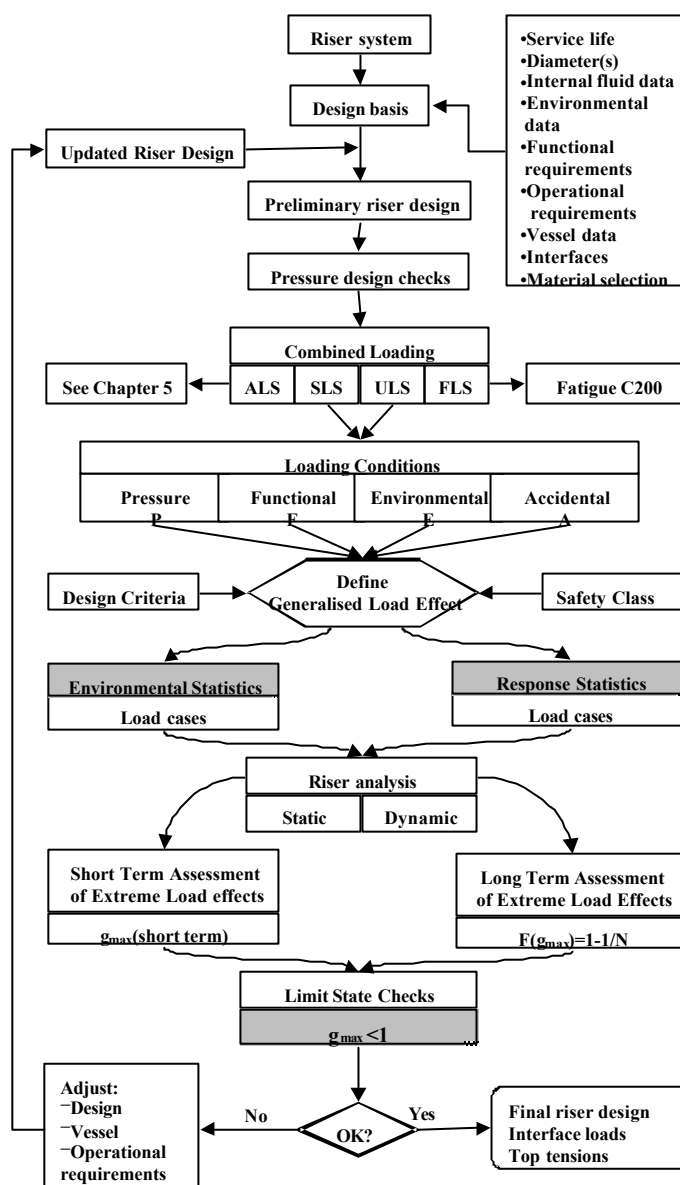


Figure 4-1 Design Approach

B. Extreme Combined Load Effect Assessment

B 100 Fundamentals

101 The characteristic load condition for SLS, ULS and ALS limit states shall reflect the most probable extreme combined load effect over a specified design time period.

Guidance note:

For permanent conditions, the most probable extreme generalised load effect during D years is commonly also denoted the D-year return period value. A D-year return period value corresponds to an annual exceedence probability of 1/D.

- end - of - Guidance -note -

102 For permanent operational conditions a 100-year return period (10^{-2} annual exceedence probability) apply.

103 For temporary operational conditions the load effect return period value depends on the seasonal timing and duration of the temporary period. The return periods shall be defined such that the probability of exceedence in the temporary state is no greater than that of the long-term operational state.

Guidance note:

If more information is not available the following return period values may be applied:

- a 100 year return period if duration in excess of 6 months.
- a 10 year return period for the actual seasonal environmental condition if duration is in excess of 3 days but less than 6 months,.
- For temporary conditions with duration less than 3 days or operations which can be terminated within a 3 days window an extreme load condition may be specified and start-up /shut down of the operation is then based on reliable weather forecasts.

- end - of - Guidance -note -

B 200 Generalised Load Effect

201 For combined loading, the acceptance criteria can be expressed by the following generic equation:

$$g(t) = g(M_d(t), T_{ed}(t), \Delta p, \mathbf{R}_k, \Lambda) \leq 1. \quad (4.1)$$

202 Where $g(t)$ is the *generalised load effect* and M_d, T_{ed} denote design values for bending moment and effective tension, respectively, see Section 5. Furthermore, Δp denotes the local differential pressure, \mathbf{R}_k is a vector of cross-sectional capacities and Λ is a vector of safety factors (i.e. material-, safety class and condition factors). Such a generic formulation covers LRFD as well as WSD acceptance criteria for combined loading; see Appendix C for details.

Guidance note:

The generalised load effect indicates the level of utilisation. $g(t) < 1$ imply a safe design and $g(t) > 1$ imply failure. See also section 3.

- end - of - Guidance -note

203 The code checks for combined loading is hence equivalent to extreme value prediction (e.g. the 100 year return period value) of the generalised load effect, i.e.

$$g_{\max} \leq 1 \quad (4.2)$$

Guidance note:

The importance of this formulation is that the combined time dependent action of bending moment and effective tension is transformed into a scalar process expressed by the generalised load effect. This approach will automatically account for the correlation between effective tension and bending moment

components and is hence capable of optimal design (i.e. allows for maximum utilisation).

The generalised load effect applies to design based on response statistics in establishing the long term probability distribution as well as short-term extreme load assessment for design based on environmental statistics.

In case of design based on environmental statistics the standard framework for response processing of results from time domain analyses can be directly applied for code checks. This will typically include application of response envelopes in case of regular wave analysis and statistical extreme value prediction in case of irregular wave analysis.

Conservative short-term estimates can be obtained by separate estimation of design values for effective tension and resulting bending moment disregarding correlation effects, i.e.

$$g(M_d^{\max}, T_{ed}^{\max}, \Delta p, \mathbf{R}_k, \Lambda) \leq 1 \quad (4.3)$$

where the indices “max” indicate extreme values. This approach may yield acceptable results when the design is driven by one dominating dynamic component. An advantage of this formulation is that it is applicable to time domain- as well as frequency domain analyses.

- end - of - Guidance -note -

B 300 Load Cases

301 The load cases form the basis for riser analysis, which determines the generalised load effects to be used for limit states controls. An adequate set of load cases (loading conditions) should be examined in order to:

- reflect extreme combined load effects;
- represent all relevant limit states;
- represent both permanent and temporary conditions ;
- represent the range of operating conditions and functional applications, and
- study sensitivities to the variation of critical parameters at different locations along the riser.

302 Different conditions may be selected for various stages in the operation, depending on the duration of the operations and the consequences of exceeding the selected conditions.

303 Environmental load effects generally depend on the applied F-loads since F-loads may influence the dynamical properties of the system (e.g. applied top tension and mass per unit length will influence the dynamic properties of the system.) Sensitivity studies shall therefore be performed to identify the most unfavourable F-load with respect to combined load effects at critical locations

304 For operating extreme conditions for combined load effects the pressure should be taken as the design pressure or a minimum value whichever is the more conservative.

Guidance note:

This implies that it is assumed that the design pressure (or minimum pressure) is likely to occur during an extreme environmental condition.

- end - of - Guidance -note -

B 400 Design Based on Environmental Statistics

401 Design criteria based on environmental statistics may be applied to establish characteristic load effects. A sufficient number of loading conditions in terms of stationary environmental conditions must be analysed in order to capture the extreme generalised load effects for all critical locations on the riser.

Guidance note:

It has traditionally been common practice to adopt the most unfavourable load effect found by exposing the riser system to multiple stationary environmental conditions as the extreme load effect. Each design condition is described in terms of a limited number of environmental parameters (e.g. significant wave height, peak period etc) and a given duration (e.g. 3-6 hours). Different combinations of wind, waves and current yielding the same return period (e.g. 100 years) for the combined environmental condition are typically applied. Furthermore, the most severe directional combination of wind, waves and current consistent with the environmental conditions at the actual site is normally applied.

The main challenge is that the return period for the characteristic load effect is unknown due to the non-linear dynamic behaviour of most riser systems. This will in general lead to an inconsistent safety level for different design concepts and failure modes. Acceptable results can however be expected for quasistatic systems with moderate non-linearities.

Guidance to computational strategies for short-term assessment of extreme load effects is given in Appendix C.

- end - of - Guidance -note -

402 If the design is based on environmental statistics, verification and/or calibration of results should be performed in the following cases:

- new concepts;
- systems with significant nonlinear response characteristics, and
- dynamically sensitive systems;

The methodology in B 500 may be applied for verification and/or calibration purposes.

403 Wave period variation shall be considered for regular and irregular wave analyses to identify most unfavourable loading condition. This is of special importance for regular wave analyses, which may be subjected to severe bias for dynamically sensitive systems. The period variation shall be performed with due consideration of the following:

- statistical variation of wave period;
- eigenvalues of the riser system;
- peaks in floater motion transfer function;
- period dependencies in load intensity (e.g. splash zone loads in case of disturbed kinematics).

B 500 Design Based on Response Statistics

501 Design based on response statistics is generally the recommended procedure consistent assessment of characteristic load effects.

Guidance note:

Design based on response statistics is the more correct approach and should be considered when deemed important.

Consistent assessment of the D-year generalised load effect will in general require a probabilistic description of the load effect due to the long-term environmental load on the riser system. The main challenge is to establish the long-term load effect distribution due to the non-linear dynamic behaviour experienced for most riser systems.

A feasible approach for establishing long term response statistics is proposed in Appendix C.

- end - of - Guidance -note -

C. Global Analysis

C 100 General

101 Global riser analysis shall be conducted for the specified design cases, see B 100 to check the relevant limit states for the riser system and establish component load effects and riser interface data. A general guidance on global load effect analysis of risers is given in Appendix A.

102 The global analyses shall be based on accepted principles of static and dynamics analysis, model discretisation, strength of materials, environmental loading and soil mechanics to determine reliable load effects on the riser system. The load effect analysis may be based on analytical calculations, numerical simulations or physical testing or a combination of these methods.

103 The global riser model shall include the complete riser system considering accurate modelling of stiffness, mass, damping and hydrodynamic load effects along the riser in addition to top and bottom boundary conditions. In particular, appropriate drag and inertia coefficients for the selected method shall be applied.

104 The riser shall be discretised with sufficient number of elements to represent environmental loading and structural response and to resolve load effects in all critical areas. Time and/or frequency discretisation shall be verified to ensure that the desired accuracy is obtained. The principles for model validation as outlined in Appendix D should be adopted.

105 Sensitivity studies shall be performed to investigate the influence from uncertain system parameters (e.g. soil data, hydrodynamic coefficients, corrosion allowance, disturbed wave kinematics, component modelling, structural damping etc.) The main purpose is to quantify model uncertainties, support rational conservative assumptions and identify areas where a more thorough investigation is needed to achieve an acceptable modelling (e.g. calibration of computer model against physical testing)

106 Static analyses should be carried out using a full nonlinear approach. Several alternatives are available in subsequent dynamic analysis restarted from the static equilibrium configuration. Treatment of nonlinearities is the distinguishing feature among available dynamic analysis techniques. Knowledge of governing nonlinearities for the

actual system as well as treatment of nonlinearities in established analysis techniques is crucial for the accuracy and hence the choice of adequate analysis strategy.

main techniques for dynamic analysis is indicated in Table 4-2. Reference is made to Appendix A for a more detailed discussion.

107 An overview of commonly used dynamic FE analysis methods is given in Table 4-1. Typical application of the

Table 4-1 Global analysis. Finite element (FE) methods overview			
<i>Method</i>	<i>Nonlinearities</i>		
	<i>Environmental Loads</i>	<i>Special loads</i>	<i>Structure</i>
Nonlinear Time domain (NTD)	Morison loading Integration to actual surface elevation.	Slug flow. Collision/interaction with other slender structures	Geometric stiffness Nonlinear material Seafloor contact. Variable hull contact Large 3D rotations
Linearised Time domain (LTD)		NA	Linearised at static equilibrium position
Frequency domain (FD)	Linearised at static equilibrium position (stochastic linearisation in case of irregular excitation)	NA	Linearised at static equilibrium position

Table 4-2 Typical analyses techniques versus applications	
<i>Method</i>	<i>Typical applications</i>
NTD	Extreme response analysis of systems with significant nonlinearities, in particular compliant configurations exposed to 3D excitation. Special FLS analyses for systems or parts of systems with highly nonlinear response characteristics (e.g. touch-down area of compliant configurations) Verification/validation of simplified methods (e.g. LTD, FD)
LTD	Extreme analysis of systems with small/moderate structural nonlinearities and significantly nonlinear hydrodynamic loading (e.g. top tensioned risers)
FD	Screening analyses. FLS analyses of systems with small/moderate nonlinearities

108 One or combinations of the following methods should be applied:

- irregular wave analysis in the time domain (design storm);
- regular wave analysis in time domain (design wave);
- irregular wave analysis in the frequency domain

109 The irregular wave analysis refers to modelling of water particle kinematics and floater motions. Extreme load effect analyses should preferably be carried out by use of time domain analyses. However, frequency domain analyses may be applied provided that the adequacy of such analyses is documented by verification against time domain analysis.

110 It shall be documented that the duration of irregular time domain analyses is sufficient to obtain extreme load effect estimates with sufficient statistical confidence. This is

of particular concern in case of combined WF and LF loading. The methodology as outlined in Appendix C may be applied.

111 Any use of simplified modelling and/or analysis techniques should be verified by more advanced modelling and/or analyses. In particular, the validation as specified in Table 4-3 should be considered for representative (critical) load cases. For further details see Appendix D.

Table 4-3 Validation analysis methods overview	
<i>Applied method</i>	<i>Method for validation</i>
Linearised time domain analysis	Nonlinear time domain analysis
Frequency domain analysis	Time domain analysis
Regular wave analysis	Irregular wave analysis

C 200 Fatigue Analysis

201 Fatigue analysis of the riser system shall considered all relevant cyclic load effects including:

- first order wave effects (direct wave loads and associated floater motions) ;
- second order floater motions ;
- thermal and pressure induced stress cycles
- vortex induced vibrations, see Appendix E.
- collisions

All modes of operations including connected, running and hang-off must be considered if relevant.

202 The fatigue response due to the first two contributors may be calculated with the same methods as for extreme response calculation. If frequency domain analysis is used, validation against irregular sea, time domain analysis shall be performed.

203 Fatigue analyses normally apply nominal values. Sensitivity analysis is needed to map criticality and give input to DFI, e.g. using half the corrosion allowance in the cross section values for in-service assessment

204 Recommended procedures for short-term fatigue damage calculation for commonly used global analysis strategies are given in Table 4-4. For further details see Appendix B.

Table 4-4 Fatigue analysis methods overview

<i>Method of Analysis</i>		<i>Fatigue damage assessment</i>		
<i>WF- response</i>	<i>LF- response</i>	<i>WF-damage</i>	<i>LF-damage</i>	<i>Combined WF+LF damage</i>
FD	FD	NB	NB	Summation / bi-modal
FD	TD	NB	RFC	Summation
TD	TD	RFC	RFC	Summation
TD for combined WF+LF excitation		RFC for combined WF+LF response		

Where :

FD = Global frequency domain analysis

TD = Global time domain analysis

WF = Wave frequency

LF = Low frequency

NB = Narrow band approximation

RFC = Rain flow cycle counting

SECTION 5 DESIGN CRITERIA FOR RISER PIPES

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A. General

A 100 Objective

101 The section provides the general framework for design of riser systems including provisions for checking of

limit states for pipes in riser systems. Design of connectors and riser components are covered in Section 6.

A 200 Application

201 This standard provides design checks with emphasis on ULS, FLS, SLS and ALS load controlled conditions. Design principles for displacement controlled conditions are discussed in D 700.

202 Requirements for materials, manufacture, fabrication and documentation of riser pipe, components, equipment and structural items in the riser system are given in Section 7.

203 Mill pressure test and system pressure test shall be performed in compliance with DNV-OS-F101.

A 300 Limit States

301 The limit states are grouped into the following four categories:

- *Serviceability Limit State* (SLS) requires that the riser must be able to remain in service and operate properly. This limit state corresponds to criteria limiting or governing the normal operation (functional use) of the riser;
- *Ultimate Limit State* (ULS) requires that the riser must remain intact and avoid rupture, but not necessary be able to operate. For operating condition this limit state corresponds to the maximum resistance to applied loads with 10^{-2} annual exceedence probability;
- *Accidental Limit State* (ALS) is a ULS due to accidental loads (i.e. infrequent loads)
- *Fatigue Limit State* (FLS) is an ultimate limit state from accumulated excessive fatigue crack growth or damage under cyclic loading.

302 As a minimum requirement, the riser pipes and connectors shall be designed for (not limited to) the potential modes of failures as listed in Table 5-1 for all relevant conditions expected during the various phases of its life.

Table 5-1 Typical limit states for the riser system

<i>Limit State Category</i>	<i>Limit State</i>	<i>Failure definition/ Comments</i>
SLS	Clearance	No contact between e.g. riser-riser, riser-mooring line, riser-hull, surface tree-floater deck, subsea tree-seabed, surface jumper- floater deck.
	Excessive angular response	Large angular deflections that are beyond the specified operational limits, e.g. inclination of flex joint or ball joint.
	Excessive top displacement	Large relative top displacements between riser and floater that are beyond the specified operational limits for top tensioned risers, e.g. stroke of telescope joint, slick joint and tensioner, coiled tubing, surface equipment and drill floor. Note that systems can be designed for exceeding displacement limits if the structural integrity is maintained.
	Mechanical function	Mechanical function of a connector during make-up/break-out.
ULS	Bursting	Membrane rupture of the pipe wall due to internal overpressure only.
	Hoop buckling (collapse)	Gross plastic deformation (crushing) and/or buckling (collapse) of the pipe cross section caused by external overpressure only.
	Propagating buckling	Propagating hoop buckling initiated by hoop buckling.
	Gross plastic deformation and local buckling	Gross plastic deformation (rupture/crushing) of the pipe cross-section in combination with any local buckling of pipe wall (wrinkling) due to bending moment, axial force and internal overpressure.
	Gross plastic deformation, local buckling and hoop buckling	Gross plastic deformation and hoop buckling of the pipe cross section and/or local buckling of the pipe wall due to the combined effect of external overpressure, effective tension and bending moment.
	Unstable fracture and gross plastic deformation	Unstable crack growth or rest ligament rupture or cross section rupture of a cracked component.
	Liquid tightness	Leakage in the riser system including pipe and components.
	Global buckling	Overall column buckling (Euler buckling) due to axial compression (negative effective tension).
ALS	Same as ULS and SLS	Failure caused by accidental loads directly, or by normal loads after accidental events (damage conditions).
FLS	Fatigue failure	Excessive Miner fatigue damage or fatigue crack growth mainly due to environmental cyclic loading, directly or indirectly. Limiting size of fatigue cracks may be wall thickness (leakage) or critical crack size (unstable fracture/gross plastic deformation).

B. Load Effects

B 100 Design Load Effects

101 Design load effects are obtained by multiplying the load effect of each category by their corresponding load effect factor. Specific examples are given below for bending moment and effective tension.

102 Design bending moment for functional and environmental induced load effects:

$$M_d = \gamma_F \cdot M_F + \gamma_E \cdot M_E + \gamma_A \cdot M_A \quad (5.1)$$

where:

M_F = Bending moment from functional loads

M_E = Bending moment from environmental loads

M_A = Bending moment from accidental loads

103 Design effective tension for functional and environmental induced load effects:

$$T_{ed} = \gamma_F \cdot T_{eF} + \gamma_E \cdot T_{eE} + \gamma_A \cdot T_{eA} \quad (5.2)$$

where

T_{eF} = Effective tension from functional loads

T_{eE} = Effective tension from environmental loads

T_{eA} = Effective tension from accidental loads

Guidance note:

Accidental loads are included in the above design load effects for completeness. Normally, F+E loads and A loads is not considered simultaneously in global analyses

- end - of - Guidance - note -

104 The effective tension, T_e is given by, see Appendix A: (tensile force is positive):

$$T_e = T_w - p_i A_i + p_e A_e \quad (5.3)$$

Where

T_w = True wall tension (i.e. axial stress resultant found by integrating axial stress over the cross-section)

p_i = Internal (local) pressure

p_e = External (local) pressure

A_i = Internal cross-sectional area

A_e = External cross-sectional area

the material resistance factor in Table 5-4 can be reduced to 1.05.

end - of - Guidance - note

B 200 Load Effect Factors

201 The design load effect is used in the design checks. Several combinations may have to be checked when load effects from several load categories enter one design check. The load effect factors shown in Table 5-2 shall be used wherever the design load effect is referred to for all limit states and safety class.

Table 5-2 Load effect factors			
Limit state	F-load effect	E-load effect	A-load effect
	$\gamma_F^{1)}$	$\gamma_E^{2)}$	γ_A
ULS	1.1	1.3	NA
FLS	1.0	1.0	NA
SLS & ALS	1.0	1.0	1.0
NOTES 1) If the functional load effect reduces the combined load effects, g_F shall be taken as 1/1.1. 2) If the environmental load effect reduces the combined load effects, g_E shall be taken as 1/1.3.			

C. Resistance

C 100 Resistance Factors

101 The following resistance factors apply, (see Section 2.C):

- safety class factor γ_{SC} linked to the actual safety class and accounts for the failure consequence.
- material resistance factor γ_m to account for material and resistance uncertainties
- a condition factor γ_c to account for special conditions specified explicitly at the different limit states where relevant, see e.g. Table 5-11.

102 Unless otherwise stated, the resistance factors applicable to all limit states are specified in Table 5-3 and Table 5-4.

Table 5-3 Safety class resistance factor γ_{SC}		
Low	Normal	High
1.04	1.14	1.26

Table 5-4 Material resistance factor γ_m	
ULS & ALS	SLS & FLS
1.15	1.0

Guidance note:

For SLS, the set of resistance factors can be defined by the owner, see G.

For ALS, the set of safety factors depends on the frequency of occurrence and is to be defined from case to case, see F. In cases, where the inherent uncertainty related to the accidental load is negligible and, where a conservative estimate is applied,

C 200 Geometrical Parameters

201 The nominal outside diameter D applies in resistance calculations for all failure modes.

202 For burst and collapse pressure design checks (i.e. D 200 and D 300) the resistance shall be calculated based on wall thickness as follows:

Mill pressure test and system pressure test condition

$$t_1 = t_{nom} - t_{fab} \quad (5.4)$$

Operational condition

$$t_1 = t_{nom} - t_{fab} - t_{corr} \quad (5.5)$$

where:

t_{nom} = Nominal (specified) pipe wall thickness

t_{fab} = Fabrication (manufacture) negative tolerance

t_{corr} = Corrosion/wear/erosion allowance

203 Resistances for all other limit states related to extreme loading shall be calculated based on wall thickness as follows:

Installation/retrieval and system pressure test

$$t_2 = t_{nom} \quad (5.6)$$

Otherwise

$$t_2 = t_{nom} - t_{corr} \quad (5.7)$$

204

Guidance note:

t_1 is the minimum wall thickness and is relevant for design checks where failure is likely to occur in connection with a low capacity. t_2 is used for design checks governed by the external loading and failure is likely to occur in connection with an extreme load effect at a location with average thickness.

- end - of - Guidance - note -

205 Variation in pipe wall thickness over the design life of the riser system shall be considered in long-term fatigue damage calculations (i.e. in-place, operational condition). An average representative pipe wall thickness may be applied in nominal fatigue stress calculations. The following approximation may be applied for a stationary corrosive environment:

$$t_3 = t_{nom} - 0.5 \cdot t_{corr} \quad (5.8)$$

For fatigue damage calculations prior to permanent operation (e.g. tow-out, installation etc) the pipe wall thickness shall be taken as:

$$t_3 = t_{\text{nom}} \quad (5.9)$$

C 300 Material Strength

301 The characteristic material strength to be used in the resistance calculations f_k is given by:

Tensile circumferential material strength

$$f_k = \min \left(f_y, \frac{f_u}{1.15} \right) \quad (5.10)$$

Compressive circumferential material strength

$$f_k = f_y \cdot \alpha_{\text{fab}} \quad (5.11)$$

Longitudinal material strength

$$f_k = f_y \cdot \alpha_c \quad (5.12)$$

Where f_y and f_u denote the characteristic yield and tensile strength given in Table 5-5. Further, α_{fab} is a fabrication factor given by 305 and α_c is a strain hardening factor given by 306. Note that α_c is a function of the pressure among others.

Table 5-5 Characteristic yield and tensile strength	
Yield stress	Tensile strength
$f_y = (\text{SMYS} - f_{y,\text{temp}}) \cdot \alpha_U$	$f_u = (\text{SMTS} - f_{u,\text{temp}}) \cdot \alpha_U$
Where	
SMYS	is the Specified Minimum Yield Stress at room temperature based on the engineering stress-strain curve.
$f_{y,\text{temp}}$	is the temperature derating factor for the yield stress; see 302.
SMTS	is the Specified Minimum Tensile Strength at room temperature based on the engineering stress-strain curve.
$f_{u,\text{temp}}$	is the temperature derating factor for the tensile strength; see 302.
α_U	is the material strength factor, see 304

Guidance note:

For reeling the effect of plastic straining after the pipe mill shall be evaluated and included in the material property.

- end - of - Guidance - note -

302 The material strength (SMYS, SMTS) is normally specified at room temperature. Possible influence on the material properties from the temperature shall be considered at temperatures above room temperature. This includes:

- yield strength, i.e. $f_{y,\text{temp}}$
- tensile strength, i.e. $f_{u,\text{temp}}$
- Young's modulus;
- thermal expansion coefficient.

303 De-rated material properties at design temperatures shall be established as input to the design and verified under manufacture.

Guidance note:

If no other information on de-rating temperature effects of the yield strength exists the recommendations for C-Mn steel, 22Cr Duplex or 25Cr Duplex stainless steel in Figure 5-1 below may be used.

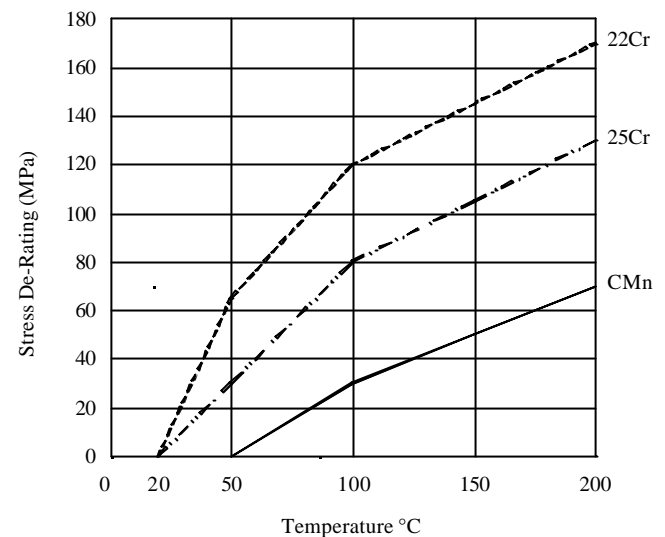


Figure 5-1 De-rating values for yield strength

Likewise, low temperature effects, e.g. during blown down in gas risers, should be considered when establishing mechanical and physical material properties.

- end - of - Guidance - note -

304 The material selection may include selection of supplementary requirement U according to DNV OS-F101. The supplementary requirement ensures increased confidence in material strength, which is reflected in a higher material strength factor α_U , given in Table 5-6.

Table 5-6 Material strength factor α_U	
Normal	Supplementary requirement U
0.96	1.00

Supplementary requirement U has a testing regime which shall ensure that SMYS is at least 2 standard deviations below the mean yield strength and that SMTS is at least 3 standard deviations below the mean tensile strength.

Guidance note:

The increased utilisation may be applied for connectors made of forging and bolts provided an equivalent testing scheme is adopted

- end - of - Guidance - note -

305 A fabrication factor α_{fab} applies to the design *compressive circumferential* yield strength for hoop buckling, local buckling and propagating buckling limit states. Unless otherwise documented, the fabrication factor α_{fab} in Table 5-7, applies for pipes manufactured by the UOE, UO or three roll bending (TRB) or similar cold deforming processes. Beneficial effect on this reduction factor due to heat treatment is allowed if documented.

Table 5-7 Fabrication factor a_{fab}		
Tensile strength or seamless pipe	Compressive strength for welded pipe	
	UOE/	UO/TRB
1.00	0.85	0.925

306 a_c is a parameter accounting for strain hardening and wall thinning given by:

$$\alpha_c = (1 - \beta) + \beta \cdot \frac{f_u}{f_y} \quad (5.13)$$

$$\beta = \begin{cases} (0.4 + q_h) & \text{for } D/t_2 < 15 \\ (0.4 + q_h)(60 - D/t_2)/45 & \text{for } 15 < D/t_2 < 60 \\ 0 & \text{for } D/t_2 > 60 \end{cases}$$

$$q_h = \begin{cases} \frac{(p_{ld} - p_e)}{p_b(t_2)} \cdot \frac{2}{\sqrt{3}} & \text{for } p_{ld} > p_e \\ 0 & \text{else} \end{cases}$$

p_{ld} is the local design pressure defined in Section 3, p_e is the external pressure and p_b is the burst resistance given in D 200.

a_c is not to be taken larger than 1.20. a_c is for illustration purpose given in Figure 5-2 in case of $(f_u/f_y) = 1.18$.

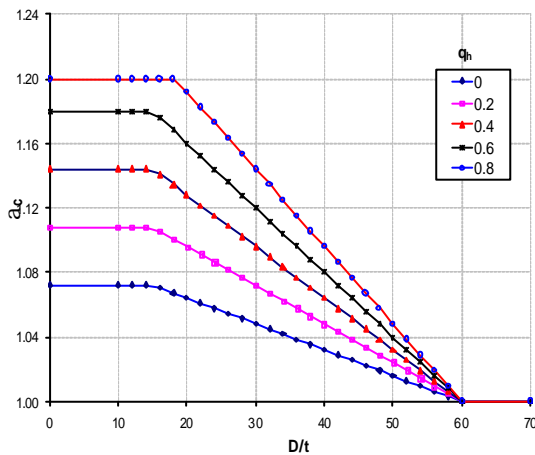


Figure 5-2 a_c versus D/t ratio and pressure ratio q_h for $(f_u/f_y) = 1.18$

D. Ultimate Limit State

D 100 General

101 The riser pipe shall be designed against relevant modes of failure listed in Table 5-1.

102 This section provides design checks with emphasis on load controlled conditions. Design principles for displacement controlled conditions are discussed in D 700.

103 If the design is based on:

- load controlled (LC) conditions
- design loads based on global riser analysis

— linear elastic and ductile materials,

accumulated plastic deformation is considered unlikely and “shake-down” can automatically be assumed

Guidance note:

A high degree of compatibility with the DNV-OS-F101 Submarine Pipeline Systems has been attempted where relevant. In general the same limit states apply for pipeline systems and dynamic riser systems but the governing failure modes differ due to different functional requirements between pipelines and risers.

Pressure and functional loads normally govern wall thickness sizing for pipelines while extreme environmental loads and fatigue govern typical dynamic riser design.

The following comments apply to this standard in relation to DNV-OS-F101:

- load combination a) in DNV-OS-F101, section 5.D 300 is not required for dynamic risers. Further, $\gamma_0=1.0$ herein;
- the additional safety class resistance factors for pressure containment for compliance with ISO is not required for dynamic risers. For compliance, see DNV-OS-F101.
- hoop buckling collapse criterion is formulated in terms of the minimum (t_1) rather than nominal (t_2) thickness;
- the propagating buckling criteria is similar but may be relaxed if the buckle is allowed to travel a short distance;
- anisotropy is not considered explicitly but the effect is implicit in the combined loading criteria for internal overpressure.

In addition a few minor differences exist.

- end - of - Guidance - note -

D 200 Bursting

201 Pipe members subjected to net internal overpressure shall be designed to satisfy the following condition at all cross sections:

$$(p_{li} - p_e) \leq \frac{p_b(t_1)}{\gamma_m \cdot \gamma_{sc}} \quad (5.14)$$

where:

p_{li} = Local incidental pressure, see Section 3

p_e = External pressure

The burst resistance p_b is given by:

$$p_b(t) = \frac{2}{\sqrt{3}} \cdot \frac{2 \cdot t}{D - t} \cdot \min \left(f_y; \frac{f_u}{1.15} \right) \quad (5.15)$$

t is a “dummy variable” to be substituted by t_1 or t_2 where relevant.

202 The local incidental pressure, p_{li} is the maximum expected internal pressure with a low annual exceedence probability, see Section 3. Normally the incidental surface pressure, p_{inc} is taken 10% higher than the design pressure, p_d , i.e.:

$$p_{li} = p_{ld} + 0.1 \cdot p_d \quad (5.16)$$

where:

p_{ld} = Local internal design pressure, see 3.B 200

203 The burst criterion is valid if the mill pressure test requirement in DNV-OS-F101 has been met. If not, a corresponding decreased utilisation shall be applied.

Guidance note:

The burst criterion is expressed in terms of the resistance for capped pipe ends. Note that the burst criterion is formulated in terms of the local incidental pressure rather than a local design pressure. Hence, the bursting limit state designs explicitly against the extreme pressure loading condition over the lifetime in compliance with standard ULS design checks. The allowable utilisation is however in compliance with recent industry practice for well-known riser types.

The nominal thickness is given by:

$$t_{nom} = t_l + t_{corr} + t_{fab}$$

when the negative fabrication thickness tolerance is absolute, t_{fab} , and

$$t_{nom} = (t_l + t_{corr}) / (1 - \% t_{fab})$$

when the negative fabrication thickness tolerance is given as a percentile of the nominal thickness, $\% t_{fab}$.

The minimum required wall thickness for a straight pipe without allowances and tolerances is given by:

$$t_l = \frac{D}{\frac{4}{\sqrt{3}} \cdot \frac{\min \left(f_y; \frac{f_u}{1.15} \right)}{\gamma_m \gamma_{SC} (p_{li} - p_e)} + 1}$$

- end - of - Guidance - note -

D 300 System Hoop Buckling (Collapse)

301 Pipe members subjected to external overpressure shall be designed to satisfy the following condition:

$$(p_e - p_{min}) \leq \frac{p_c(t_l)}{\gamma_{SC} \cdot \gamma_m} \quad (5.17)$$

Where p_{min} is a minimum internal pressure.

302 The resistance for external pressure (hoop buckling), $p_c(t)$, is given by:

$$(p_c(t) - p_{el}(t)) \cdot (p_c^2(t) - p_p^2(t)) = p_c(t) \cdot p_{el}(t) \cdot p_p(t) \cdot f_0 \cdot \frac{D}{t} \quad (5.18)$$

Solution of the equation above can be found in DNV-OS-F101. The elastic collapse pressure (instability) of a pipe is given by:

$$p_{el}(t) = \frac{2 \cdot E \cdot \left(\frac{t}{D} \right)^3}{1 - \nu^2} \quad (5.19)$$

The plastic collapse pressure is given by:

$$p_p(t) = 2 \frac{t}{D} \cdot f_y \cdot \alpha_{fab} \quad (5.20)$$

303 The initial departure from circularity of pipe and pipe ends, i.e., the initial ovality is given by:

$$f_0 = \frac{D_{max} - D_{min}}{D} \quad (5.21)$$

304 The initial ovality shall not be taken less than 0.005 (0.5%). Maximum ovality from fabrication is given in section G 200. Ovalisation caused during the construction and installation phase is to be included in the ovality. The ovalisation due to external pressure or moment in the as-installed position shall not be included.

Guidance note:

p_{min} is the local minimum internal pressure taken as the most unfavourable internal pressure plus static head of the internal fluid. For installation p_{min} equals zero. For installation with water-filled pipe, p_{min} equals p_e .

- end - of - Guidance - note -

D 400 Propagating Buckling

401 To ensure that a possible local buckle remains local and does not lead to successive hoop buckling (collapse) of neighbouring pipe sections a propagating buckling (collapse) check is required:

$$(p_e - p_{min}) \leq \frac{p_{pr}}{\gamma_c \gamma_m \gamma_{SC}} \quad (5.22)$$

where $\gamma_c = 1.0$ if no buckle propagation (once initiated) is allowed. If the buckle is allowed to travel a short distance (where the neighboring pipe section acts as buckle arrestors) γ_c may be reduced to 0.9.

The resistance against buckling propagation, p_{pr} , is given by:

$$p_{pr} = 35 \cdot f_y \cdot \alpha_{fab} \cdot \left(\frac{t_2}{D} \right)^{2.5} \quad (5.23)$$

402 If the pipe design is sufficient to meet the above propagation criterion, the system hoop buckling (collapse) criterion is also met. If conditions are such that propagating buckles are possible, means to prevent or arrest them should be considered in the design.

Guidance note:

For a pipe designed to meet the hoop buckling (external collapse) criteria outlined above, hoop buckling may still be initiated at a lower pressure by accidental means. Examples of such means would be impact or excessive bending due to tensioner failure. Once initiated, such a collapse may form a propagating buckle that will travel along the pipe until the external pressure drops below the propagation pressure or until a change in property arrests the buckle. The consequences of such a failure should be evaluated.

If buckle arrestors are in pipe sections subjected to fatigue, any fatigue degradation should be evaluated due to stress concentration factors.

Connectors and riser joints may be considered equivalent to buckle arrestors, i.e. it may not be necessary to design the riser for propagating buckling.

- end - of - Guidance - note -

System effects should be considered for installation methods involving many pipe sections being exposed to a similar loading condition. If detailed information is not available a condition factor $\gamma_c=1.05$ multiplied with γ_{sc} γ_m apply.

- end - of - Guidance - note -

D 500 Combined Loading Criteria

501 Pipe members subjected to bending moment, effective tension and net internal overpressure shall be designed to satisfy the following equation:

$$\{\gamma_{sc} \cdot \gamma_m\} \left\{ \left(\frac{|M_d|}{M_k} \cdot \sqrt{1 - \left(\frac{p_{ld} - p_e}{p_b(t_2)} \right)^2} \right)^2 + \left(\frac{T_{ed}}{T_k} \right)^2 \right\} + \left(\frac{p_{ld} - p_e}{p_b(t_2)} \right)^2 \leq 1 \quad (5.24)$$

where:

- M_d = Design bending moment, see B 100
- T_{ed} = Design effective tension, see B 100
- p_{ld} = Local internal design pressure, see 3.B 200
- p_e = Local external pressure

M_k is the (plastic) bending moment resistance given by:

$$M_k = f_y \cdot \alpha_c \cdot (D - t_2)^2 \cdot t_2 \quad (5.25)$$

T_k is the plastic axial force resistance given by:

$$T_k = f_y \cdot \alpha_c \cdot \pi \cdot (D - t_2) \cdot t_2 \quad (5.26)$$

$p_b(t_2)$ is the burst resistance given by Eq. (5.15).

Guidance note:

The failure modes controlled by this limit state comprise yielding, gross plastic deformation and wrinkling due to combined loading.

The design criterion may be viewed as a (plastic) Von Mises criterion in terms of cross sectional forces and plastic cross sectional resistance. It is equivalent to the plastic limit bending moment capacity (including the effect of strain hardening and wall thinning) for $(T_{ed}/T_k) \ll 1$. It reduces to the traditional wall thickness Von Mises criterion, see e.g. API RP 2RD, for pressure and effective tension load effects only.

- end - of - Guidance - note -

502 Pipe members subjected to bending moment, effective tension and net external overpressure shall be designed to satisfy the following equation:

$$\{\gamma_{sc} \cdot \gamma_m\}^2 \left\{ \left(\frac{|M_d|}{M_k} \right)^2 + \left(\frac{T_{ed}}{T_k} \right)^2 \right\} + \{\gamma_{sc} \cdot \gamma_m\}^2 \left(\frac{p_e - p_{min}}{p_c(t_2)} \right)^2 \leq 1 \quad (5.27)$$

Where the hoop buckling capacity $p_c(t)$ is given by Eq. (5.18).

Guidance note:

The failure modes controlled by this semi-empirical limit state is yielding and combined local buckling and hoop buckling due to combined bending, tension and external over-pressure.

D 600 Alternative WSD Format

601 As a more easy-to-use alternative the following Working Stress Design (WSD) format may be used for the combined loading check for pipes with D/t ratio less than 30. The present WSD is based on explicit limit states for combined loading and provides results on the conservative side compared to the corresponding LRFD limit states.

602 For the WSD format the design load effects equals the corresponding characteristic load effect, i.e. the load effect factors and resistance factors equals unity: $\gamma_F = \gamma_E = \gamma_A = \gamma_{sc} = \gamma_m = 1.0$. Instead, the basic usage factor shown in Table 5-8 apply:

Table 5-8 Usage factor h for combined loading		
Low	Normal	High
0.83	0.79	0.75

603 Pipe members subjected to bending moment, effective tension and net internal overpressure shall be designed to satisfy the following equation:

$$\left\{ \left(\frac{|M|}{M_k} \cdot \sqrt{1 - \left(\frac{p_{ld} - p_e}{p_b(t_2)} \right)^2} \right)^2 + \left(\frac{T_e}{T_k} \right)^2 \right\} + \left(\frac{p_{ld} - p_e}{p_b(t_2)} \right)^2 \leq \eta^2 \quad (5.28)$$

where all parameters are defined in D 500.

604 Pipe members subjected to bending moment, effective tension and net external overpressure shall be designed to satisfy the following equation:

$$\left(\left(\frac{|M|}{M_k} \right)^2 + \left(\frac{T_e}{T_k} \right)^2 \right)^2 + \left(\frac{p_e - p_{min}}{p_c(t_2)} \right)^2 \leq \eta^4 \quad (5.29)$$

D 700 Displacement Controlled Conditions

701 Loads and load effects may be classified as follows:

- Load Controlled conditions (LC or primary), or
- Displacement Controlled conditions (DC secondary) or
- combined load types.

702 A load-controlled condition is one in which the structural response is primarily governed by the imposed loads.

703 A displacement-controlled condition is one in which the structural response is primarily governed by imposed geometric displacements.

704 Displacement controlled conditions should be subdivided into:

- conditions with *static* (functional and pressure) loads;
- conditions with *dynamic* (environmental) loads

705 In *static* DC loading conditions the following fundamental design principles apply:

- the primary load effect (i.e., LC part of the load effect) shall fulfil the load controlled criteria in this standard ignoring the secondary load effects (i.e., DC part of load effect);
- the total (primary and secondary) load effect must be checked against the strain limits and acceptance criteria for displacement controlled conditions in DNV-OS-F101;
- accumulated plastic deformation must be considered.

706 In *dynamic* DC loading conditions (low-cycle) fatigue often becomes the limiting condition for extreme loading conditions. A more rational and fundamental design principle is to require that inelastic displacements caused by cyclic loads is not allowed. Hence, the total strain must be confined to the elastic region.

707 If the bending moment can be assumed secondary a condition factor $\gamma_c=0.85$ may be multiplied on the bending moment in D 500 and D 600.

Guidance note:

Examples where bending stress may be considered secondary:

- a riser bent into conformity with a continuous curved structure such as a reel.
- in areas where the geometric equilibrium shape of the riser is not influenced by the bending stiffness (i.e. governed by the geometric stiffness due to the effective tension).

The latter must be documented by analysis with and without bending stiffness for both static and dynamic loading conditions.

- end - of - Guidance - note -

708 Displacement controlled conditions must be documented. Pipe sections and components subjected to inelastic deformations shall be designed with due consideration of accumulated plastic deformation (ratcheting) such as incremental hoop buckling (accumulated ovality) and plastic (low cycle and ultra low cycle) fatigue.

E. Fatigue Limit State

E 100 General

101 The riser system shall have adequate safety against fatigue within the service life of the system. Reference is made to section 4 and **Appendix B** for more details with respect to fatigue design and analysis.

102 All cyclic loading imposed during the entire service life, which have magnitude and corresponding number of cycles large enough to cause fatigue damage effects, shall be

taken into account. Temporary phases like transportation, towing, installation, running and hang-off shall be considered.

103 All critical sites for anticipated crack initiation for each unique component along the riser shall be evaluated. These sites normally include welds and details that causes stress concentrations.

104 The fatigue assessment methods may be categorised into:

- methods based on S-N curves (see E 200);
- methods based on fatigue crack propagation; calculations (see E 300).

105 Normally, the methods based on S-N curves are used during design for fatigue life assessment. Fatigue crack propagation calculations may be used to estimate fatigue crack growth life and to establish NDT inspection criteria to be applied during both fabrication and in-service.

106 If representative fatigue resistance data are not available, a direct fatigue testing of the actual components shall be performed with due regard of the chemical composition of the internal and external environment.

107 The stress to be considered for fatigue damage accumulation in a riser is the *cyclic* (i.e., time-dependent) principal stress.

108 The governing cyclic nominal stress component, σ for pipes is normally a linear combination of the axial and bending stress given by:

$$\sigma = \frac{T_e}{\pi \cdot (D - t_3) \cdot t_3} + \frac{32 \cdot M \cdot (D - t_3)}{\pi \cdot (D^4 - (D - t_3)^4)} \quad (5.30)$$

109 This combined stress varies around the circumference of the riser pipe. For cases where the waves are incident from several different directions, the fatigue damage must hence be calculated at a number of regularly spaced points to identify the most critical location.

E 200 Fatigue assessment using S-N curves

201 When using the calculation methods based on S-N curves, the following shall be considered:

- assessment of short-term distribution of nominal stress range ;
- selection of appropriate S-N curve ;
- incorporate thickness correction factor;
- determination of stress concentration factor (SCF) not included in the S-N curve, see e.g. DNV-RP-C203
- determination of accumulated fatigue damage D_{fat} over all short term conditions.

202 The fatigue criterion, which shall be satisfied, may be written:

$$D_{fat} \cdot DFF \leq 1.0 \quad (5.31)$$

where

$$D_{fat} = \text{Accumulated fatigue damage (Palmgren-}$$

Miner rule)

DDF = Design fatigue factor, see Table 5-9

Table 5-9 Design fatigue factors DFF		
Safety class		
Low	Normal	High
3.0	6.0	10.0

203 The design S-N curve shall be based on the mean-minus-two-standard deviations curves for the relevant experimental data, see DNV-RP-C203.

E 300 Fatigue assessment by crack propagation calculations

301 A damage tolerant design approach applies. This implies that the riser components shall be designed and inspected so that the maximum expected initial defect size would not grow to a critical size during service life or time to first inspection. Crack propagation calculations typically contain the following main steps:

- determination of long-term distribution of nominal stress range ;
- selection of the appropriate crack growth law with appropriate crack growth parameters. Crack growth parameters (characteristic resistance) shall be determined as mean plus 2 standard deviations.
- estimation of the initial crack size and geometry and/or any possible time to crack initiation. Best estimate initial crack size (mean value) shall be applied. Crack initiation time is normally neglected for welds ;
- determination of cyclic stress in the prospective crack growth plane. For non-welded components the mean stress shall be determined;
- determination of final or critical crack size (through the thickness, unstable fracture/gross plastic deformation) ;
- integration of the fatigue crack propagation relation with respect to the long-term stress range distribution to determine the fatigue crack growth life.

302 The fatigue crack growth life shall be designed and inspected to satisfy the following condition:

$$\frac{N_{tot}}{N_{cg}} \cdot DDF \leq 1.0 \quad (5.32)$$

where:

- N_{tot} = total number of applied stress cycles during service or to in-service inspection
- N_{cg} = Number of stress cycles necessary to increase the defect from the initial to the critical defect size
- DDF = Design fatigue factor, see Table 5-9.

303 The assumed initial defect size, $a_i/2c_i$ for surface defects and $2a_i/2c_i$ for embedded defects, is the expected value of defects left after fabrication and NDT. The

expected initial defect size (mean value) shall be established based on an evaluation of the detection capability of the inspection method, access for inspection during fabrication, the thickness and geometry of the structure, manufacture method, surface finish, welding method, full or partial penetration weld and the number of passes used to complete the weld.

304 The maximum acceptable initial crack size may be used to evaluate detection limits of NDT methods for the actual component.

Guidance note:

For surface cracks starting from the transitions between weld/base material, a crack depth of 0.1 mm (e.g. due to undercuts and micro-cracks at bottom of undercuts) may be assumed if other documentation about crack depth is not available. The surface crack depth to total defect length ($a_i/2c_i$) should be assumed low (less than 1:5) if no other documentation is available. Light grinding of hot spot areas should be considered to remove undercuts and increase reliability of the inspection, see [Appendix B](#).

For single sided girth welds, lack of penetration defects is hard to detect by NDT. Crack depths in the range of 1 to 2 mm may be hard to find. Using a reliable welding procedure is important for such cases, especially for the root pass. Machining off the root pass is considered to significantly improve the fatigue quality.

Some codes have reduced life requirements for fatigue crack growth vs. SN, e.g. a factor of 5 for fatigue crack growth versus 10 for S-N. Note that these codes defines the initial crack size to be based on the 90 % probability of inspection level for the applied NDT method and not the mean level as applied in this standard.

- end - of - Guidance - note -

E 400 In-service Fatigue Inspections

401 The S-N curve approach may be used for screening purposes to identify the most likely regions where fatigue cracks may appear during service. Time to first in-service inspection may be based on crack growth versus time results with the criteria given in Table 5-9 in combination with fabrication/installation records. The in-service inspection plans after first inspection shall be based on the inspection results obtained and the plans updated accordingly. For defects found, fatigue crack calculations to establish residual life shall be based on the sizing accuracy of the applied method and the expected value shall be used for fatigue assessment.

402 Necessary data shall be logged during the life cycle for documenting and analysis of fatigue status for temporary risers. The log shall typically include running sequence of joints, riser configuration, field data (water depth, pressure, density, etc.), floater data including top tension and the length of time and sea-state for each mode of operation. This log shall be reviewed regularly to assess the need for fatigue crack inspections.

403 In-place NDT or removal of the riser for dry inspection is considered acceptable means of inspection.

F. Accidental Limit State

F 100 Functional requirements

101 The Accidental Limit State (ALS) is a limit state due to accidental loads or events. Accidental loads shall be understood as loads to which the riser may be subjected in case of abnormal conditions, incorrect operation or technical failure. Accidental loads typically results from unplanned occurrences. Normally, the following design checks apply:

- resistance against direct accidental load. (Typically discrete events with an annual frequency of occurrence less than 10^{-2});
- ultimate resistance and consequence assessment due to exceedence of a SLS introduced to define operational limitations;
- post-accidental resistance against environmental loads (if the resistance is reduced by structural damage caused by the accidental loads).

102 Relevant failure criteria and accidental loads in terms of frequency of occurrence and magnitude shall be determined based on risk analyses and relevant accumulated experiences. Account shall be taken of other loads that might reasonably be present at time of the accidental event. Further, accidental loads shall be determined with due account of the factors of influence. Such factors may be personnel qualifications, operational procedures, the arrangement of the installation, equipment, safety systems and control procedures.

F 200 Categories of accidental loads

201 Accidental loads may be categorised into (not limited to):

- fires and explosions
- impact/collisions, such as:
 - infrequent riser interference (see H 100)
 - impact from dropped objects and anchors
 - impact from floater/floating objects
- hook/snag loads, such as :
 - dragging anchor
- failure of support system, such as :

- heave compensating system malfunction (loss or stuck), e.g. tension system or draw works motion compensator
- loss of buoyancy, e.g. air cans for spar units
- loss of mooring line, tendon or guidewire
- dynamic positioning (DP) failure (drive-off or drift off)
- exceedence of incidental internal overpressure:
 - loss of pressure safety system
 - failure of well tubing or packers, etc.
 - pressure surge
 - well kill – bullheading
- environmental events
 - earthquake
 - tsunamis
 - iceberg

Guidance note:

Environmental load conditions with a 10 000 year return period as a normal “tail” behaviour in the long term probability distribution function is implicit in the ULS design criteria and need not be considered as an accidental (or abnormal) load condition for risers.

Accidental environmental events should be assessed assuming 1) a return period value with reasonable likelihood of not being exceeded during the design life (e.g. 200 years) and 2) a rare intense event (e.g. earthquake) with recurrence interval from several hundred to a few thousand year.

- end - of - Guidance - note -

F 300 Characteristic accidental load effects

301 Accidental loads and load effects are determined by the frequency of occurrence and their magnitude. Loads occurring at the time of an accidental event do not normally need to be assumed concurrent with an extreme environmental load condition. However, the damaged structure resulting from an accidental load event shall be able to resist relevant pressure and functional loads in an extreme environmental load condition. Characteristic accidental load effects and load combinations for different operating modes are given in Table 5-10.

Table 5-10 Characteristic accidental load effects and combinations for different operational modes					
Limit State Category	Mode of Operation	Load effect category			
		P-loads	F-loads	E-loads	A-loads
ALS Intact Structure	Not Operating	Expected value	Expected value associated with the A-loads.	Expected specified or expected extreme value associated with the A-loads.	Value dependent on measures taken and magnitude and probability of occurrence.
	Operating	Characteristic design pressure or incidental as suitable.			
ALS Damaged Structure	Temporary, Not Operating	Expected value	¹ Combined load effect defined with an annual probability of exceedence = 10 ⁻¹		Not applicable
	Operating	Characteristic design pressure or incidental as suitable.			
NOTE 1) E-loads may be determined on weather forecast if time to repair is short and protective measures can be taken. If the repair period is confirmed to a season, the probability of exceedence may be relaxed i.e., E-loads may relate to a season rather than a year.					

F 400 Design against accidental loads

401 The design against accidental loads may be done by direct calculation of the effects imposed by the loads on the structure, or indirectly, by design of the structure as tolerable to accidents. Example of the latter is tensioner failure where the tensioner shall provide sufficient integrity to survive certain environmental scenarios without further progressive collapse.

402 Design with respect to accidental load must ensure that the overall failure probability complies with the target values in Table 2-5. This probability can be expressed as the sum of the probability of occurrence of the i'th damaging event, P_{Di} , times the structural failure probability conditioned on this event, $P_{f|Di}$. The requirement is accordingly expressed as:

$$\sum P_{f|Di} \cdot P_{Di} \leq P_{f,T} \quad (5.33)$$

where $P_{f,T}$ is the target failure probability according to Table 2-5. The number of discretisation levels must be large enough to ensure that the resulting probability is evaluated with sufficient accuracy.

403 The inherent uncertainty of the frequency and magnitude of the accidental loads, as well as the approximate nature of the methods for determination of accidental load effects, shall be recognised. Sound engineering judgement and pragmatic evaluations are hence required.

404 A simplified design check with respect to accidental load may be performed as shown in Table 5-11 below multiplied on appropriate load effect factors selected according to Table 5-2 and resistance factors according to Table 5-3 and Table 5-4. The adequacy of simplified design check must be assessed based on the summation above in order to verify that the overall failure probability complies with the target values in Table 2-5.

Table 5-11 Simplified Design Check for Accidental loads			
Prob. of occurrence	Safety Class Low	Safety Class Normal	Safety Class High
$>10^{-2}$	Accidental loads may be regarded similar to environmental loads and may be evaluated similar to ULS design check		
$10^{-2} - 10^{-3}$	To be evaluated on a case by case basis		
$10^{-3} - 10^{-4}$	$\gamma_c = 1.0$	$\gamma_c = 1.0$	$\gamma_c = 1.0$
$10^{-4} - 10^{-5}$	Accidental loads or events may be disregarded	$\gamma_c = 0.9$	$\gamma_c = 0.9$
$10^{-5} - 10^{-6}$		$\gamma_c = 0.8$	
$<10^{-6}$			

Guidance note:

Standard industry practice assumes safety factors equal to 1.0 for accidental event with a probability of occurrence equal to 10^{-4} and survival of the riser is merely related to a conservative definition of characteristic resistance. In this standard accidental loads and events are introduced in a more general context with a link between probability of occurrence and actual failure consequence. For combined loading, the simplified design check proposes a total safety factor in the range 1.1-1.2. This range is consistent with standard industry practice interpreted as corresponding to safety class Normal for accidental loads with a probability of occurrence equal to 10^{-4} .

The ALS analysis may provide extreme loads for the design of wellhead and rig equipment, and identify the need for deliberately introducing weak links in the system. Such weak links may be required to ensure that unacceptable escalation, i.e. controlled riser failure above the subsea valve, does not occur in case of accidents (in particular floater drive-off or drift-off events or failure of draw works heave compensation system). When maximum load is calculated in a potentially weak link, a high characteristic value for the resistance of the link should be used.

- end - of - Guidance - note -

G. Serviceability Limit State

G 100 General

101 Serviceability limit states are most often associated with determination of acceptable limitations to normal operation. In many cases, the Owner will specify requirements however, the designer must also carry out evaluations with respect to riser serviceability and identify relevant SLS criteria for the riser system.

Guidance note:

FMEA, HAZOP and design review meetings are useful systematic procedures that can lead to identification of SLS and for reviewing the consequences of setting operating limitations and of exceeding those limitations.

- end - of - Guidance - note -

102 It is important that all operating limitations and/or design assumptions are clearly highlighted and implemented in the operating procedures.

103 Exceeding a SLS shall not lead to failure and an ALS shall be defined in association with exceedance of SLS. In addition, the frequency and consequences of events after exceeding an SLS shall be evaluated. Such events will typically be controlled by maintenance/inspection routines and by implementation of early warning or fail-safe type systems in the design.

104 Serviceability limit states for the global riser behaviour are associated with limitations with regard to deflections, displacements and rotation of the global riser or ovalisation of the riser pipe. Some examples are given in the subsequent sections.

G 200 Ovalisation limit due to bending

201 Risers shall not be subjected to excessive ovalisation and this shall be documented. In order to prevent premature local buckling, the flattening due to bending together with the out-of-roundness tolerance from fabrication of the pipe shall be limited to 3.0 %:

$$f_0 = \frac{D_{\max} - D_{\min}}{D_o} \leq 0.03 \quad (5.34)$$

202 The requirement may be relaxed if:

- a corresponding reduction in moment resistance has been included;
- geometrical restrictions are met, such as pigging and tool access requirements; and
- additional cyclic stresses caused by the ovalisation have been considered.

203 Ovalisation shall be checked for point loads at any point along the riser system. Such point loads may arise at

free-span shoulders, artificial supports and support settlements.

204 Special consideration shall be made of ovalisation after loading causing plastic strains, e.g. reeling, unreeling of pipes and riser interference/impact.

G 300 Riser stroke

301 For a top tensioned riser, a tensioner pulls upward on the top part of the riser in order to limit bending and maintain constant tension. The tensioner must continue to pull as the riser and the floater move vertically relative to each other. The travel of the tensioner is called its 'stroke'. Riser stroke influences the design requirements for tensioner, draw works, clearance between surface equipment and drill floor, length of slick joint, etc.

302 Riser systems shall be designed to have sufficient stroke such that damages to riser, components and equipment are avoided.

303 The up- and down-stroke calculations must include effects from environmental response, tension, pressure (end cap effects), temperature, tide, storm surge, swell, make-up (riser production tolerances), set down/pull down effects and floater draught. For permanent risers, effects from subsidence and settlements shall be evaluated.

304 Environmental response includes static and dynamic stroke. The static stroke is due to current loading and set down effect due to floater mean offset. The floater mean offset includes effects from static wind and mean wave drift. The wave loading introduces relative motions between the floater and the riser, i.e. dynamic stroke.

305 The most unfavourable fluid density shall be considered. Additionally, tension changes and length variations needs to be taken into account.

G 400 Examples

401 Examples of SLS for drilling and work-over riser with subsea BOP are outlined in the following Table 5-12.

402 Examples when drilling with a surface BOP (e.g. TLP, SPAR) the riser is part of the well control system and may not be disconnected and hung-off. Some examples of how this may influence SLS are summarised in Table 5-13.

403 Examples for export and import riser serviceability limits should be set for riser installation and pigging, see Table 5-14.

404 Examples for a production riser with a surface tree the riser is part of the well control system and may not be disconnected and hung-off. Some SLS examples are given in Table 5-15.

405 Other serviceability limits may be determined to limit the degradation of riser coatings and attachments or for allowances due to wear and erosion.

Table 5-12 Examples of SLS for drilling and work-over with subsea BOP			
	<i>Function</i>	<i>SLS criteria</i>	<i>Comment</i>
Flex-joint or ball joint Operating limits for specific operations	Drilling with fluid returns	Limit fatigue on drill string and wear on wellhead/riser	Usually monitor flex-joint angle and follow weather forecast and adjust mooring to minimise joint angle
	Guide tools or assemblies into the well	Excessive angle may result in getting stuck or not being able to land the string properly	Due to tight tolerances
	Over-pull	Avoid overloading the wellhead, BOP and connectors	Over-pull may be used to check that a connector is made up properly or in an attempt to release a stuck string
	Disconnect and Hang off	Approaching the resistance of the wellhead/BOP and connectors	For a normal hang-off scenario sufficient time shall be allowed for pulling the down-hole string
Riser stroke	Hang off	Approaching the resistance of the tensioner system	Weather is resulting in excessive platform motion and offset.
Umbilical, choke, kill and other attachments	BOP and well control	Avoid damage	Risk and consequences of damage may govern criteria for interference

Table 5-13 Examples of SLS for drilling and work-over with surface BOP			
	<i>Function</i>	<i>SLS criteria</i>	<i>Comment</i>
Flex-joint or Stress-joint Operating limits for specific operations	Drilling with fluid returns	Limit fatigue on drill string and wear on wellhead/riser	Usually monitor flex-joint angle or stress-joint curvature. It is not normally feasible to adjust moorings
	Guide tools or assemblies into the well	Excessive angle may result in getting stuck or not being able to land the string properly	Due to tight tolerances
	Over-pull	Avoid overloading the wellhead, BOP and connectors	Over-pull may be used to check that a connector is made up properly or in an attempt to release a stuck string
Riser installation	Running and retrieving the riser	A weather limitation would be set to avoid riser interference	Usually run on guide-wires in close proximity to other risers

Table 5-14 Examples of SLS for export and import risers			
	<i>Function</i>	<i>SLS criteria</i>	<i>Comment</i>
Riser installation	Running and retrieving the riser	A weather limitation would be set to avoid riser interference	Usually run on guide-wires in close proximity to other risers
Pigging	Inspection or cleaning	Pig launching and associated temporary loading	

Table 5-15 Examples of SLS for production risers with surface tree			
<i>Component</i>	<i>Function</i>	<i>Reason for SLS</i>	<i>Comment</i>
Riser installation	Running and retrieving the riser	A weather limitation would be set to avoid riser interference	Usually run on guide-wires in close proximity to other risers
Riser stroke	Limit the frequency of bottom-out	The tensioner may be designed for bottom-out	Energy absorption criteria shall be specified
	Limit the design requirements for the jumper from the surface tree to the topside piping	The tensioner may be designed for bottom-out	Energy absorption criteria shall be specified

H. Special Considerations

H 100 Interference

101 The riser system design shall include evaluation or analysis of potential interference with other risers, mooring lines, tendons, hull, the seabed, and with any other

obstruction. Interference shall be considered during all phases of the riser design life.

102 A feasible design approach may be categorised into:

- No Collisions allowed
- Collisions allowed

103 A first step is hence to determine whether collisions are likely to occur or not. If collision occur, it must be documented that the structural integrity is not endangered, i.e. the pipe capacity is sufficient for both SLS and ULS (incl. ALS & FLS) conditions. This requires an assessment of collision frequency, location, force impulse or relative riser velocity prior to the impact. Separate local calculations/analyses will in general be required for assessment of pipe stresses during impact.

Guidance note:

Owing to the complexity of interference analyses, due balance between simplified- and advanced analyses is recommended to obtain efficient analyses:

- screening analyses using a simplified approach to identify critical conditions or configurations;
- detailed analyses of identified critical conditions or components using state-of-the-art interference analyses.

Screening analyses may imply use of

- simplified environmental loads, e.g. current only, simple profile without directionality;
- simplified Wake Induced Oscillation (WIO) and Vortex Induced Vibration (VIV) models for current only or undisturbed flow models for waves;
- simplified onset of collision criteria.

Detailed analyses for criticality assessment of collisions may include:

- hydrodynamic interaction models;
- global collision models;
- dedicated CFD calculations;
- explicit collision load effect models;
- explicit limit-state design criteria..

- end - of - Guidance - note -

104 Model testing for verification of structural capacities, hydrodynamic interaction models and global analysis methodology is recommended.

H 200 Unstable Fracture and Gross Plastic Deformation

201 Pipe members, including components and girth welds shall have adequate safety due to unstable fracture for a representative part or through-wall crack during the service life of the riser.

202 Defect assessment of crack like defects should normally be performed in accordance with BS 7910 Level 2A failure assessment diagram Partial safety factors for flaw size, fracture toughness and yield strength should be as given in BS 7910, Appendix K, Table K2 while load effect factors shall be in accordance with B 200.

Guidance note:

The partial factors in Table K2 in BS 7910 annual target probabilities of 10^{-3} , $7 \cdot 10^{-5}$, and 10^{-5} correspond to those for safety class Low, Normal and High given in this standard.

- end - of - Guidance - note -

203 Defects assessment at fatigue sensitive locations shall be additional to fatigue crack evaluations, see E.

Guidance note:

Fatigue failure in the S-N curve approach, see E 200, is normally based on through wall cracks. Where through wall cracks are applied as failure criteria, it should be ensured that through wall cracks should not cause unstable fracture.

Normally, brittle fracture in riser systems is avoided by selection of material with sufficient ductility and Charpy V notch impact energy and by performing NDT during fabrication to ensure that only acceptable defects are present in the riser system after fabrication.

Unstable fracture may occur under unfavourable combinations of geometry, fracture toughness, crack like welding defects and stress levels. The risk of unstable fracture increases in general when the state of "plain strain" is approached at the crack tip. This occurs in general with large material thickness, low temperature, high loading rates, high strength material and deep cracks subjected to bending. Fracture toughness data as KIC, JIC or CTODC values are necessary to perform defect assessment.

The failure assessment diagram is a two-criteria failure model that considers unstable fracture, gross plastic deformations (plastic limit load), and the interaction between these mechanisms.

- end - of - Guidance - note -

204 For ALS evaluations, normally no partial load effect factors are required for load effects, flaw size and toughness, i.e. all partial safety factor shall be taken as unity. Normally, the riser pipe is designed based on the principle that plastic hinges may develop without giving rise to unstable fracture. In such case, the nominal stress for unstable fracture shall not be less than the design (yield) stress of the member.

H 300 Global Buckling

301 Global buckling (Euler buckling) implies buckling of the pipe as a beam-column in compression. The procedure is as for "ordinary" compression members in air using the concept of effective tension.

302 A negative effective tension may cause a riser to buckle as a beam-column in compression. Distinction shall be made between load-controlled and displacement-controlled buckling. Excessive load-controlled buckling involves total failure and is not accepted while a displacement controlled buckling may be acceptable if the post-buckling condition is acceptable.

303 The global buckling resistance for load-controlled condition may be calculated according to recognised stability criteria in structural design codes, e.g. ISO 13819-2.

304 Displacement-controlled buckling may be acceptable, provided it does not result in other failure modes. This implies that global buckling may be acceptable provided that:

- local buckling criteria are fulfilled in the global post buckling configuration;
- displacement/curvatures/angles of the riser are acceptable and
- cyclic effects are acceptable.

305 Special care shall be given when a small decrease in top tension of a top-tensioned metallic riser could cause excessive bending moment. In that case, the designer shall establish a minimum effective tension that gives a margin above the tension that is predicted to cause excessive bending moments.

Guidance note:

It is essential that an appropriate tensioned-beam model is used for the analysis of global buckling. The consequence of a too-small positive effective tension is excessive curvature and

bending moment near the location of minimum effective tension.

Note that members above the tension joint for top tensioned risers may be subjected to compressive forces for some riser types

- end - of - Guidance - note -

SECTION 6 CONNECTORS AND RISER COMPONENTS

Contents

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B. Connector Designs

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B 200 Design and Qualification Considerations

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B 400 Local Analysis

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C 100 Documentation

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A. General

A 100 Objective

101 This section gives requirements in relation to design, analysis and qualification of metal connectors and components used in riser design. The requirements apply also to other riser components and at transitions to the pipe wall thickness. Reference is made to ISO/CD 13628-7 for further details on design, analysis and requirements.

Relevant sections include 5.8, 6.5 and 6.8.

102 The aim of the design is to ensure that the connectors and riser components have adequate structural resistance, leak tightness and fatigue resistance for all relevant load cases. Resistance against accidental loads such as fire and impact shall also be considered when applicable.

Guidance note:

Riser connectors basically provide a means of connecting and disconnecting riser joints or equipment. The most commonly used types of riser connector design comprises:

- threaded types;
- hub type;
- dog types, and
- bolted flanges designed for face-to-face contact.

- end - of - Guidance - note -

B. Connector Designs

B 100 Functional Requirements

101 Riser connectors shall allow for multiple makeup and breakout in a reliable manner. The connector may permit for interchangeability between connector halves to allow riser joints to be run in any sequence.

102 The external profile of all riser components shall not restrict the passage of equipment like guideframes and specialised tooling required for riser installation/retrieval, inspection and maintenance, if applicable.

103 For permanent risers, provisions shall be made on the riser joint/connector to allow for attachment of an anode (bracelet). Electrical connection to the riser shall be made by welding or other qualified method, and shall be made to a low stress part of the connector. Other methods may be used.

104 The riser pipe and components shall provide an internally flush bore to ease running components into a well, pigging and maintenance operation when applicable.

105 The design shall ensure that any trapped water/fluid does not interfere with the installation or operation of the connector.

106 For further functional requirements see ISO/CD 13628-7 Section 5.8

B 200 Design and Qualification Considerations

201 Connectors shall be designed to sustain the design loads and deformations arising from make-up/break-out, external loads applied to the pipe body, thermal gradients and internal and external pressure loads without exceeding the connector design resistance. All relevant limit states must be considered.

202 The connectors should be designed to be at least as strong as the pipe or weld with respect to strength, fatigue, leakage and fire resistance.

203 As a minimum, the following loading parameters/conditions shall be considered and documented by the manufacturer when designing connectors and components:

- make-up loads;
- internal and external pressure including test pressure;
- bending moments and effective tensions;
- cyclic loading;
- thermal load effects (trapped fluid/water, dissimilar metals) and thermal transients;
- break-out loads.

204 Issues which may require considerations in ULS and ALS, include (not limited to):

- local buckling;
- unstable fracture and excessive yielding;
- leak tightness;
- thread disengagement.
- galling tendency between sliding elements

205 Deformations, deflections and finish damage, which adversely affects the use, may require consideration in SLS.

206 The FLS capacity shall be verified to ensure that the connector will not fail due to cyclic loading, see ISO/CD 13628-7 section 6.5.3.

207 For connectors intended to be used in corrosive environment, either the connector including components shall be designed in such a way that an acceptable corrosion control can be implemented at the joint, or the connector shall be constructed of, or coated with, a corrosion-resistant material.

208 All riser connectors shall be qualified for the application based on finite element analysis in combination with performance qualification testing. Using analytical or numerical calibration of the qualified connector, representative connectors of the same type may be designed by analytical methods (design equations) in combination with finite element analysis whenever necessary.

209 Connector make-up shall be performed according to a qualified procedure considering factors, such as friction, lubrication, etc., in order to reduce the uncertainty in the preload of the connector and ensure that the preload is within the design limits.

Guidance note:

It is considered reasonable that the analysis or tests, which should be carried out on connectors to be used on risers, should demonstrate fit for purpose of their function. This does not necessarily mean they have to be as strong and reliable as the connecting pipe or weld. For static strength, plastic hinge may preferably develop in the pipe before failure of the connector occurs in order to increase the ductility in the riser system. However, the minimum requirements are given above.

In cases where "weak links" are introduced to protect components against accidental loads, i.e. drive-off, drift-off or tensioner system failure, a connector with known breaking resistance may be applied.

- end - of - Guidance - note -

B 300 Seals

301 Connectors shall provide a seal between the mating segments that is compatible with any fluids that will pass through the riser. The seal must maintain its integrity under all external and internal loading conditions. Seal designs are either integral or non-integral. Integral seals are built into the connector and are non-replaceable. Non-integral seals use separate seal elements that can be removed and replaced.

302 Seal design for connectors and riser components shall include consideration of external pressure. Seal design shall also consider operating conditions what may result in frequent changes in the external loads and internal pressures, which combined with external pressure results in frequent pressure reversals on sealing mechanism. All operating conditions (i.e. commissioning, testing, start-up, temperature, operation, blow-down, etc.) shall be considered.

303 Seal rings wetted with internal fluid shall include the same internal corrosion allowance as the connecting pipe and be of compatible material. Alternatively, seals and sealing surface shall be corrosion resistant in the actual environment.

304 The seal and the connector including any bolts and preload shall be considered together as a system to determine the sealing performance. The effect of sealing performance by the connector includes effects such as torque of pin/box connectors and bolt resistance and preload.

305 Metal-to-metal seals are preferred as the primary seals on riser connectors. For permanent risers where metal-to-metal seals are not utilised, redundant seals (primary plus backup) should be provided.

306 Seals for riser connectors should be static, i.e. sealing should take place between surfaces which have little or no movement relative to each another.

307 Connectors exposed to cyclic loading shall utilise non-load-carrying seals in order to maintain high reliable against leakage with time.

308 Seals of high reliability should be used to confine flammable fluids, fluids under high pressure and corrosive fluids. Seals must be selected with consideration to the required service life, the service exposure in terms of chemical aggressiveness and temperature as well as pressure and relative displacements that need to be accommodated.

Guidance note:

All seals are sensitive to damage during handling, installation and re-assembly. A single seal therefore may have modest reliability. To enhance the reliability, a double seal may be provided. To achieve redundancy, the two seals should be of a different design without common failure modes.

- end - of - Guidance - note -

B 400 Local Analysis

401 Local FE analysis should be performed for connectors and structural components, including landing blocks, taper joints, tension joints, flex/ball joints, slick joints, complex riser joint cross sections (multiple pipes). Loads and boundary conditions for use in local analysis shall be obtained from the global analysis procedure. Guidance on FE analysis of connectors and riser components is given in ISO/CD 13628-7 section 6.8.

402 The most unfavourable combination of specified tolerances shall be used in connection with FE analysis for strength, leakage and fatigue (SCF's),

C. Documentation

C 100 Documentation

101 The documentation for the connector shall as a minimum comply with the requirements of ISO/CD 13628-7 section 6.8.15.

C 200 Operating and maintenance manuals

201 The documentation for the connector shall as a minimum comply with the requirements of ISO/CD 13628-7 section 6.8.16.

SECTION 7 MATERIALS

Contents

A. General

- A 100 Objective
- A 200 Application
- A 300 Material Selection

B. Additional Requirements

- B 100 General
- B 200 Long term properties

A. General

A 100 Objective

101 This section specifies the requirements for materials, manufacture, fabrication and documentation of riser pipe, components, equipment and structural items in the riser system, with regard to the characteristic properties of materials which shall be obtained after heat treatment, expansion, final shaping and assembly. The requirements are relevant both for pressure containing and for load carrying parts.

A 200 Application

201 The requirements in this section are applicable for metallic risers of the following materials:

- carbon Manganese steel;
- clad/lined steel; and
- corrosion resistant alloys (CRA) including ferritic austenitic (duplex) steel, austenitic stainless steels, martensitic stainless steels ("13% Cr"), other stainless steels and nickel based alloys.

202 This standard applies to risers fabricated from linepipe material meeting internationally recognised codes for materials, manufacturing, coatings, fabrication and NDT methods and procedures in general with the exceptions given in Table 7-1 and in part B of this section.

203 The additional considerations in Table 7-1 could be met by additional evaluations and/or specifications to the applied codes or by applying the material, welding and NDT requirement in DNV-OS-F101 and in part B of this section.

204 The design utilisation in this standard depends on the material quality and level of control, see [Section 5](#). If a higher utilisation is used, the principles and requirements in DNV-OS-F101, Submarine Pipeline Systems, supplementary requirement U, shall be applied for all metallic materials included in this section.

A 300 Material Selection

301 The materials selected shall be suitable for the intended use during the entire service life. The materials for use in the riser system shall have the dimensions and

mechanical properties, such as strength, ductility, toughness, corrosion and wear resistance, necessary to comply with the assumptions made in the design.

302 Materials for riser systems shall be selected with due consideration of the internal fluid, external environment, loads, temperatures (maximum and minimum), service life, temporary/permanent operations, inspection/ replacement possibilities and possible failure modes during the intended use. The selection of materials shall ensure compatibility of all components in the riser system. All elastomers and other non-metallic materials shall have documented compatibility with all fluids to which they could be exposed including pressure and temperature cycles.

303 All materials liable to corrode shall be protected against corrosion. Special attention should be given to local complex geometry, welds, areas that are difficult to inspect/repair, consequences of corrosion damage, and possibilities for electrolytic corrosion.

304 Requirements for corrosion allowance shall comply with DNV-OS-F101. Special consideration shall be given to the splash zone.

Guidance note:

The external corrosion allowance in the splash zone for CMn steel is usually taken as 6-8 mm.

- end - of - Guidance - note -

305 All sliding surfaces shall be designed with sufficient additional thickness against wear and tear. Special attention should be given to the following where applicable: clamped supports, sliding supports, slick joints, dynamic seals, ball joints and telescopic joints.

306 The possibility for "sour" service conditions shall be evaluated for all riser components, which can be exposed to fluids with H₂S during the lifetime of operation of the riser.

307 The quality of the materials used shall be tested/documented. Requirements to testing and control, i.e. mechanical and corrosion testing, non-destructive testing, dimensional and weight verification, shall be determined during design, manufacture and fabrication, based on the consequence with respect to failure and experience.

B. Additional Requirements

B 100 General

101 Risers shall be made in seamless or longitudinally welded pipes.

102 The riser components shall be forged/extruded rather than cast whenever a favourable grain flow pattern,

a maximum degree of homogeneity and the absence of internal flaws are of importance.

103 Accumulated plastic strain, ϵ_p , resulting from installation and operation shall be treated in accordance with the principles of DNV-OS-F101, sec 5 D1000.

104 However, the accumulated plastic strain limits of 0.3% and 2.0% applies only to the DNV-OS-F101 linepipe specification. Equivalent criteria have to be developed for other materials based on the fracture properties, welding and NDT applied.

Guidance note:

Treatment of accumulated strains in accordance with DNV-OS-F101:

- Requirements and guidelines to performance of ECA at accumulated strains $\epsilon_p \geq 0.3\%$ are given in DNV-OS-F101, sec 5, D1100 and sec 12.
- Supplementary requirement P in DNV-OS-F101 shall apply for riser pipes with accumulated strain $\epsilon_p \geq 2\%$.

- end - of - Guidance - note -

105 Reduction of area Z of cast and forged C-Mn fine grain and low alloy steel shall be $\geq 35\%$. For heavy wall components with SMYS above 420 MPa a higher ductility level may be required. Requirement for ductility in the through thickness direction shall be considered.

106 Limitations on SMYS on parts exposed to cathodic protection shall be according with DNV-RP-B401.

107 Generic base polymer(s) ASTM D1418, physical property requirements, storage and age control requirements shall be defined for non-metallic pressure containing parts.

B 200 Long term properties

General

201 The long term material properties with regard to fatigue and corrosion shall be documented. Special consideration shall be given as to whether regular inspection intervals or replacements can be applied (as for temporary risers used for drilling, completion / workover) or if inspection only is possible by means of remote control equipment (as for permanent risers used for export, import, production, injection).

Fatigue properties

202 Adequate fatigue life of base metal and weldments shall be verified by fatigue analyses that are based on fatigue testing (S-N fatigue or fatigue crack growth testing) or existing fatigue data.

Guidance note:

- when test results in terms of existing fatigue data are used as basis for fatigue analyses, the tests shall have been conducted on materials with expected fatigue properties equal to the chosen material and in a representative internal/external environment (including corrosion protection if relevant);
- selection of SN curves shall match the weld detail and quality;
- where sufficient and relevant test data are not available, further testing shall be conducted.

- end - of - Guidance - note -

203 It is strongly recommended to specify tight dimensional requirements at pipe ends for SCR's in order to reduce the stress concentration factors associated with the girth welds. This can be obtained by the use of supplementary requirement D in with DNV-OS-F101.

204 NDT of longitudinal welds shall include 100% control for transverse imperfections, and be in accordance with NDT Level I in DNV-OS-F101 or similar.

205 Weldments and other components with high fatigue loads shall be identified, and extended NDT of these shall be considered. Extended NDT can take place in the form of spot checks performed by other qualified operator.

Corrosion

206 For temporary risers manufactured from C-Mn steel, reduction in wall thickness due to internal corrosion shall be evaluated. An evaluation shall take into consideration the material properties, internal environment as well as the maintenance and inspection procedures that shall be applied. Effects of corrosion shall be accounted for with a minimum of 1mm allowance unless it can be documented that a corrosion allowance can be eliminated.

207 The external surface for temporary risers shall be protected by a suitable coating system in addition to routine coating repair and preservation of damaged coating.

208 Special considerations shall be given to riser pipes to be used for fluids containing hydrogen sulphide and defined as "sour service" according to NACE Standard MR0175. This can be obtained by the use of supplementary requirement S in DNV-OS-F101.

Wear

209 Wear resistance shall be considered, particularly for drilling risers or other wear exposed components. Adequate wear resistance shall be verified by analyses and / or testing. Manufacturing process, machining and fabrication shall also be considered.

Table 7-1 Additional Considerations										
DNV-OS-F101 Sec 6. D	Recognised codes Additional considerations ¹	Load effect calculations	Resistance						Content	
			Collapse	Local buckling	Pressure Containment	Strain limits ² (0.3% & 2%)	Increased utilisation	Fatigue ³	Sour service	Fracture arrest
Included	“Recognised” linepipe code	X	X					X		
	Ovality ⁴			X						
	Mill test ⁵				X					
	Fracture properties, Welding and NDT ⁶					X				
Suppl. P	Ductility ¹⁰			X		(X)				
Suppl. U	Statistics ⁷						X			
Suppl. D	Dimensional requirements ³							X		
Suppl. S	Sour service								X	
Suppl F	Fracture arrest									X
NDT level I ⁸	NDT					(X)		X		
High strength steel (yield stress > 555) ⁹			X	X		(X)				

- 1 The “additional considerations” shall constitute input to an evaluation regarding the highlighted topic. Such an evaluation shall end up with resulting specifications or guidance as required.
- 2 See B 103 of this section.
- 3 See B 202 and 203 of this section.
- 4 The moment capacity formulation is valid for $(D_{\max} - D_{\min})/D$ less than 3%, ref. DNV-OS-F101 Sec.5 D800
- 5 Mill test requirement in accordance with DNV-OS-F101 Sec.6 E1100 (hoop stress to be at least 96% of SMYS)
- 6 Criteria to be based on a fracture mechanic assessment
- 7 To document that SMYS is at least 2 standard deviations below the mean yield stress and that SMTS is at least 3 standard deviations below the mean ultimate strength “
- 8 See B 204 and 205 of this section
- 9 DNV-OS-F101 is limited to yield stress less than 555. The effect of “other” stress-strain curves for high strength steel shall be evaluated if relevant
- 10 Testing, strain hardening

SECTION 8 DOCUMENTATION AND VERIFICATION

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C 300 Verification during the fabrication phase

A. General

A 100 Objective

101 This section gives requirements for documentation and verification of riser systems during design, fabrication, installation and operational phases.

B. Documentation

B 100 Design

101 Design documentation shall, as far as practicable, be concise, non-voluminous, and should include all relevant information for all relevant phases of the lifetime of the riser system. The design documentation shall be presented in such a form that it is readily applicable for design review and third party verification.

102 Documentation shall be available to the purchaser or the purchaser's agents. Submittals and/or approval procedures shall be agreed between the purchaser and the supplier. Documents that are considered proprietary and confidential shall be available for review.

B 200 Design basis

201 A design basis document shall be established in the initial stages of the design process. The design basis document normally include

- information supplied by the owner;
- procedures for riser system and component analysis including analysis models and applied computer programmes;
- all applicable load cases, limit states and safety classes for all relevant temporary and operating design conditions.

202 A summary of those items normally to be included in the design basis document is included in Appendix F.

B 300 Design analysis

301 The design analysis documentation shall be self-contained and self-explanatory setting forth in full detail, including, but not limiting to the following items:

- a summary including design check key results and illustrations in figures;
- explanation of notations and abbreviations;
- introduction including the objective of the document and a brief description of the riser system;
- design basis if not included in a separate document, see B 200;
- calculation input data, including material details, assumptions for calculations and details of the computer programs
- reference number of the standard/guideline/textbook including the reference number for the formulae;
- full traceability of the calculations performed;
- wall thickness selection including minimum thickness, tolerances, corrosion, wastage and other allowances where applicable;
- graphs for the geometric model, including boundary conditions;
- key results presented in a clear and concise manner (i.e. utilisation ratios along the riser) and evaluation of the results in the light of the limit states and assumptions made in the analysis wrt. procedure/methods;
- relevant component and interface design loads, including sources and assumptions;
- assumptions made with respect to treatment, inspection and maintenance of the riser system in service.

302 Drawings shall be provided for the fabrication and construction of the riser system, including but not limited to:

- floater layout drawings with risers;
- riser fabrication drawings; and
- drawings of the corrosion protection system.

B 400 Manufacture and fabrication

401 The following information shall be prepared prior to start of or during manufacture of pipes, components, equipment, structural and other fabricated items:

- material and manufacturing specifications;
- Manufacturing Procedure Specification (MPS);
- Quality Plans;
- welding procedure specifications/qualification records if relevant;
- NDT procedures;
- manufacturing/fabrication procedures; and
- manufacturer's/fabricator's quality system manual.

402 All relevant documentation shall be submitted to owner, including but not limited to:

- fabrication procedures, incl. test requirements and acceptance criteria, personnel qualification records, etc.;
- material certificates for e.g. pipes, piping components, riser clamps, bolts, anodes, seal rings;
- fabrication procedure qualification reports including welding procedure qualification records;
- test records (visual, NDT, tests on samples, dimensional, heat treatment, pressure testing, FAT, etc.);
- necessary as-built drawings;
- complete statistics of chemical composition, mechanical properties and dimensions for the quantity delivered;
- coating and corrosion protection data sheets; and
- all non-conformances identified during manufacture and fabrication, and repairs performed

B 500 Installation and Operation

501 Installation and Operational requirements shall be documented in a Riser Installation and Operation Manual(s). The manual(s), which should be prepared jointly by the designer and the owner, defines how to safely install, operate and maintain the riser and its component systems.

502 The following information shall be prepared prior to start of installation:

- Failure Mode Effect Analysis (FMECA) and HAZOP studies;
- installation and testing specifications and drawings;
- installation Manuals;
- operational procedures for e.g. handling, running, operation, emergency disconnect, hang-off;
- contingency procedures; and
- contractor Quality System manual.

503 The Riser Installation and Operational Manual should contain as a minimum the following information:

- step-by-step procedure for handling, transportation, running/retrieving, operating, preservation and storage of the riser system;
- operating limits for each mode of operation;
- inspection and maintenance procedures for each component;
- manufacturers drawings of the riser system components outlining critical dimensions, weights and part numbers of various components;
- recommended spare parts list.

B 600 DFI Résumé

601 A DFI Résumé shall be prepared for riser systems including equipment and components. It shall contain all relevant data and documentation used for:

- the design, fabrication and installation phase
- operation of the riser system and

- preparation of plans for periodic inspections of the riser system

602 Documentation referred to in the DFI Résumé shall be kept for the lifetime of the riser system and shall be easily retrievable at any time.

603 The main objectives of the DFI résumé are to ensure that only necessary information is kept available, to facilitate the safe, effective and rational operation, and maintenance and modifications of the riser system and input to the preparation of plans for periodic inspection

604 The purpose of the DFI résumé is to:

- provide a reference key to the detail technical documentation;
- provide a system description for the riser system ;
- provide a summary of all design, fabrication and installation including, responsibility, requirements, verification activities, deviations, detail design, follow-on engineering, design basis data, and critical design areas with references to underlying detailed documentation;
- provide recommendations, requirements and sufficient information for the operation, in-service inspection, integrity evaluation, maintenance activities and modification or re-qualification throughout the entire lifetime of the installation.

605 The DFI résumé is a historical document. Any changes to the riser system after start-up will be a part of operation history and shall be reflected in a condition résumé. The DFI résumé is therefore not supposed to be updated based on events/changes made in the operation phase.

B 700 Filing of documentation

701 Maintenance of complete files of all relevant documentation during the life of the riser system is the responsibility of the owner.

702 The engineering and as-built files shall, as a minimum, comprise the documentation from design, fabrication, installation and commissioning.

703 The engineering documentation shall be filed by the Owner or by the engineering contractor for a minimum of 10 years. Design basis and key data for the riser system shall be filed for the lifetime of the system. This includes documentation from design to start-up and also documentation from possible major repair or re-construction of the riser system.

704 Files to be kept from the operational and maintenance phases of the riser system shall, as a minimum, include final in-service inspection reports from start-up, periodical and special inspections, condition monitoring records, and final reports of maintenance and repair.

C. Verification

C 100 General requirements

101 Compliance with provisions contained in relevant national and international regulations or decisions made pursuant to such regulations, shall be verified.

102 The extent of the verification and the verification method in the various phases shall be assessed. The consequences of any failure or defects that may occur during construction of the riser system and its anticipated use shall receive particular attention in this assessment.

103 The verification shall confirm whether the riser system satisfies the requirements for the specific location and method of installation and operation, taking into consideration the design, including material selection and corrosion protection, and the analysis methods used.

104 There shall be organisational independence between those who carry out the design work, and those who verify it.

105 Independent analyses shall to the extent practicable possible be performed using different software as applied in design.

106 Verification work and findings shall be documented.

C 200 Verification during the design phase

201 Verification of design should include checking of the following items:

- that specifications are in compliance with the applicable rules and regulations etc;
- appropriate personnel qualifications and organisation of the design;
- calculations of loads and load effects;
- that accidental loads are in compliance with the results from the risk analyses ;
- the usefulness of computer software, and that the programmes are adequately tested and documented.
This is of particular importance when programmes are

used in dealing with new problems, constructions or in case of new/modified software;

- independent calculations should be performed of the riser system including riser components of significance to the overall safety. The calculations should be sufficiently accurate and extensive to demonstrate clearly that the dimensions are adequate;
- that measuring requirements are complied with, e.g. for environmental data;
- that deviations during fabrication and installation are assessed and if necessary corrected;
- that drawings are in accordance with calculations and specifications ;
- that corrosion-, wear- and erosion protection measures are adequate;
- that the design of important structural details are adequate.

C 300 Verification during the fabrication phase

301 Verification during fabrication should include the following items to check that:

- the specifications are in accordance with public regulations/provisions and safety requirements ;
- satisfactory work instructions and procedures are prepared;
- personnel qualifications are in accordance with the requirements;
- the methods and equipment of suppliers and at the fabrication site are satisfactory with regard to control of dimensions and quality of riser pipe, components and materials;
- dimensions including assembly tolerances, NDT detection limits, materials, surface protection and work performance are in accordance with the basic assumptions made during design;
- deviation procedures are adequate during fabrication
- the transportation and storage of materials and fabricated assemblies are adequate.

SECTION 9 OPERATION, MAINTENANCE AND REASSESSMENT

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A. General

A 100 Objective

101 The objective of this section is to provide requirements for operation and in-service inspections. This section also provides general guidance on structural integrity assessment of risers to demonstrate fitness for purpose in case deviations from design appear during operation.

B. In-service Inspection, Replacement and Monitoring

B 100 General

101 Risers shall be operated, maintained and inspected to maintain an acceptable safety level throughout the service life of the riser. They should also be inspected after potentially damaging incidents and to confirm that any repairs have been properly performed. Inspections relating to areas such as the following may be necessary for risers and riser components:

- overloaded/permanently deformed riser string components;
- fatigue cracking (e.g. girth welds, connectors, anode attachment welds);
- leaks (loosening of mechanical connectors, seal ring damage);
- damage, e.g. dents, scratches, loosened or heavily distorted coating;
- internal and external wear;
- internal and external corrosion, see DNV-OS-F101, section 10.
- anti-corrosion/abrasion coatings;

- cathodic protection;
- marine growth;
- soil conditions at seabed, e.g. touch down point;

102 Risers should be visually examined for factors such as external damage, pipe distortion, excessive marine growth, external corrosion, general pipe configuration and sliding of buoyancy modules and/or ballast. Defects should be documented with respect to type, size and location. The influence of defects on structural or pressure integrity should be assessed.

B 200 Riser Inspection

201 The inspection philosophy should be an integral part of the design. Criticality of components and ease of inspection should be considered early to ensure that provisions are made for adequate inspection.

202 The designer should ensure that necessary inspection methods or replacement procedures are available and are scheduled and described in adequate detail as part of the operating and maintenance documentation for the facility.

203 Parts that are damaged repaired or particularly exposed and where failure will incur serious consequences shall be subject to particular attention in the planning of in-service inspection and maintenance.

204 Risers to be inspected for fatigue cracks should be inspected in accordance with the principles given in section 5.E 300.

Guidance note:

Equipment consumables such as seals, lubrication, periodically disconnected components and paint should generally be inspected or replaced on a scheduled basis. Moreover, the equipment should be designed to facilitate these maintenance operations. Manufacturer supplied data should include recommended maintenance operations and intervals.

- end - of - Guidance - note -

205 The maximum interval between inspections should be based on the component's predicted time to failure divided by a safety factor. The safety factor should account for uncertainties in time-to-failure predictions, risks of failure and ease of inspection. The designer should also consider the time required for repairs or replacement when determining maximum inspection intervals. Inspection intervals should be developed for each mode of failure such as fatigue, abrasion, wear, ageing and corrosion.

206 If the maximum inspection interval is longer than the intended service life, inspection is not expected to be necessary and need not be included in the operation and maintenance documents. However, if during operation the intended service life is extended beyond the original maximum inspection interval of a component, then the component should be inspected and refurbished if necessary or replaced.

B 300 Riser monitoring

301 The riser's internal and external operating condition should be monitored to reveal whether design conditions have been exceeded. This monitoring should include the recording of riser response and tension (if relevant) as well as the composition, pressure and temperature of the riser contents. Wall thickness measurements by internal means, e.g. pigs and by external means at selected reference points should be considered.

Guidance note:

A riser monitoring system is not mandatory, but it is useful for setting and maintaining precise tension, for monitoring riser dynamics and for design verification. The riser monitoring system can also be applied in connection with active floater positioning for reduction of stresses, top/bottom flex-joint etc of e.g. drilling risers. The system can also be used to record and estimate riser fatigue damage.

- end - of - Guidance - note -

B 400 Guidelines for inspection intervals

401 The following factors should be taken into account when determining inspection intervals:

- safety class;
- specific intervals based on criteria discussed elsewhere in this section;
- present condition and service history, e.g., age, results of previous inspections, changes in design operating or loading conditions or prior damage and repairs;
- redundancy;
- riser type and location, e.g., deep water or new design with few long term operating examples.

402 The intervals given in the Table 9-1 should not be exceeded unless experience or engineering analysis justifies longer intervals. In such cases, justification for changing guideline inspection intervals, based on the factors listed in this section, should be documented and retained by the owner.

Table 9-1 Guideline for inspection intervals		
Component	Inspection type	Interval
Above water components	Visual	1 year
Below water components	Visual	3-5 years
All components	NDT	As needed
Cathodic protection	Visual or Potential Survey	3-5 years
Areas of known or suspected damage	As appropriate	After exposure to design event
Components retrieved to surface	As recommended by manufacturer	After disconnect

B 500 Condition Summary

501 The DFI Résumé is a historic document, which is completed at the start of the operational phase.

502 Modifications, change of use, damage or detrimentation of the riser system shall be included in an updated condition summary. The condition summary shall provide user groups with an overall picture of the actual condition and functioning of the riser system during the operational phase. This document should be updated annually. Verification activities should be considered also for the operational phase.

C. Reassessment

C 100 General

101 An existing riser shall undergo an integrity assessment to demonstrate fitness for purpose if one or more of the following conditions exists:

- extension of service life beyond the originally calculated design life;
- damage or deterioration to a riser component;
- change of use that violates the original design or previous integrity assessment basis;
- departure from the original basis of design, e.g. by
 - change in environmental data or re-location;
 - change in floater;
 - change in internal fluid;
 - change in top tension for TTR's.

102 Assessment of existing risers should be based on the most recent information of the riser. Load data should be revised according to latest met-ocean data and the current layout of the riser.

103 In case of change of use, repair, modifications, damage or detrimentation of the riser system, measures shall be implemented to maintain an acceptable safety level.

C 200 Ultimate Strength

201 The ultimate strength of damaged members should be evaluated by using a rational, justifiable engineering approach, e.g. DNV RP-F101 may be applied.

202 The riser pipe or riser component must have sufficient ductility to develop the failure mechanism in question and large inelastic displacements or fractures due to repeated yielding must not occur. Local buckling or other non-linear instabilities must be considered in the calculation.

C 300 Extended Service life

301 Extended service life may be based on results from performed inspections throughout the prior service life. Such an evaluation should be based on:

- reliability of inspection method(s) used;
- elapsed time from last inspection performed and/or inspection/repair history.

Guidance note:

In some situations, even where cracks are not found it should be considered to perform a light grinding at the hot spot areas

of the riser systems to remove undercuts and increase the reliability of the inspection.

Detected cracks may be ground and inspected again, to document that they are removed. The remaining life of such a repair should be assessed in each case.

- end - of - Guidance - note -

C 400 Material Properties

401 . Material properties may be revised from design values to 'as built' values based on material certificates. The yield and tensile strength may be taken as the minimum guaranteed yield and tensile strength given in material certificates.

402 Alternatively, material tests may be used to establish the characteristic 'as built' yield strength. Due consideration must be given to the inherent variability in the data. The determination of characteristic values shall be in accordance with the evaluation procedure given in ENV 1993 1-1, Annex Y.

C 500 Dimensions and Corrosion Allowance

501 Strength assessment shall be based on 'as built' dimensions, reduced for corrosion allowance.

502 For unprotected or cathodically protected steel, the section thickness and the expected corrosion may be updated based on the measured values. Section thickness for use in the strength assessment may be calculated from the measured section thickness combined with the expected corrosion in the remaining lifetime, based on the observed rate of corrosion.

Guidance note:

DNV RP-F101 Corroded Pipelines gives guidance on assessment of pipes corrosion/erosion defects including local wall thinning due to fabrication tolerances and grind repairs.

- end - of - Guidance -note -

C 600 Cracked Pipes and Components

601 Pipes and components containing cracks should be repaired/replace as soon as possible.

APPENDIX A GLOBAL ANALYSIS

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A. General

A 100 Objective

101 The objective of this Appendix is to give guidance on global riser system analysis referred to present technical level of tailor-made FE computer codes for static and dynamic analysis of slender structures.

A general generic presentation is used as the basic methods of analysis can be applied to a wide range of riser systems. Comments related to recommended procedures for specific riser systems are addressed whenever appropriate. The focus will be on the following essential issues:

- general overview of global system behaviour and important nonlinearities;
- general overview of analysis techniques with emphasis on treatment of nonlinearities;
- overview of important load models (e.g. effective tension, hydrodynamic loading, internal fluid flow, structural damping etc);
- guidance to global analysis to provide consistency with the guideline requirements, and
- state-of-the-art review of recent developments regarding analysis techniques of particular interest for deep water riser systems (e.g. coupled floater/slender structure analysis).

102 The overall intention with the present document is to support practical implementation of the LRFD and WSD design formats and provide background information for selection of adequate method of analysis.

103 The document should not be regarded as a self-contained document on analysis but rather as an introduction to basic principles and more detailed guidance on selected important topics. Functional description and extended use of references is applied to describe well established procedures, general techniques and accepted modelling practice (guidelines, handbooks and technical papers)

104 In particular, API RP 2RD should be consulted for a more detailed technical description as well as modelling guidance of special components such as tensioner, flex-joint, stress-joint, ball-joint etc (mainly sections A.2, A.6.2, A.6.4.2, A.6.3.5 and A.6.5). Reference is also made to API RP 2RD, sections A.6.4.4.1 and A.6.5.1 for modelling of multiple tubular cross-sections in global analyses.

B. Physical Properties of riser systems

B 100 General

101 The purpose of this section is to give a brief overview of characteristic physical properties and governing nonlinearities of riser systems. Such information is crucial when selecting analysis strategy to describe the static and dynamic behaviour when the system is exposed to environmental loading due to current, waves and floater motions.

102 The main functional requirements to marine risers is to provide for transfer of fluids and gas between seafloor and a floater, as well as allow for transportation of various well operation tools. Risers are therefore commonly grouped into the following categories, reflecting the area of application:

- drilling risers;
- workover/completion risers;
- export/injection risers;
- production risers.

These categories differ with respect to typical dimensions, cross-sectional composition, types of operation, functional requirements and design load conditions.

103 Risers will typically be operated from a floater. A main concern in selection of the global riser configuration is how floater motions should be absorbed by the riser system. It is therefore convenient to distinguish between *top tensioned* - and *compliant* risers to reflect the principle applied for absorption of floater motions. Characteristic properties of these main riser categories are discussed separately below.

104 There is also a significant potential for *hybrid* riser configurations, combining the properties of tensioned and compliant risers in an efficient way, examples are given by e.g. Espinasse et al (1989)

B 200 Top tensioned risers

201 Vertical risers supported by a top tension in combination with boundary conditions that allows for relative riser/floater motions in vertical direction are denoted top tensioned risers. Furthermore, the riser is constrained to follow the horizontal floater motion at one or several locations. The intended (idealised) behaviour is that the applied top tension should maintain a constant target value regardless of the floater motion. Hence, the effective tension distribution along the riser is mainly governed by functional loading due to the applied top tension and the effective weight of the riser. The relative riser/floater motion in vertical direction is commonly denoted stroke. Applied top tension and stroke capacity are the essential design parameters governing the mechanical behaviour as well as the application range. Top tensioned risers are applicable for all functional purposes as mentioned above and will hence represent an attractive alternative for floaters with rather small heave motion (e.g. TLP, Spar platforms, deep draft floaters (DDF) and semi-submersibles).

202 Top tensioned risers operated from TLP's and semi-submersibles are equipped with a separate (hydraulic) heave compensation system to account for the floater motions and at the same time maintain a constant target value for the applied top tension. Bending moments are mainly induced by horizontal floater motions and transverse loading due to current and wave action. A pronounced peak in the bending moment distribution is normally seen close to the wave zone.

203 An alternative solution is used for Spar platforms where the top tension is obtained from buoyancy modules attached along the upper part of the riser inside the moonpool. Several supports are introduced along the riser system to constrain the riser motion in transverse hull direction. There are no constraints (except from friction forces) in longitudinal direction allowing the hull to move relative to the riser system. Bending moments in risers operated from a shell Spar are mainly due to the resulting horizontal hull motion as well as hydrodynamic loading from the entrapped water in the moonpool. Pronounced peaks in the bending moment distribution are normally found at the support locations.

204 The static and dynamic behaviour of top tensioned risers is largely governed by the applied top tension. The effective weight of the riser system defines the lower limitation for the applied top tension to avoid compressive effective tension in the riser at static position. A significant higher top tension must however be applied to account for imperfect tensioner arrangements and allow for redundancy in case of partial loss of top tension. Increased top tension can also be applied to reduce the probability of collision in riser arrays and limit the mean angles in bottom of the risers. The applied top tension is commonly specified in terms of increase relative to the effective weight of the riser system, also denoted as overpull. The required overpull is system dependent with a typical range of 30%-60%.

205 Steel pipes have traditionally been applied for conventional water depths. Titanium and composite pipes are suggested for deep water applications in order to keep the top tension requirement at an acceptable level. Steel risers with buoyancy modules attached can alternatively be applied for deep water.

206 The cross-sectional composition depends on the functional applications. Export, import and low pressure drilling risers are normally single tubular risers. Multi-tube cross-sections may typically be found in high pressure drilling- and workover risers as well as production risers.

207 A taper joint, flex-joint or ball-joint is applied to reduce bending stresses at termination to the seafloor. A flex-joint or ball-joint may be applied to reduce bending stresses at termination to the floater. A taper joint may also be included at the keel of Spar and other deep draught floaters.

B 300 Compliant riser configurations

301 Compliant riser configurations are designed to absorb floater motions by change of geometry, without use of heave compensation systems. Compliant risers are mainly applied as production, export and injection risers. The required

system flexibility is for conventional water depths normally obtained by arranging non-bonded flexible pipes in one of the 'classical' compliant riser configurations: Steep S, Lazy S, Steep Wave, Lazy Wave, Pliant Wave or Free Hanging (catenary).

302 In deep-water, it is however also possible to arrange metallic pipes in compliant riser configurations. Free Hanging Risers in steel have been installed in the Gulf of Mexico (Phifer et al 1994), and Lazy Wave configurations in steel and titanium have been proposed as deep-water riser systems for TLP and Semi-submersibles. A Lazy Wave configuration with increased horizontal extension termed Long Wave is proposed for application of metallic risers for a deep water Floating Production Ship and Offloading facility (FPSO) for North sea conditions (Karunakaran et al 1996). In such applications it may also be desirable to apply pre-bend pipe sections to reduce the dynamic curvature at critical locations along the riser (i.e. hog and sag bends). Single pipe cross-sections are typically applied for compliant riser configurations

303 Compliant riser systems will in general experience significantly larger static and dynamic excursions when compared to top tensioned risers. The floater motion characteristics will in many situations be decisive for the dynamic tension and moment variation along the riser (e.g. TLPs, Semi-submersibles, Ships). Environmental load effects will consequently also be of greater concern for compliant configurations. Critical locations on compliant risers are typically the wave zone, hog -and sag bends, touch down area at seafloor and at the terminations to rigid structures.

304 Titanium may offer several benefits relative to steel for some of these configurations. This is due to a low modulus of elasticity (half that of steel) implying a higher degree of flexibility. Furthermore, the yield stress is typically higher than for steel and the specific weight is much lower (about half the steel weight).

305 Termination to rigid structures is an essential design issue for compliant riser configurations. Possible solutions are carefully designed bend stiffener, ball joint or flex joint. The primary design requirement is to limit bending curvature and pipe stresses, the secondary design requirement is to minimise forces on the supporting structure.

B 400 Nonlinearities

401 A basic understanding of important nonlinearities of riser systems is of vital importance for system modelling as well as for selection of adequate global analysis approach. Nonlinearities will also be decisive for the statistical response characteristics for systems exposed to irregular loading. An essential issue is how nonlinear properties of the riser system and hydrodynamic loading mechanisms transform the wave frequency Gaussian excitation (i.e. waves and 1st order floater motion) into non-Gaussian system responses. Important nonlinearities that always should be carefully considered can be summarised as:

3. Geometric stiffness (i.e. contribution from effective tension to transverse stiffness). Tension variation is hence a nonlinear effect for risers;
4. Hydrodynamic loading. Nonlinearities are introduced by the quadratic drag term in the Morison equation expressed by the relative structure-fluid velocity and by integration of hydrodynamic loading to actual surface elevation;
5. Large rotations in 3D space;
6. Material nonlinearities, and
7. Contact problems in terms of seafloor contact (varying location of touch down point and friction forces) and hull/slender structure contact.

402 The relative importance of these nonlinearities is strongly system and excitation dependent. Nonlinearities due to item 1) and 2) will, at least to some extent, always be present. Item 3) is relevant for two-axial bending due to in-plane as well as out of plane excitation, while 4) and 5) are more system specific nonlinear effects. It should be noted that external hydrostatic pressure is not considered to be a nonlinear effect as hydrostatic pressures normally will be handled by the effective tension / effective weight concept (Sparks 1984) in computer programs tailor made for slender structure analysis (e.g. Engseth et. al 1988, O'Brien et. al. 1988).

C. Global riser system analysis

C 100 Purpose of global analysis

101 The purpose of global riser system analyses is to describe the overall static and dynamic structural behaviour by exposing the system to a stationary environmental loading condition. A global cross sectional description in terms of resulting force/displacement relations (axial force versus axial elongation, bending moment versus curvature and torsion moment versus twist angle) is applied in such analyses. Relevant global response quantities can be grouped into the following main categories:

- resulting cross-sectional forces (effective tension, bending moments, torsional moment);
- global riser deflections (curvature, elongation, angular orientation);
- global riser position (co-ordinates, translations, distance to other structures, position of touch down point on seafloor, etc), and
- support forces at termination to rigid structures (resulting force and moments).

These response quantities are given directly as output from global riser analyses. It should be noted that the frequency content in all response quantities can be WF or combined WF and LF depending on the analysis strategy applied in the global response analysis.

102 Subsequent detailed cross sectional analysis to determine local stresses and strains can be performed using resulting cross sectional forces from the global analysis as boundary conditions and considering possible

external/internal pressure loading. Detailed component analysis can also be performed by application of resulting forces and deformations obtained from global analyses as boundary conditions in local quasi-static analyses (e.g. flex-joint, taper joint and bend stiffener analysis).

103 Procedures for evaluation of LRFD capacity checks for combined loading are addressed separately in Appendix C

C 200 General modelling/analysis considerations

201 A Finite Element (FE) approach is normally considered for global riser system analysis. The most important features required for adequate modelling and analysis of deep water systems in general can be summarised as:

- 3D formulation allowing for unlimited translations and rotations;
- conventional small strain slender beam- and bar elements including material- and geometric stiffness and allowing for nonlinear material properties;
- seafloor/riser and hull/riser contact formulations;
- adequate structural damping formulation;
- hydrodynamic loading according to the Morison equation expressed by the relative water/structure velocity and acceleration;
- regular- and irregular loading due to waves and floater motions;
- current modelling;
- special features allowing for efficient modelling of components such as swivels, hinges, buoyancy modules, clump weights, flex-joints etc;
- nonlinear static analysis, and
- nonlinear time domain dynamic analysis.

202 The computational efforts of nonlinear time domain dynamic analysis considering a detailed global riser response model can be substantial. This is in particular the case for irregular analyses where rather long simulations in general are required to estimate extreme responses with sufficient statistical confidence. It is therefore desirable to apply simplified analysis strategies as a supplement to the general advanced approach in order to achieve more efficient computer analyses.

203 The basic strategy to obtain efficient analyses is to use a simplified response model and/or use of simplified timesaving FE analysis methodologies such as 2D formulations and linearized time- and frequency domain dynamic analyses, see C 500 for a description. Other strategies such as use of special designed quasistatic analysis for bend stiffeners (e.g. Sødahl and Larsen 1989) and simulation of critical events identified by a simplified approach (e.g. Passano 1995) can also be applied to gain computational efficiency. The latter approach can be highly beneficial when the wanted results are relatively few extreme responses of a complex system exposed to irregular excitation.

204 Model uncertainties will always be present in numerical simulations of marine structures. Deviations from the unknown 'true' response will depend on method of

analysis as well as the response model. Simplifications introduced to achieve analyses that are more efficient will in most cases lead to an increased model uncertainty. A judgement regarding trade-off between computational efficiency and model uncertainty will therefore always be involved when strategies for cost effective analysis are decided. Issues that often must be considered in the decision process are briefly described in the following:

- the acceptable accuracy is dependent on the purpose of the analysis, i.e. the required accuracy of the analysis. This 'target accuracy' is dependent on the purpose for which the results will be used.
- the acceptable loss in accuracy by introduction of a simplified approach must be seen in relation to other uncertainties involved. (e.g. uncertainties related to modelling of environmental loading, floater motions, cross sectional properties, tension control etc.) The standard approach often applied in practical analyses is based on engineering judgement and experience possibly supported by some simple parametric studies.
- numerous simplified analyses will normally produce more information regarding overall static- and dynamic system behaviour when compared to a reduced number of advanced analyses. With limited computer resources available this should always be kept in mind when deciding the analysis strategy. Different conclusions may be drawn depending on scope of work (feasibility, preliminary design, detailed design, final verification). Simple methods allowing for a broad analysis scope is attractive in the early analysis stage while more specialised advanced analyses of identified critical conditions are of more interest in final stages.
- the simulation length used in stochastic analyses is crucial to obtain sufficient confidence of extreme response estimates. It can be shown that the statistical uncertainty roughly will be reduced proportional to the square root of the simulation length. The benefit from long simplified simulations versus reduced simulation length using a more advanced tool must be considered carefully when available computer resources are limited.

C 300 Static finite element analysis

301 The purpose of the static analysis to establish the static equilibrium configuration due to static loading (weight, buoyancy, top tension, current) for given locations of riser terminations to rigid structures (e.g. terminations to seafloor and floater). Static analysis is always the first step in global riser analysis and defines the starting point for subsequent eigenvalue- and dynamic analyses. Static riser analyses are normally performed using a nonlinear FE approach. Following standard FE terminology, it is convenient to distinguish between the following basic loading components:

1. volume forces (weight and buoyancy);
2. specified forces (e.g. applied top tension);
3. prescribed displacements (displacement of terminal points from stressfree- to specified positions), and
4. displacement dependant forces (current loading).

302 Each of these load components is in a standard FE approach applied in one or several load increments starting from an initial stressfree configuration (i.e. user defined reference configuration defining the state of no stress) to obtain the static riser configuration. Static equilibrium is ensured by equilibrium iteration at each load increment.

Guidance note:

The load components are for compliant riser configurations often applied one by one in the order 1-3-4 (2 is irrelevant for compliant riser configurations) or alternatively 1 followed by simultaneous application of 3 and 4.

The situation is somewhat different for top tensioned risers where the effective weight of the riser system is carried by the applied top tension. This requires that 2 is applied before- or simultaneous with 1 to avoid instability problems if the riser is modelled to be free to translate vertically at upper end.

These examples illustrates that application order of the defined load components can be decisive for the efficiency and stability of the static solution procedure. Load application order should therefor be considered carefully to avoid instability problems.

- end - of - Guidance - note -

303 Some computer programs tailor made for slender structure analysis offers an alternative strategy utilising the catenary solution as starting point for FE analysis (e.g. Engseth et al 1988, O'Brien and McNamara 1989). The basic idea behind this approach is that the overall influence from bending stiffness is moderate for compliant riser configuration, which means that the FE and catenary solutions are close. In this approach, application of volume forces (1) and prescribed displacements (3) is replaced by one equilibrium iteration starting from the catenary solution established by e.g. the procedure described by Peyrot and Goulois (1979). This combined use of catenary/FE analysis gives a significant reduction in computation time for compliant riser systems and, perhaps most important, helps to avoid instability problems often encountered during application of prescribed displacements for such systems.

C 400 Finite element eigenvalue analysis

401 Eigenvalue analysis is used to determine the eigenfrequencies and eigenmodes of the riser system. The analysis represent a fundamental check of the dynamic properties of the riser system and should always be considered as the first step in the dynamic system analysis. Eigenvalue analysis is of particular interest in the early stage design of deep water tensioned risers operated from Tension leg and Spar platforms to avoid unwanted resonance dynamics.

C 500 Dynamic finite element analysis

501 Risers, station-keeping system and floater comprise an integrated dynamic system responding to environmental loading from wind, waves and current in a complex way. Coupled static-and dynamic analysis of the complete system is in general required to establish the floater motions of deep water systems in terms of mean position and combined wave- and low frequency motions. In such analyses, it will normally be sufficient to apply a rather crude slender

structure model, see D for an introduction to coupled analysis

502 Global riser system analyses are, however, normally performed considering forced excitation due to wave frequency (WF) floater motions as well as direct wave and current loading. The WF floater motions are computed in the frequency domain. A representative mean floater position accounting for average environmental forces as well as low frequency (LF) motions is usually applied in riser system analysis. It should however be noted that the described approach only is applicable to riser systems that do not respond dynamically to LF floater motions. Combined WF and LF forced vessel motions should be considered in riser analysis if riser dynamics is significantly influenced by low frequency excitation.

503 Treatment of nonlinearities is the distinguishing feature among available analysis techniques. Based on the identified nonlinearities, it is obvious that the response characteristics of riser systems in general are non-Gaussian. Time domain analysis is consequently the primary method of analysis, especially concerning prediction of extreme response.

504 Commonly used dynamic FE analysis techniques, treatment of nonlinearities and main area of application are summarised in the following.

- *nonlinear time domain analysis* based on step by step numerical integration of the incremental dynamic equilibrium equations. A Newton-Raphson type of equilibrium iteration is applied at each time step. The nonlinear approach will give an adequate description of all nonlinear effects and will consequently give a good representation of a possible non-Gaussian response. Nonlinear simulations will typically be needed for systems undergoing large displacements, rotations or tension variations or in situations where description of variable touch down location or material nonlinearities are important;
- *linearized time domain analysis* based on linearization of the dynamic equilibrium equations with regard to stiffness, damping and inertia forces at static equilibrium position, (i.e. structural linearization). This means that the system stiffness, damping and mass matrices are kept constant throughout the analysis and that system displacement vector can be found by a simple back substitution at each time step. Nonlinear hydrodynamic loading according to the Morison equation is, however, still included. The linearized approach is far more efficient than nonlinear analysis and is hence an attractive alternative when hydrodynamic loading is the major nonlinear contributor. A typical application is analysis of tensioned risers with moderate transverse excursions.
- *frequency domain analysis* based on linearization of stiffness-, damping-, inertia-, and external forces at static equilibrium position (i.e. structural and load linearization). Stochastic linearization for combined wave/current loading is required for irregular analysis. Frequency domain analysis will always give a Gaussian

response and is therefore in general not recommended for extreme response prediction. The main application area is fatigue calculations and long-term response statistics to identify design conditions to be applied in time domain analyses. The computation time is small when compared to time domain analyses.

These techniques can give significantly different results depending on the actual system characteristics, see e.g. Rooney et al (1990) for application examples for a top tensioned TLP production/injection riser.

D. Combined floater/slender structure analysis

D 100 General

101 Floater, risers and mooring lines comprise an integrated dynamic system responding to environmental loading due to wind, waves and current in a complex way. Current loading and damping due to the slender structures (i.e. risers, tethers and mooring lines) may significantly influence the low frequency floater motions of deep water mooring systems. Consistent treatment of these coupling effects is decisive for adequate prediction of floater motions as well as slender structure response for some deep water concepts such as slack- and taut moored FPSO's (Ormberg et al 1998) and Spar platforms (Colby et al 1999). This section is dedicated to discussion of analysis methodologies for the complete system involving fully coupled system analysis, coupled floater motion analysis as well as traditional de-coupled floater motion analysis. Floater motion analysis and detailed slender structure analysis are carried out separately in the two latter approaches to achieve computations that are more efficient.

For a more comprehensive discussion of techniques for analysis of the complete system, see for instance Ormberg et al (1997), Ormberg and Larsen (1997), Ormberg et al (1998) and Colby et al (2000).

102 The discussion of coupled analysis is mainly focused on application to nonlinear systems (e.g nonlinear restoring characteristics from slender structures) with significant LF floater motions. The intended application area is typically coupled analysis of FPSO's and Spar platforms. The LF motions of these systems may be significantly influenced by slender structure coupling effects.

D 200 Coupled system analysis

201 All relevant coupling effects can be consistently represented using a fully coupled analysis where the floater force model is introduced in a detailed Finite Element (FE) model of the complete slender structure system including all mooring lines and risers. Non-linear time-domain analysis considering irregular wave frequency (WF) and low frequency (LF) environmental loading is generally required to give an adequate representation of the coupled floater/slender structure dynamics on non-linear systems. It should be noted that this approach yields dynamic equilibrium between the forces acting on the floater and

slender structure response at every time instant. It will therefore be no need for assessment of the low frequency damping from the slender structure, as this contribution is automatically included in the slender structure response. The output from such analyses will be floater motions as well as a detailed slender structure response description (e.g. tension in mooring lines as well as tension, moment, shear, curvature and displacement in risers).

202 The computational efforts required for coupled system analysis considering a detailed model of the slender structure including all mooring lines and risers are substantial and should therefore mainly be considered as a tool for final verification purposes.

203 Coupled floater motion analysis in combination with subsequent slender structure analysis as discussed in the sections D 300 – D 400 is generally recommended to achieve a more efficient and flexible analysis scheme. By careful modelling, this approach is capable of predicting floater motions and detailed slender structure response with same precision as the complete coupled system analysis.

D 300 Efficient analysis strategies considering coupling effects

301 Several strategies can be proposed to achieve computational efficiency. All strategies have in common that the floater motion- and slender structure analyses are carried out separately. The first step is always a floater motion analysis. Computed floater motions are then applied as loading in terms of forced boundary displacements in subsequent slender structure analysis. Risers and critically loaded mooring lines are analysed one by one in the slender structure analyses contributing to computational flexibility as well as a significant reduction in computation time.

302 The most direct way to proceed is to apply time series of combined WF and LF floater motions computed by the floater motion analysis as boundary conditions in the slender structure analyses as shown in Figure A-1 (branch a). This approach will also capture possible LF slender structure dynamics as well as influence from LF response (possibly quasi-static) on the WF response. Such effects may be of importance for some deepwater mooring line- and riser designs.

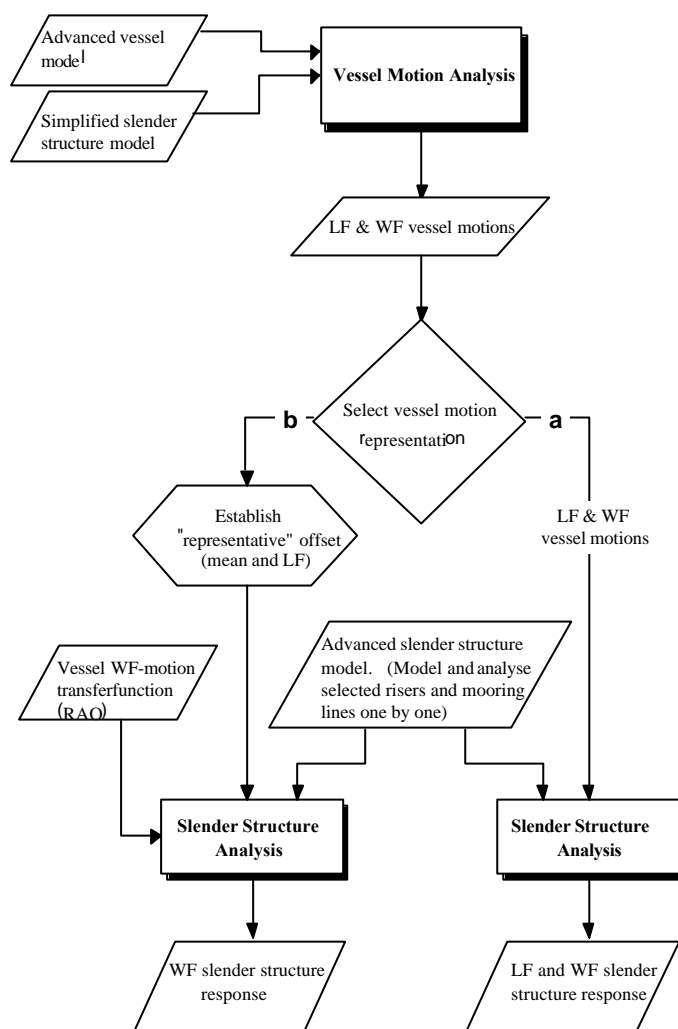


Figure A-1 Vessel motion analysis

303 Traditional assumptions can alternatively be applied considering WF floater motions as dynamic excitation while LF floater motions are accounted for by an additional offset, see Figure A-1 (branch b). The slender structure is consequently assumed to respond quasi-statically to LF floater motions.

304 For guidance regarding calculation of representative floater offset, reference is made to e.g. section 6.2.2 in API RP 2SK.

305 Treatment of coupling effects in the floater motion analysis is decisive for the validity of this approach. Floater motions can be simulated using a coupled – or de-coupled approach as described in sections D 400 and D 500, respectively.

D 400 Coupled floater motion analysis

401 The primary purpose of coupled floater motion analysis is to give a good description of floater motions, detailed slender structure response is secondary. It can therefore be proposed to apply a rather crude slender structure FE model (crude mesh, no bending stiffness etc.) in the coupled analysis still catching the main coupling effects (restoring, damping, and mass). The numerical solution technique as well as floater force model is however

identical to the approach applied in coupled system analysis as described above.

402 This approach gives a significant reduction in computation time due to a reduced number of degrees of freedom in the coupled analyses. Case studies of deep water mooring systems verify that the floater motions can be accurately predicted with acceptable computation time using a simplified modelling of the slender structures (Ormberg et al 1998).

D 500 De-coupled floater motion analysis

The purpose of this approach is to compute rigid body floater motions considering static-, low frequency and wave frequency environmental loading. LF motions are computed by step-wise numerical integration in time domain, while WF motions normally are computed in frequency domain.

501 The floater force model is identical to the model applied in coupled analyses as described above. The slender structures are represented in a simplified way in terms of static restoring force characteristics and a constant LF viscous damping. The restoring force characteristics may include effects from current loading on the slender structures. If not, it is possible to account for current loading on the slender structures in terms of an equivalent constant force acting on the floater. The computation time is small when compared to the coupled floater motion analysis.

502 Assessment of the LF damping for the actual environmental condition is crucial for the LF floater motion analysis. This information can be extracted from model tests of the complete system or from coupled floater motion analysis as discussed in 303. It has been experienced that time histories covering roughly 20-25 LF motion cycles is required to obtain adequate damping estimates, see e.g. Ormberg et al (1998) for further details. It should however be emphasised that the damping contribution from the slender structures for some systems is sensitive to the environmental excitation. The damping estimate should therefore preferably be based on the same environmental condition as considered in the de-coupled floater motion analysis.

503 Efficient analysis and consistent treatment of coupling effects can hence be achieved by splitting the floater motion analysis in a rather ‘short’ coupled floater motion simulation and ‘long’ de-coupled floater motion simulation. The LF damping estimated from the coupled floater motion analysis is applied in the de-coupled floater motion analysis to obtain consistent treatment of coupling effects. Furthermore, the computational efficient de-coupled approach allows for long simulations to achieve the required statistical confidence.

E. Hydrodynamic loading on slender structures

E 100 General

101 The hydrodynamic loading on slender structures can be expressed by the Morison equation in terms of the

relative fluid-structure velocities and accelerations. The fluid and structural velocity and acceleration vectors are in a FE approach known in the global reference frame. The fluid velocities and acceleration vectors can be found by considering relevant contributions from wave kinematics (regular or irregular, undisturbed or disturbed), current (constant velocity or velocity and acceleration) or moonpool kinematics. The latter calls for special attention and is discussed separately below.

102 Hydrodynamic loading in normal and tangential pipe directions is normally computed independently according to the so-called cross-flow (or independence) principle. This approach requires that the fluid and structural acceleration vectors are decomposed in the instantaneous normal and tangential pipe directions.

103 Formulation of the normal load component is dependent on the actual shape of the cross-section. The Morison equation is therefore discussed separately for circular and double-symmetric cross-sections, which cover most situations of practical interest.

104 Hydrodynamic loading according to the Morison formulation is a major source to nonlinearities in the response characteristics of slender structures. Hence, treatment of the Morison type of loading is an essential issue when selecting method of analysis, see C. It is however also most important to keep in mind that the eigenmodes and eigenvalues of the system are influenced by the added mass term in the Morison equation. Added mass contributions should therefore be carefully evaluated as a part of eigenvalue analysis in order to do an adequate assessment of the governing eigenmodes and eigenperiods of the system (e.g. added mass of air cans for Spar riser systems).

E 200 Morison equation for circular cross-sections

The Morison equation for circular cross-sections can be expressed as:

$$f_n = \frac{1}{2} \rho C_D^n D_h |v_n - \dot{r}_n| (v_n - \dot{r}_n) + \rho \frac{\pi D_b^2}{4} C_M^n \ddot{v}_n - \rho \frac{\pi D_b^2}{4} (C_M^n - 1) \ddot{r}_n \quad (A.1)$$

$$f_t = \frac{1}{2} \rho C_D^t D_h |v_t - \dot{r}_t| (v_t - \dot{r}_t) + \rho \frac{\pi D_b^2}{4} C_M^t \ddot{v}_t - \rho \frac{\pi D_b^2}{4} (C_M^t - 1) \ddot{r}_t$$

where:

f_n	Force per unit length in normal direction
f_t	Force per unit length in tangential direction
ρ	Water density
D_b	Buoyancy diameter (i.e. equivalent diameter for description of resulting buoyancy on a general riser cross section)
D_h	Hydrodynamic diameter
v_n, \dot{v}_n	Fluid velocity and acceleration in normal direction
\dot{r}_n, \ddot{r}_n	Structural velocity and acceleration in normal direction.

C_D^n, C_M^n	Drag and inertia coefficients in normal direction
v_t, \dot{v}_t	Fluid velocity and acceleration in tangential direction
\dot{r}_t, \ddot{r}_t	Structural velocity and acceleration in tangential direction.
C_D^t, C_M^t	Drag and inertia coefficients in tangential direction

201 In addition, $C_A = C_M - 1$ is defined as the added mass coefficient. The two first terms are in FE implementations included in the external load vector while the latter term (added mass term) is included in the mass matrix. Hence, it is important to observe the eigenmodes and eigenperiods of the system will be influenced by the added mass term.

202 The described formulation is applicable to bare circular pipes as well as equivalent circular pipe models (e.g. equally spaced circular cylindrical buoyancy elements on a circular pipe as illustrated in Figure A-2). The cross-flow principle is in the latter case somewhat questionable, though, and special attention should be paid to the selection of hydrodynamic coefficients, see the SINTEF handbook (1992), section A.4.2.2.

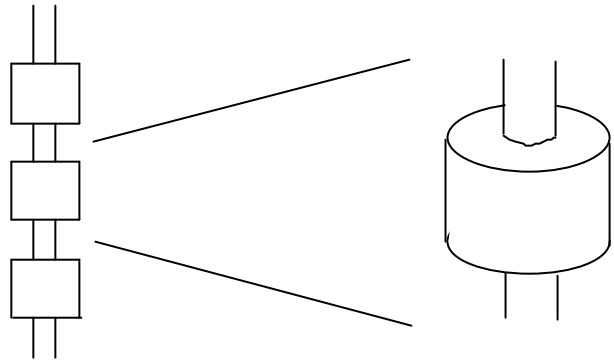


Figure A-2 Pipe with attached buoyancy elements

E 300 Morison equation for double symmetric cross-sections

301 The Morison equation can be extended to double symmetric cross sections by decomposing the normal velocities and accelerations in direction of the local cross-sectional symmetry axes. These local symmetry axes are denoted y and z in the following and are shown in Figure A-3.

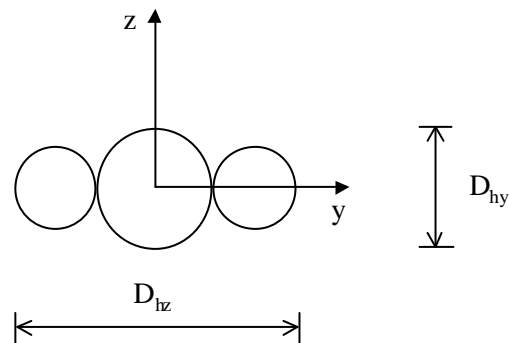


Figure A-3 Definition of local cross sectional axes

302 The force components in tangential and normal y- and z-directions can be expressed as:

$$\begin{aligned} f_{ny} &= \frac{1}{2} \rho C_D^{ny} D_{hy} |v_{ny} - \dot{r}_{ny}| (v_{ny} - \dot{r}_{ny}) + \rho A_b C_M^{ny} \dot{v}_{ny} - \rho A_b (C_M^{ny} - 1) \ddot{r}_{ny} \quad (\text{A.2}) \\ f_{nz} &= \frac{1}{2} \rho C_D^{nz} D_{hz} |v_{nz} - \dot{r}_{nz}| (v_{nz} - \dot{r}_{nz}) + \rho A_b C_M^{nz} \dot{v}_{nz} - \rho A_b (C_M^{nz} - 1) \ddot{r}_{nz} \\ f_t &= \frac{1}{2} \rho C_D^t D_{ht} |v_t - \dot{r}_t| (v_t - \dot{r}_t) + \rho A_b C_M^t \dot{v}_t - \rho A_b (C_M^t - 1) \ddot{r}_t \end{aligned}$$

where:

f_{ny}, f_{nz}	Force per unit length in normal y – and z-directions
f_t	Force per unit length in tangential direction
ρ	Water density
A_b	Cross-sectional buoyancy area
D_{hy}, D_{hz}	Hydrodynamic diameter (i.e. projected area) in normal y- and z-directions
D_{ht}	Hydrodynamic reference diameter in tangential direction
v_{ny}, \dot{v}_{ny}	Fluid velocity and acceleration in normal y-direction
v_{nz}, \dot{v}_{nz}	Fluid velocity and acceleration in normal z-direction
v_t, \dot{v}_t	Fluid velocity and acceleration in tangential direction
$\dot{r}_{ny}, \ddot{r}_{ny}$	Structural velocity and acceleration in normal y-direction
$\dot{r}_{nz}, \ddot{r}_{nz}$	Structural velocity and acceleration in normal z-direction
\dot{r}_t, \ddot{r}_t	Structural velocity and acceleration in tangential direction
C_D^{ny}, C_M^{ny}	Drag and inertia coefficients in normal y-direction
C_D^{nz}, C_M^{nz}	Drag and inertia coefficients in normal z-direction
C_D^t, C_M^t	Drag and inertia coefficients in tangential direction

303 In addition, the inviscid moment per unit length about the longitudinal axis (i.e. tangential direction) can be expressed as

$$M_t = -m_{66} \ddot{\Omega} + \rho A_b (C_M^{ny} - C_M^{nz}) (v_{ny} - \dot{r}_{ny}) (v_{nz} - \dot{r}_{nz}) \quad (\text{A.3})$$

where m_{66} is the added moment (see Table 4.3 p.145 in Newman 1977) and Ω is the angular velocity. The last term is the Munk-moment.

304 The described model is applicable for modelling of hydrodynamic loading on more complex cross-sections such as pipe bundles, combined pipe-umbilical cross sections etc. The force resultant will in general not follow the direction of

the velocity. Note that this model is not applicable for rotational symmetric cross sections, as the correct Morison formulation will not be retrieved.

The inviscid force and moment for a general cross-section is discussed by Newman (1977) p 139

E 400 Principles for selection of hydrodynamic coefficients

401 The hydrodynamic coefficients are dependent on a number of parameters:

- body shape;
- Reynolds number $Re = UD/\nu$, where U is the free stream velocity, D is the diameter and ν is the kinematic viscosity;
- Keulegan Carpenter number $KC = U_M T/D$, where U_M is the free stream velocity amplitude of the oscillatory flow and T is the period of oscillation;
- roughness ratio k/D , where k is the characteristic dimension of the roughness on the body;
- reduced velocity $U/f_n D$, where f_n is the natural frequency of the riser;
- relative current number U_c/U_M , where U_c is the current velocity and U_M is the velocity of the oscillatory motion.

402 An extensive discussion on the dependence of the hydrodynamic coefficients on several of these parameters can be found in Sarpkaya and Isaacson (1981) and Sumer and Fredsøe (1997). Their presentation is concentrated on circular cylinders with different Re , KC and roughness ratio. Nevertheless, it can be difficult to decide the coefficients based on the above-mentioned criteria, for instance due to varying flow conditions or lack of information. For practical purposes, it is often sufficient to use a simplified consideration to select the coefficients in Morison's equation. As a first approximation, use values for steady flow. For circular bare pipes natural choices are $C_M = 2$ and $C_D = 0.7 - 1.0$. A more detailed discussion is found in the SINTEF handbook (1992)

For riser with buoyancy elements, reference is made to the Sintef handbook (1992), section A4.2.2. The tangential forces can be equally important to the normal forces.

403 Focus should always be given to selecting hydrodynamic coefficients slightly on the conservative side. In such considerations, it is important to distinguish between areas where the drag term act as excitation (e.g. wave zone) and areas where the drag term act as damping (e.g. parts of the riser system insignificantly influenced by wave loading). Slightly high/low values should be selected for areas where the drag term act as excitation/damping, respectively. A sharp distinction between areas with excitation or damping is not always possible. Therefore, a sensitivity study should always be performed to support rational conservative assumptions when a high level of confidence is required.

F. Marine growth

101 Marine growth on slender structures will influence the loading in terms of increased mass, diameter and hydrodynamic loading.

102 Site dependent data for marine growth are normally specified in terms of density, roughness and depth variation of thickness. The marine growth characteristics are basically governed by the biological and oceanographic conditions at the actual site. The relative density of marine growth is in the range of 1-1.4 depending on the type of organisms.

103 The thickness of marine growth to be included in design analyses will in addition be dependent on operational measures (e.g. regular cleaning, use of anti fouling coating) as well as structural behaviour (e.g. less marine growth is normally considered for slender structures with significant dynamic displacements).

104 Field measurements at the actual location combined with field experience regarding the extent of marine growth on similar structures will therefore be the reference for specification marine growth to be considered in design analyses

105 In FE analyses, it is recommended to increase mass, buoyancy diameter and drag diameter according to the specified depth variation of marine growth. In addition, the hydrodynamic coefficients should be assessed with basis in the roughness specified for the marine growth.

G. Hydrostatic pressure loading

101 Loading due to external and internal pressure acting on a pipe section is normally treated in terms of the effective weight/tension concept (Sparks 1984):

$$\begin{aligned} T_e &= T_w - A_i P_i + A_o P_o \\ W_e &= m_p g + A_i \rho_i g - A_o \rho_o g \end{aligned} \quad (\text{A.4})$$

Where :

T_e	Effective Tension
T_w	True wall tension (i.e. axial stress resultant found by integrating axial stress over the cross-section)
A_o, A_i	External- and internal cross sectional areas
W_e	Effective weight (i.e. submerged weight of pipe including content)
M_p	Mass of pipe
ρ_o, ρ_i	External- and internal fluid densities
G	Acceleration of gravity
P_o, P_i	External- and Internal pressure

102 Hydrostatic pressure is acting normal to instantaneous orientation of the pipe and can hence be classified as a non-conservative loading (follower load). The

main advantage of the effective weight/tension formulation is that loading due to hydrostatic pressure is represented by vertical conservative forces (i.e. the non-conservative pressure force model is replaced by an equivalent conservative volume force model). This is of vital importance for efficiency and stability in computer implementations as pressure integration over the deformed pipe geometry is avoided.

103 The physical significance of the effective tension can be summarised as:

- the geometric stiffness is governed by the effective tension. This means that the effective tension is the overall governing stiffness parameter for the vast majority of slender structures;
- global buckling and stability is governed by the effective tension;
- the effective tension formulation is applicable to any general shaped volume stiff cross section (i.e. cross sectional volume is not influenced by the hydrostatic pressure).

104 The effective tension formulation is also directly applicable to multipipe cross-sections (i.e. pipes inside pipes) by summation of effective tension and effective weight contributions from all pipes, see e.g. Skomedal (1990) for further details.

H. Internal fluid flow

H 100 General

101 Loading due to internal fluid flow is normally included in terms of the hydrostatic pressure and mass contribution in global riser analyses.

102 The hydrostatic pressure is treated by the effective weight/effective tension concept as described in section G for static and dynamic analyses. In dynamic analyses, the mass of the internal fluid is included in the effective mass defined as the cross-sectional mass including content $m_e = m_p + \rho_i A_i$. Hence, the effective mass is consistent with the effective weight (i.e. the effective weight corresponds to the submerged weight of the effective mass). This model is formally correct for static and dynamic analyses of risers conveying a hydrostatic internal fluid (i.e. no fluid flow through the pipe is considered).

103 Additional loading (centrifugal and coriolis forces) is however introduced due to the internal fluid flow through the pipe. The significance of the additional loading is briefly discussed in the following for three fluid flow categories: steady flow, accelerated uniform flow and slug flow.

H 200 Steady flow

201 Steady flow corresponds to e.g. normal production with a homogenous fluid flow with constant velocity through the pipe. The effect of a steady flow on a static riser configuration can be summarised as (Fylling et al 1986, Patel and Seyed 1989):

- the effective tension is not affected by the steady flow;

- the steady flow causes an increase in the true wall tension and a corresponding axial elongation, and
- the static configuration is only affected by the axial elongation caused by the steady flow. This effect is negligible for compliant riser configurations, but may have some significance for calculation of the vertical upper end position of top tensioned risers.

202 The effective tension including the effect of steady internal fluid flow can be expressed by:

$$T_e = T_w - A_i P_i + A_o P_o - \rho_i A_i v_i^2 \quad (\text{A.5})$$

Where v_i is the steady internal fluid velocity. Steady flow is hence seen to modify the wall tension in a similar manner to internal pressure, i.e., by increasing the wall tension and leaving the effective tension unchanged. It should be observed that the increase in wall tension $\Delta T_w = \rho_i A_i v_i^2$ is independent of curvature and flow direction.

203 The steady fluid flow will introduce additional loading on a curved pipe exposed to dynamic excitation by e.g. forced support displacements. Model tests of a submerged U-shaped flexible hose considering a range of fluid velocity and support motion combinations have been conducted to investigate this effect (Sintef 1992). It was concluded that dynamic response was insignificantly influenced by the steady fluid flow, indicating that this loading type is of less importance for riser systems.

H 300 Accelerated uniform flow

301 Sudden stop or start of the internal fluid flow will cause an *accelerated uniform flow*. This flow pattern will result in a transient in-plane excitation of the riser system. The global response to this excitation can be predicted by nonlinear time domain analysis using the load model as described for slug flow conditions in H 400.

H 400 Slug flow

401 Slug flow is characterised by an alternating flow of liquid slugs and gas pockets. "Steady state" slug flow can be classified as either hydrodynamic slugging or terrain induced slugging governed by the site specific elevation profile of the flowline. Severe slug flow is typically related to the latter condition. Transient slug conditions can in addition occur during start-up, operational changes of flow rate and pigging operations. Slug volumes seen during pigging are usually the largest slug volumes seen during normal operation. For a more detailed discussion of slug flow characteristics as well as review of numerical simulation techniques to predict the slug flow, see e.g. Burke and Kashou (1995).

402 Slug flow can hence be considered as a time dependent variation of internal flow velocity and density at any location along the riser. Implementation of an adequate load model due to such flow conditions is needed for prediction of the global riser response due to slug flow by nonlinear time domain analyses. For such applications, it is convenient to parameterise the slug flow in terms of velocity, length and density of each individual slug as well

as the slug frequency defining the time interval between successive slugs. All these quantities may in general be considered as stochastic variables. Furthermore, the velocity, density and length will in general change (according to deterministic considerations) as the slug passes through the riser. All relevant data characterising the slug flow is input to the global response analysis and is typically established by numerical multi-flow simulations and/or laboratory measurements supported by field experiences.

403 The load model accounting for the slug flow must in general include contributions due to mass, weight, centrifugal force and the coriolis force as the slugs travel through the pipe (the latter term is often considered less important and consequently omitted). Furthermore, it is assumed that the slug flow and riser motions can be treated independently (i.e. the slug flow through the pipe is not influenced by the motion of the riser). For further details and examples of practical application see e.g. Fylling et al (1986), Patel and Seyed (1989) and Sanderson et al (1999)

404 Dynamic effects due to slug flow is normally most pronounced in areas along the riser with high curvature due to the centrifugal load component (e.g. hog/sag bend, close to supports, touch down area). Passage of large slugs through a gas riser may also introduce significant quasistatic change in riser configuration due to change in effective weight by the slug mass. In addition, slug frequencies close to governing eigenfrequencies of the riser system should be considered carefully. Response due to slug flow is expected to be most pronounced for deep water compliant gas riser configurations (e.g. metallic lazy wave configurations). Possible slug flow excitation should therefore always be carefully evaluated for deepwater compliant riser configurations.

I. Forced Floater Motions

101 Forced floater motions are defined as displacements imposed on the riser due to motions of the surface floater. These forced displacements may be introduced at several elevations on the riser depending on type of floater (e.g. Semi, TLP, Spar, Ship).

102 Riser support motions may be obtained in several ways, e.g. using time series from model testing, or coupled/de-coupled analyses, or frequency domain results. The most appropriate method (time-/frequency domain) has to be selected, depending on riser system and floater being considered.

103 The frequency domain solution implies selecting an appropriate quasistatic offset (mean + slowly varying) and heel/tilt (e.g. Spar) and superimposing the wave frequency (WF) motions. WF floater motions are usually given as RAO's (response amplitude and phase angle). Special care has to be exercised when transferring the RAO's from e.g. a motion analysis program to a purpose made riser analysis program.

104 If LF displacements/rotations are of importance for determination of resulting riser responses the optimum

solution is to perform time domain analyses (WF and LF included). Simplified frequency domain analyses can however be performed to assess the LF riser responses/importance.

105 High frequency (HF) motions (e.g. ringing and springing for TLP's) will usually not be of concern for the riser system. This has to be evaluated on a case by case situation. Typically, high ringing accelerations of a TLP may have to be evaluated in case of heavy riser components (trees) at deck level.

106 The presence of the floater gives rise to changes in the fluid kinematics (velocity, acceleration and direction). This disturbance is most easily determined by use of radiation/ diffraction analysis programs. The outputs from such programs are RAO's for disturbed kinematics (velocity components) consistent with the floater motion RAO's. For large volume floaters and risers located close to e.g. columns/pontoons, this disturbance must be determined and accounted for in design.

J. Hydrodynamic loading in moonpool

J 100 General

101 Treatment of hydrodynamic loading on slender structures in the moonpool may be of vital importance for some floater concepts (e.g. Deep draft floaters and shell Spar platforms)

J 200 Moonpool kinematics

201 Kinematics of the entrapped water in the moonpool area can in principle be treated in the same way as the disturbed wave kinematics described in section I (i.e. in terms of transfer functions for moonpool kinematics consistent with the hull motion transfer functions). This approach requires that the entrapped water is included in the hydrodynamic model used to compute the floater motion characteristics. Such calculations will however require a very careful modelling to achieve a realistic picture in case of complicated moonpool geometry and/or multiple risers in the moonpool. Special attention should be focused on possible resonant modes of the entrapped water.

202 Due to the complexity of the problem, it is often desirable to apply a simplified model in practical calculations.

A simplified model for the moonpool kinematics can be obtained by assuming that the entrapped water follows the hull motion rigidly. Fluid velocity and acceleration components can then be found at any location in the moonpool by straightforward transformations of the hull motions (i.e. translations and rotations at a specified location on the floater, centre of gravity is typically selected as motion reference point). This formulation is applicable for FD as well as TD analysis. The latter approach allows for consistent treatment of moonpool kinematics due to simultaneous WF and LF floater motions.

It is recommended that models of moonpool kinematics are verified against model tests.

J 300 Hydrodynamic coefficients

301 Uncertainty is connected to the hydrodynamic coefficients applicable inside a moonpool. Assuming that the entrapped water follows the hull motion rigidly, the hydrodynamic loading in the normal direction can be expressed as:

$$f_n = \frac{1}{2} \rho C_D^n D_h |v_H - \dot{r}_n| (v_H - \dot{r}_n) + \rho \frac{\pi D_b^2}{4} \dot{v}_H + \rho \frac{\pi D_b^2}{4} (C_M^n - 1)(v_H - \ddot{r}_n) \quad (\text{A.6})$$

where v_H , \dot{v}_H are the hull velocity and acceleration components normal to the riser.

302 The riser motions relative to the moonpool are to a large extent governed by how the riser is supported inside the moonpool. The riser motion in transverse moonpool direction will typically be constrained at several locations along the riser (e.g. shell Spar). The excitation force is hence not very sensitive to the C_D and C_M values due to the small relative motion between the fluid and the riser (see equation above). The "Froude Krylov"-term, i.e. the inertia contribution due to fluid acceleration, is governing for the excitation forces. Accurate assessment of the drag and inertia coefficients may therefore not be necessary for adequate modelling of hydrodynamic loading for this support condition. The C_M value will however influence the eigenvalues of the riser system.

303 Sensitivity studies considering riser dynamics and eigenvalues should always be performed to support decisions regarding choice of hydrodynamic coefficients to yield conservative response estimates. It should also be observed that the drag term will act as damping. A slightly low value is recommended as a conservative estimate.

K. Structural damping

K 100 Global Rayleigh damping model

101 The Rayleigh damping model commonly adopted for description of structural damping:

$$C = \alpha_1 M + \alpha_2 K \quad (\text{A.7})$$

This means that the global damping matrix (C) is found as a linear combination of the global mass (M) and global stiffness (K) matrices. α_1 and α_2 are denoted the mass- and stiffness proportional damping coefficients, respectively. The motivation for adopting this model is mainly due to computational conveniences. One of the advantages is that the damping matrix is orthogonal with respect to the eigenvectors of the system, which allows for a simple expression of the modal damping ratio \mathbf{x} (i.e. damping relative to critical) at angular frequency \mathbf{w} :

$$\zeta = \frac{1}{2} \left(\frac{\alpha_1}{\omega} + \alpha_2 \omega \right) \quad (\text{A.8})$$

102 In practical calculations, \mathbf{a}_1 and \mathbf{a}_2 can be selected to give required modal damping ratios ζ_i and ζ_j at specified angular frequencies ω_i and ω_j , respectively. Explicit expressions are given in standard textbooks on structural dynamics, e.g. Clough and Penzien (1975).

103 The proportional damping model applies to all global degrees of freedom and will hence give the same damping level in all parts of the structure. It should also be observed that the mass proportional damping would give damping due to rigid body motions. The mass proportional damping is therefore normally neglected for compliant structures undergoing large rigid body motions (Sintef 1992). For a stiffness proportional damping model, the structural damping at angular frequency ω is given by:

$$\xi = \alpha_2 \frac{\omega}{2} \quad (\text{A.9})$$

104 The stiffness proportional damping is seen to increase linearly with the frequency. In practical applications, \mathbf{a}_2 is selected to give a realistic damping level at the dominating *dynamic* frequency. For combined WF and LF response, \mathbf{a}_2 is selected to give a realistic damping at the dominating wave frequency (typically peak period in the wave spectrum). The proposed model will hence give damping in the wave frequency range (i.e. dynamic frequency range) and for all practical purposes no damping in the low frequency range (i.e. quasi-static frequency range). This is considered to be a realistic model, as damping is not considered to be of significance for prediction of the quasi-static low frequency response.

105 The Rayleigh damping model is applicable to all relevant global analysis strategies (nonlinear and linearized time domain and frequency domain analyses). However, application in nonlinear time domain analyses call for special attention. The global mass and stiffness matrices will in a nonlinear time domain analysis be a function of the instantaneous nodal positions and rotations. The following implementations of the Rayleigh damping model can hence be applied:

- *updated* formulation which means that the Rayleigh damping matrix is based on instantaneous mass and stiffness matrices;
- *constant* formulation which means that the Rayleigh damping matrix is based on mass and stiffness matrices at static equilibrium position (i.e. the damping matrix is kept constant throughout the analysis).

106 The latter approach is in general recommended due to better performance regarding numerical stability and computational efficiency. This is in particular the case for low effective tension problems using a stiffness proportional damping model. For such problems, damping is typically needed to stabilise the solution when geometric stiffness is lost due to low dynamic effective tension. The updated

stiffness proportional formulation would hence give a low damping when most needed to stabilise the solution.

K 200 Local Rayleigh damping models

201 The global Rayleigh damping model, as discussed in the previous section, applies to all global degrees of freedom and is hence limited to specification of an overall realistic structural damping level. However, for some applications it is desirable to have more flexible damping models. The following extensions of the Rayleigh model have been proposed:

- *local spatial damping* to facilitate specification of different damping levels in different parts of the structure. In practical implementation, this can be achieved by specification of damping coefficients for element subsets before assembly of global system matrices;
- specification of different damping levels in different local deformation modes (i.e. axial, bending and torsional deformation modes). In practical implementation, this can be achieved by specification of local damping coefficients related to axial, bending, and torsional deformations in local element system before transformation and assembly of global system matrices. For further details, see Bech et al (1992).

202 The local models can be applied in combination and used in updated as well as constant damping formulations as discussed in the previous section. The main drawback with the local damping models is that the orthogonality with respect to the system eigenvectors is lost. The simple closed form expression for modal damping presented above is therefore formally not applicable for specification of the damping level.

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APPENDIX B FATIGUE ANALYSIS

Contents

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A. General

A 100 Objective

101 This objective of this Appendix is to support section 5.E on fatigue assessment of risers subjected to repeated fluctuations and provide details on fatigue analyses methods recommended in Section 4.C 200. Extensive references are given to the DNV RP-C203, Fatigue Strength Analysis.

A 200 Application

201 The assessment procedure assumes that the riser has been designed in accordance with all other requirements in this standard.

A 300 Fatigue design

301 In general, the fatigue life of a component can be broken down into two phases: Crack initiation and propagation. In the case of un-welded components (e.g., seamless pipes and machined components), the crack initiation period represents the bulk of the total fatigue life. This is particularly noticeable at high fatigue lives where the fatigue crack initiation period may exceed 95% of the fatigue life. In the case of machined components, once a fatigue crack has grown to a detectable size, the component is virtually at the end of its useful life and will normally be withdrawn from service if repair is not possible.

302 In the case of welded joints, weld toe/root discontinuities are generally present. These behave as pre-

existing cracks. Consequently, the bulk of the fatigue life of a welded joint can be attributed to fatigue crack propagation.

303 The difference in the crack initiation phase of parent material and welded joints has significant effects on overall fatigue performance. In general, the fatigue strength of an un-welded component increase with material tensile strength due to the increased initiation life associated with higher strength materials. In the case of welded joints however, the fatigue strength is relatively unaffected by material tensile strength because the bulk of the fatigue life of a welded joint is spent in the propagation phase. Although crack propagation rates can change from one material to another and from one environment to another, there is no consistent trend with regard to tensile strength.

A 400 Methods for fatigue damage assessment

401 A typical sequence in fatigue design of a riser is shown in Table B-1.

Table B-1 Summary of a typical fatigue assessment procedure	
Task	Comment
Define fatigue loading.	Based on operating limitations including WF-, LF and possible VIV load effects.
Identify locations to be assessed.	Structural discontinuities, joints (girth pipe welds, connectors, bolts), anode attachment welds, repairs, etc.
Global riser fatigue analysis.	Calculate short-term nominal stress range distribution at each identified location.
Local joint stress analysis.	Determination of the hot-spot SCF from parametric equations or detailed finite element analysis.
Identify fatigue strength data.	SN-curve depend on environment, construction detail and fabrication among others.
Identify thickness correction factor	Apply thickness correction factor to compute resulting fatigue stresses
Fatigue analyses	Calculate accumulated fatigue damage from weighted short-term fatigue damage.
Further actions if too short fatigue life.	Improve fatigue capacity using.: <ul style="list-style-type: none"> — more refined stress analysis — fracture mechanics analysis. — change detail geometry — change system design. — weld profiling or grinding — improved inspection /replacement programme

For a general introduction to methodology for fatigue damage assessment, reference is made to DNV RP-C203 Sec 1.3.

B. Fatigue analysis procedures

B 100 General

101 Three different contributions to fatigue damage should be addressed: The wave-induced, the low-frequency and the vortex-induced stress cycles. The former two are addressed in the following, while the latter is described in Appendix E.

102 A general approach for calculation of wave- and low-frequency fatigue damage contributions is based on application of the following procedure:

- the wave environment scatter diagram is subdivided into a number of representative blocks;
- within each block, a single sea-state is selected to represent all the sea-states within the block. The probabilities of occurrence for all sea-states within the block are lumped to the selected sea-state;
- the fatigue damage is computed for each selected short-term sea-state for all the blocks;
- the weighted fatigue damage accumulation from all sea-states can be expressed as:

$$D_L = \sum_{i=1}^{N_s} D_i P_i \quad (\text{B.1})$$

Where

- D_L Long-term fatigue damage
- N_s Number of discrete sea states in the wave scatter diagram
- P_i Sea state probability. Normally parameterised in terms of significant wave height, peak period and wave direction, i.e. $P(H_s, T_p, q)_i$
- D_i Short term fatigue damage

B 200 Basic fatigue damage methodology

201 The basic fatigue capacity is given in terms of S-N curves expressing the number of stress cycles to failure, N , for a given constant stress range, S :

$$N = \bar{a} S^{-m} \quad (\text{B.2})$$

or equivalently:

$$\log(N) = \log(\bar{a}) - m \log(S) \quad (\text{B.3})$$

Where \bar{a} and m are empirical constants established by experiments.

202 The stress range to be applied in fatigue damage calculations is found by application of a stress concentration factor as well as a thickness correction factor to the nominal stress range :

$$S = S_0 \cdot \text{SCF} \cdot \left(\frac{t_3}{t_{\text{ref}}} \right)^k \quad (\text{B.4})$$

Where:

S_0 Nominal stress range

SCF Stress concentration factor

$$\left(\frac{t_3}{t_{\text{ref}}} \right)^k \quad \text{Thickness correction factor}$$

The thickness correction factor applies for pipes with a wall thickness t_3 greater than a reference wall thickness, t_{ref} , =25mm. The thickness exponent, k , is a function of the actual structural design and hence also related to S-N curve, see DNV RP-C203 Sec 2. and section E for further details.

203 Bilinear (two-slope) S-N curves in log-log scale are also frequently applied for representation of the experimental fatigue capacity data, i.e.

$$N = \begin{cases} \bar{a}_1 \cdot S^{-m_1} & S > S_{sw} \\ \bar{a}_2 \cdot S^{-m_2} & S \leq S_{sw} \end{cases} \quad (\text{B.5})$$

m_1 and m_2 are fatigue exponents (the inverse slope of the bi-linear S-N curve) and \bar{a}_1 and \bar{a}_2 are characteristic fatigue strength constant defined as the mean-minus-two-standard-deviation curve. S_{sw} is the stress at intersection of the two SN-curves given by:

$$S_{sw} = 10^{\left(\frac{\log(\bar{a}_1) - \log(N_{sw})}{m_1} \right)} \quad (\text{B.6})$$

N_{sw} is the number of cycles for which change in slope appears. $\log(N_{sw})$ is typically 6-7. For further details reference is made to DNV RP-C203.

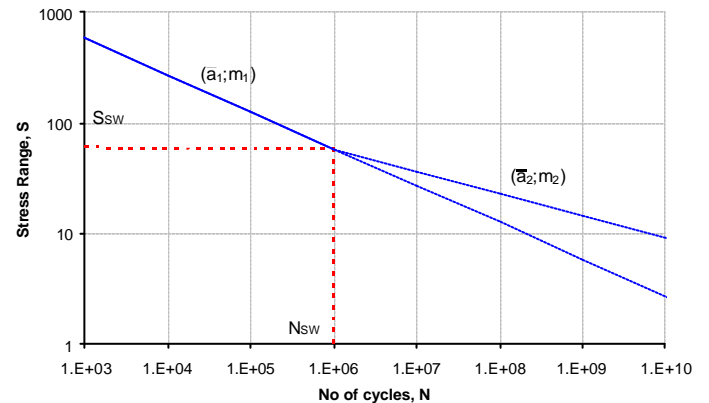


Figure B-1 Basic definitions for two-slope SN-curves

204 The Miner-Palmgren rule is adopted for accumulation of fatigue damage from stress cycles with variable range:

$$D = \sum_i \frac{n(S_i)}{N(S_i)} \quad (\text{B.7})$$

Where $n(S_i)$ is the number of stress cycles with range S_i and $N(S_i)$ is the number of stress cycles to failure as expressed by B.3.

The expected fatigue damage per unit time can for a linear S-N curve in log-log scale be expressed as:

$$D = \frac{f_0}{a} \int_0^{\infty} s^m f_s(s) ds = \frac{f_0}{a} E[S^m] \quad (\text{B.8})$$

Where f_0 is the mean number of stress cycles per unit time and $f_s(s)$ is the probability density function (PDF) for the stress cycles. The expected fatigue damage is hence directly related to the m -th order moment, $E[S^m]$ (or μ_m) of the stress cycle PDF. For a bi-linear SN-curve in log-log scale the corresponding expression becomes:

$$D = \frac{f_0}{a_2} \int_0^{s_{sw}} s^{m_2} f_s(s) ds + \frac{f_0}{a_1} \int_{s_{sw}}^{\infty} s^{m_1} f_s(s) ds \quad (\text{B.9})$$

Equation (B.8) and (B.9) constitutes the basic formulation for assessment of the short-term fatigue damage in each stationary environmental condition as expressed by (B.1).

(B.8) and (B.9) can also be applied to compute the long-term fatigue damage directly from the long-term distribution of stress cycles. For an introduction to methodology for establishment of long-term response distributions, reference is made to Annex C.

B 300 Global fatigue analysis procedures

301 The basis for fatigue damage calculations is global load effect analyses to establish the stress cycle distributions in a number of stationary short-term environmental conditions. The general principles for selection of analysis methodology and verification of simulation model as outlined in Annex A and Annex D respectively should be adhered to.

302 The short-term fatigue conditions should be selected carefully to give an adequate representation of the stress cycles for the lifetime of the riser system. The selection must be based on a thorough physical knowledge regarding static- and dynamic behaviour of the riser system with special attention to FE modelling, hydrodynamic loading, resonance dynamics and floater motion characteristics. Sensitivity studies should be performed to support rational conservative assumptions regarding identified uncertain parameters (e.g. soil properties for fatigue analysis in the touch-down area of SCR's)

303 Fatigue analysis will normally involve global load effect analyses in a number of low- to moderate sea-states. This is because the main contribution to the total fatigue damage in most cases comes from low- to moderate sea-states with high probability of occurrence rather than a few extreme sea-states. Compared to extreme response analysis, the degree of non-linearity involved is generally smaller. Adequate results can hence be obtained by use of linearized time domain- or frequency domain analyses in many cases. However, any use of simplified analysis methodology shall be verified against nonlinear time domain analyses.

304 The fatigue damage will generally have contributions from wave frequency (WF)- as well as low frequency (LF) stress cycles. The WF floater motions as well as direct wave loading on the riser govern WF fatigue damage, while the LF floater motions govern LF fatigue damage. The relative

importance of WF and LF fatigue damage is strongly system dependent and will in addition vary significantly with the location along the riser. It is always recommended to do an assessment of the relative contributions from WF and LF stress cycles to the fatigue damage to support rational decisions regarding choice of method of analysis. LF fatigue damage may be disregarded if it is documented by proper analyses that the LF fatigue damage is negligible when compared to WF fatigue damage.

305 Adequate fatigue life shall be documented for all parts of the riser system. Examples of critical areas wrt. fatigue damage of metallic risers are given in the following:

- the areas close to upper/lower termination of top tensioned risers will normally experience significant dynamic bending stress variation. Fatigue close to upper termination is normally governed by WF stress cycles while LF response may be of significance close to the seafloor termination. Accurate modelling of boundary conditions and stiffness properties is required (e.g. taper joints, stiffness characteristics of flex-joints etc);
- the splash zone is normally a critical area for top tensioned as well as compliant riser configurations mainly due to WF bending stress cycles. Description of wave loading up to actual wave elevation is of vital importance for accurate prediction of fatigue damage. Due regard should also be given to possible disturbances in the wave kinematics caused by the presence of the floater. Time domain analyses supported by sensitivity studies to confirm adequacy of load model is recommended (i.e. results are sensitive to mesh size as well as wave kinematics);
- seafloor touchdown area is a critical area for steel catenary risers and other proposed compliant riser configurations. Soil properties, mesh size and mean floater position are important for prediction of fatigue damage. Time domain analyses are generally recommended together with sensitivity studies to support rational conservative assumptions regarding soil properties. The adequacy of the mesh applied in the touchdown area should also be confirmed by sensitivity studies, and
- considerations regarding resonance dynamics and combined WF and LF fatigue damage are of special importance for spar risers (in particular for integral air-can solutions). Critical locations are typically close to riser supports in the hull area. Special attention should be given to possible LF stress cycles at the keel joint.

C. Narrow Band Fatigue Damage Assessment

C 100 General

101 The basic assumption in narrow-band fatigue damage estimation is that the stress cycles (S) can be determined directly from the stress maxima (S_a). Each cycle's range is assumed to be twice the value of the corresponding value of the local stress maximum, yielding:

$$S = 2 \cdot S_a \quad (\text{B.10})$$

Furthermore, the number of stress cycles per unit time is given directly by the zero crossing frequency, f_0 of the stress response process.

C 200 Narrow Band Gaussian Fatigue Damage

201 If the stress response process is assumed to be narrow banded and Gaussian, the distribution of local stress maxima, S_a , is defined by a Rayleigh probability density as:

$$f_s(s_a) = \left(\frac{s_a}{\sigma^2} \right) \exp \left(-\frac{s_a^2}{2\sigma^2} \right) \quad (\text{B.11})$$

where s_a is the local stress maximum and σ is the standard deviation of the stress response process.

202 For a linear SN-curve (in log-log scale) the fatigue damage per unit time can be expressed as:

$$D = \frac{f_0}{a} (2\sqrt{2}\sigma)^m \Gamma \left(\frac{m}{2} + 1 \right) \quad (\text{B.12})$$

where $\Gamma(\cdot)$ is the gamma function given by

$$\Gamma(\varphi) = \int_0^\infty e^{-t} t^{\varphi-1} dt \quad (\text{B.13})$$

203 For a bi-linear SN-curve (in log-log scale) the corresponding fatigue damage becomes

$$D = \frac{f_0 \cdot (2\sqrt{2}\sigma)^{m_1}}{a_1} G_1 \left\{ \left(1 + \frac{m_1}{2} \right) \left(\frac{S_{sw}}{2\sqrt{2}\sigma} \right)^2 \right\} + \frac{f_0 \cdot (2\sqrt{2}\sigma)^{m_2}}{a_2} G_2 \left\{ \left(1 + \frac{m_2}{2} \right) \left(\frac{S_{sw}}{2\sqrt{2}\sigma} \right)^2 \right\} \quad (\text{B.14})$$

where G_1 and G_2 is the complementary incomplete Gamma function and incomplete Gamma function, respectively

$$G_1(x, \varphi) = \int_x^\infty e^{-t} t^{\varphi-1} dt \quad (\text{B.15})$$

$$G_2(x, \varphi) = \int_{-\infty}^x e^{-t} t^{\varphi-1} dt$$

204 The fatigue damage is hence directly expressed by the standard deviation and zero-crossing frequency of the stress response process. This formulation is of special convenience for frequency domain analyses where results from the global analyses are expressed in terms of the auto-spectral density, $S_{\sigma\sigma}(\omega)$, of the stress response process.

The standard deviation, σ and zero crossing frequency f_0 are hence given as:

$$\sigma = \sqrt{m_0} \quad (\text{B.16})$$

$$f_0 = \sqrt{\frac{m_2}{m_0}} \cdot \frac{1}{2\pi} \quad (\text{B.17})$$

Where m_n is the n^{th} response spectral moment given by

$$m_n = \int_0^\infty \omega^n S_{\sigma\sigma}(\omega) d\omega \quad (\text{B.18})$$

C 300 Narrow Band Non-Gaussian Fatigue damage

301 For time domain analyses, the two-parameter Weibull distribution model is frequently employed as a generalisation of the Rayleigh distribution for the local maxima (i.e., for Non-Gaussian stress-response processes). The Weibull probability density function is given by:

$$f_s(s_a) = \alpha^{-\beta} \beta s_a^{\beta-1} \exp \left(-\left(\frac{s_a}{\alpha} \right)^\beta \right) \quad (\text{B.19})$$

Note that the Rayleigh distribution in (B.11) is obtained for $\beta=2$ and $\alpha = \sqrt{2}\sigma$

The Weibull distribution may be fitted to the short-term (or long-term) distribution of the local maxima. The Weibull distribution parameters (α : scale, β : shape) are linked to the statistical moments $\hat{\mu}$, $\hat{\sigma}$ for the local maxima as follows:

$$\hat{\mu} = \alpha \Gamma \left(1 + \frac{1}{\beta} \right) \quad (\text{B.20})$$

$$\hat{\sigma} = \alpha \sqrt{\Gamma \left(1 + \frac{2}{\beta} \right) - \Gamma \left(1 + \frac{1}{\beta} \right)^2}$$

These equations can be used to establish moment estimates of the distribution parameters with basis in sample estimates $\hat{\mu}$, $\hat{\sigma}$ from time domain simulations.

302 The fatigue damage per unit time in the general case of a bi-linear SN-curve can then be expressed analytically as follows:

$$D = \frac{f_0 \cdot (2\alpha)^{m_1}}{a_1} G_1 \left\{ \left(1 + \frac{m_1}{\beta} \right) \left(\frac{S_{sw}}{\alpha} \right)^\beta \right\} + \frac{f_0 \cdot (2\alpha)^{m_2}}{a_2} G_2 \left\{ \left(1 + \frac{m_2}{\beta} \right) \left(\frac{S_{sw}}{\alpha} \right)^\beta \right\} \quad (\text{B.21})$$

D. Wide band Fatigue Damage Assessment

D 100 General

101 For marine risers, the stress response is normally neither narrow-banded nor completely wide-banded. In a wide-band response a strict relationship between the stress cycles and stress maxima and minima do not exist. For this reason the distribution of stress cycles can not be evaluated

accurately from the distribution of stress maxima. The following procedures exist to describe fatigue damage for a wide band process:

- cycle counting algorithms,
- semi-empirical solutions, or
- simplified analytical solutions

102 Wide band fatigue assessment is of special importance for fatigue assessment of combined WF/LF stress response. It is in general applicable to results from time domain analyses but can also be applied in connection with frequency domain analyses through a transformation of frequency domain results to time domain (by e.g. FFT-simulation)

D 200 Cycle counting

201 The fatigue damage may be obtained by counting the stress cycles in the actual or simulated stress time histories. Specials purpose counting algorithms have been developed with techniques applicable to non-Gaussian stress time histories. The recommend method is the Rain Flow Counting (RFC) method.

202 The RFC method provides an estimate of the stress probability density function (i.e. sample estimate of $f(S)$ and of the average number of stress cycles per unit time.). For a linear S-N curve, (B.8) can subsequently be applied for estimation of fatigue damage in each stationary short-term condition. Extension to more general S-N curves (e.g. bilinear) is straightforward.

203 The response process due to combined wave- and low frequency excitation is generally wide-banded. Time domain simulation and cycle-counting procedures will accordingly be relevant.

204 Cycle counting methods represent time domain estimates of fatigue damage. Statistical uncertainties will therefore always be present in the estimates. Sensitivity studies should therefore be conducted to document that adequate fatigue damage estimates have been obtained. This is of special importance for combined WF/LF stress time histories or in cases with SN-curves with large (inverse) slope (i.e. large 'm').

D 300 Semi-empirical Solutions

301 A number of semi-empirical expressions have been proposed in the literature to correct the narrow band fatigue damage calculation for the effects of a broad bandwidth. An often used approach is based on the assumption that the true damage D_{RFC} (i.e. using a rain flow counting technique) can be established from a corrected narrow-band result:

$$D_{RFC} = D_{NB} \kappa_{RFC} \quad (B.22)$$

where D_{NB} is the narrow banded Gaussian fatigue damage given by C 200 and κ_{RFC} is a correction factor. Wirshing and Light, see e.g. Barltrop & Adams proposed the following expression:

$$\kappa_{RFC}(m) = a + (1-a)(1-\epsilon)^b \quad (B.23)$$

where

$$a = 0.926 - 0.033m$$

$$b = 1.587m - 2.323$$

where ϵ is the bandwidth parameter defined by (note that $\epsilon=1$ for a broad banded process and $\epsilon=0$ for a narrow banded process):

$$\epsilon = \sqrt{1 - \frac{m_2^2}{m_0 m_4}} \quad (B.24)$$

302 As a promising alternative, Dirlik, see e.g. Barltrop & Adams proposed an empirical closed form expression for the stress probability density function.

D 400 Analytical Solutions for Bi-modal Spectra

401 Accurate analytical solutions to fatigue damage estimates can be obtained for well-separated bi-modal stress spectra (e.g. a process with a combination of low frequency and wave frequency Gaussian component). Reference is given to Jiao & Moan (1990), where a correction function on a form similar to (B.22) have been derived by analytical means assuming two independent narrow-banded Gaussian process.

402 In case the process may be assumed to be composed of two independent Gaussian stress response processes an upper bound on the estimated fatigue damage can be obtained by adding the variances of the contributions directly. The zero-crossing frequency may be expressed as a combination of the respective zero-crossing frequencies based on expressions for the sum of two independent Gaussian processes.

E. Fatigue Capacity S-N Curves

E 100 General

101 The fatigue design is based on use of S-N curves obtained from fatigues testing. For practical fatigue design, welded joints are divided into several classes, each with a corresponding S-N curve. Fatigue capacity data for joint classifications of relevance for risers are given in Table B-2. The joint classifications apply to typical joints/details for risers subjected to cyclic bending moment and tension. For further details, reference is made to DNV RP-C203, Sec 2.3 and Appendix 1.

102 If fatigue data does not exist for the material, detail and environment under consideration, S-N curves should either be developed by testing, use of fracture mechanics assessment or by use of lower bound S-N curves. Special care shall be taken for chemical environments not covered by DNV RP-C203.

103 A stress concentration factor (SCF) applies to account for possible stress magnification due to imperfect geometry of two adjacent joints (e.g. due to fabrication tolerances and installation procedures). The SCF may be calculated by detailed FE analyses or by closed form

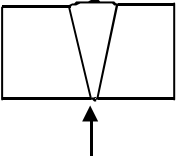
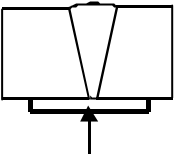
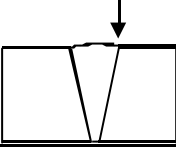
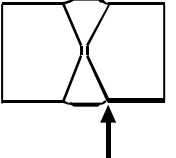
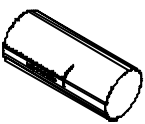
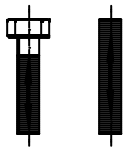
expressions for the actual structural detail. The following closed form expression applies for welded riser joints /1/:

$$SCF = 1 + \frac{3e}{t_3} \exp\left(-(D/t_3)^{-0.5}\right) \quad \textbf{(B.25)}$$

where e is the representative eccentricity due to geometrical imperfections to be applied in fatigue design. Assessment of

the representative eccentricity shall be based on detailed information regarding production tolerances and installation/welding procedures supported by rational conservative assumptions as appropriate for the actual design.

Table B-2 S-N curves for Risers

Description		Tolerance requirement ²⁾	S-N curve; according to DNV RP-C203	Thickness exponent k	SCF
Welding	Geometry and hot spot				
Single side		$e \leq \min(0.1t_3, 3 \text{ mm})$	F1	0.00	1.0
		$e > \min(0.1t_3, 3 \text{ mm})$	F3	0.00	1.0
		$e \leq \min(0.1t_3, 5.4 \text{ mm})$	F3	0.00	1.0
Single side on backing		$e \leq \min(0.1t_3, 2 \text{ mm})$	F	0.00	1.0
		$e > \min(0.1t_3, 2 \text{ mm})$	F1	0.00	1.0
		$e \leq \min(0.15t_3, 4 \text{ mm})$	F1	0.00	1.0
Single side		$e \leq \min(0.15t_3, 4 \text{ mm})$	D	0.15 ¹⁾	Eq. (E.1)
Double side		$e \leq \min(0.15t_3, 4 \text{ mm})$	D	0.15 ¹⁾	Eq. (E.1)
Seamless pipe			B1	0.00	1.0
Machined components			B1	0.00	FEM-analysis
Automatic longitudinal seam welded pipes			B2	0.00	1.0
Steel bolts and threaded joints in tension			F1 (cold-rolled) W3 (cut threads)	0.40 ¹⁾	1.0
<p>NOTE 1 The thickness penalty applies only for thickness greater than 25 mm. No benefit can be taken for sections thinner than 25 mm. For bolts, the reference thickness is the stress diameter.</p> <p>NOTE 2 For girth weld eccentricities greater than $0.15t_3$ or 4 mm, whichever is the smaller, special considerations apply, e.g. engineering critical assessment.</p>					

F. References

Bartrop & Adams "Dynamics of Fixed Offshore Structures", Third Edition, Butterworth & Heinemann.

Jiao, G. & Moan, T. "Probabilistic Analysis of Fatigue due to Gaussian Load Processes", Probabilistic Engineering Mechanics, 1990, Vol. 5, No.2.

APPENDIX C ASSESSMENT OF EXTREME LOAD EFFECT FOR COMBINED LOADING

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A. General

A 100 Objective

101 The objective of this Appendix is to provide an introduction to practical implementation of LRFD and WSD design checks for combined loading based on the generalised load effect formulation introduced in Section 3. The main focus is on consistent implementation of the LRFD design format.

102 Two fundamentally different methods can be applied for assessment of the characteristic load effects:

- Based on environmental statistics
- Based on response statistics

The purpose of this document is to give an outline of these strategies with emphasis on the computational efforts involved in practical applications as well as inherent limitations.

B. Design principles

B 100 General

101 Riser systems in general are highly non-linear structures due to nonlinearities introduced by hydrodynamic loading, geometric stiffness, large rotations in 3-D space and possible material nonlinearities as well as seafloor contact. The relative importance of these nonlinearities is strongly system and excitation dependent. Time domain finite element analysis therefore constitutes the primary method of analysis for slender structures. For a more detailed discussion, reference is made to Appendix A.

B 200 Design based on environmental statistics

201 It has traditionally been common practice to adopt the extreme response found by exposing the system to multiple stationary design environmental conditions as the characteristic extreme response. Each design condition is hence described in terms of a limited number of environmental parameters (e.g. H_s , T_p etc) and a given duration (e.g. 3-6 hours). Different combinations of wind, wave and current yielding the same return period for the combined environmental condition are typically applied. Examples of relevant combinations to obtain 100-years design conditions are given in Table C-1. The 'associated' return periods must be assessed with basis in environmental statistics for the actual location.

Table C-1 Examples of typical 100-years design environmental conditions

Case	Wind [year]	Waves [year]	Current [year]
A	100	Associated	Associated
B	Associated	100	Associated
C	Associated	Associated	100

202 Wind loading is indirectly included in the global riser system analysis as an important contributor to mean floater position and low frequent floater (LF) motions. Waves and wave frequent (WF) floater motions are included as dynamic loading in the global riser system analysis while LF floater motions normally are included as a representative static offset. The offset accounting for LF motions is additional to the mean floater offset governed by mean environmental loading. Reference is given to Appendix A for further discussion of analysis strategies. For guidance regarding calculation of representative floater offset, reference is made to e.g. section 6.2.2 in API RP 2SK.

203 Either regular or irregular wave loading is considered in the global response analyses. The former is denoted *design wave* approach while the latter is denoted a *design storm* approach.

204 The most severe directional combination of wind, waves and current consistent with the environmental conditions at the actual site should be applied for permanent installations. This will in most cases imply that waves, current and floater offset are (conservatively) assumed to act in the same direction. Analyses are performed for assumed critical directions (typically 'near, far and cross' conditions) and final characteristic response is identified as the most unfavourable from the analyses.

205 A wave period variation shall in addition be performed to identify the most unfavourable loading condition. At least 3 different periods covering a realistic variation range (e.g. 90% confidence interval) should be considered. Alternatively, simultaneous variation of wave-height and period (e.g. H_s , T_p) as described by environmental contours can be applied for more consistent identification of critical conditions.

206 The main problem related to design criteria based on environmental statistics is that the return period for the characteristic load effect is unknown due to the non-linear dynamic behaviour of most riser systems. This will in general lead to an inconsistent safety level for different design concepts and failure modes. Acceptable results can however be expected for quasistatic systems with moderate nonlinearities. A verification of design criteria should be performed in the following situations:

- New concepts
- Systems with significant nonlinear response characteristics
- Dynamically sensitive systems

The verification should be based on long-term extreme load effect assessment as discussed in section F for critical conditions.

B 300 Design based on response statistics

301 Consistent assessment of the D-year load effect will in general require a probabilistic response description due to the long-term environmental action on the riser system. The load effect with a return period of D-years, denoted x_D , can formally be found from the long-term load effect distribution as:

$$F_X(x_D) = 1 - \frac{1}{N_D} \quad (\text{C.1})$$

where :

N_D - total number of load effect maxima during D years.

$F_X(x)$ - long-term peak distribution of the (generalised) load effect

302 The main challenge related to this approach is to establish the long-term load effect distribution due to the non-linear dynamic behaviour experienced for most riser systems.

Guidance to possible computational strategies is further outlined in F. The described procedures have been applied for assessment of design loads for riser systems in research activities but are yet not established as standard industry design practise. However, design based on response statistics is in general the recommended procedure and should be considered whenever practical possible for consistent assessment of characteristic load effects (especially for verification purposes when shortcomings in the traditional approach based on environmental statistics have been identified). This is of particular importance for ULS conditions which normally are associated with the most pronounced nonlinear response characteristics.

C. Implementation of the LRFD design format

C 100 General

This section gives an introduction to consistent implementation of LRFD capacity checks for combined loading considering global time domain analysis. Main focus is placed on implementation of design equations for ULS conditions as this is the most general approach. Relevant simplifications in case of SLS and ALS conditions are briefly discussed. Acceptance criteria are established for design based on environmental statistics (short term approach) as well design based on response statistics (long term approach). Statistical techniques for extreme load effect estimation for a short- and long term design approach are discussed separately in E and F respectively.

C 200 Generalised load effect

201 Consistent treatment moment/tension correlation is a key issue for efficient capacity checks for combined loading. For this purpose it is convenient to consider generalised loading expressed by the following generic equation:

$$g(t) = g(M_d(t), T_{ed}(t), \Delta p, \mathbf{R}_k, \Lambda) \quad (\text{C.2})$$

Where $g(t)$ is the generalised load effect (or utilisation function) at a specific location on the riser and M_d , T_{ed} denote design values for bending moment and effective tension, respectively. Furthermore, Δp denote the local differential pressure, \mathbf{R}_k is a vector of cross-sectional capacities and Λ is a vector of safety factors (i.e. material-, safety class and condition factors). The importance of this formulation is that the combined time dependent action of bending moment and tension is transformed into a scalar process expressed by the generalised load effect.

C 300 Short-term acceptance criteria

301 The code checks for combined loading in a stationary design condition is hence reduced to extreme value prediction of the generalised load effect, i.e.

$$g_{\max} \leq 1 \quad (\text{C.3})$$

Where g_{\max} is a representative extreme value of $g(t)$. The maximum value of $g(t)$ applies in a design wave approach (excluding the start-up transient), while statistical extreme value prediction is required in a design storm approach, see below

302 The standard framework for response processing of results from time domain analyses can therefore be directly applied for code checks. This will typically include application of response envelopes in case of regular wave analysis and statistical extreme value prediction in case of irregular wave analysis

303 Statistical estimation of the expected extreme value (or most probable extreme value) for a given duration (e.g. 3-6 hours) is hence required in case of irregular analyses. It should however be noted that $g(t)$ always will be a non-Gaussian response process. This is because the bending moment components and effective tension normally are non-Gaussian response processes and because the limit state function defines a non-linear transformation of these time series. Expected extremes of non-Gaussian time histories are in practical applications normally estimated from a parametric probabilistic model (e.g. Weibull) fitted to the simulated realisation of individual response peaks (i.e. peaks of $g(t)$). Reference is made to E for a further discussion

304 This approach will automatically account for the correlation between effective tension and bending moment components and is hence capable of optimal design (i.e. allow for maximum utilisation).

305 Conservative estimates always could be obtained by separate estimation of design values for effective tension and resulting bending moment disregarding correlation effects which formally may be expressed as:

$$g(M_d^{\max}, T_{ed}^{\max}, \Delta p, R_k, \Lambda) \leq 1 \quad (\text{C.4})$$

where indices $^{\max}$ indicate extreme values. This approach may yield acceptable result when the design is driven by one dominating dynamic component (typically bending moment for top tensioned risers with well functioning heave compensation system).

C 400 Long term acceptance criteria

Consistent extreme load effect estimate for combined loading can be found as a percentile in the long-term distribution of the generalised load effect. The acceptance criterion can hence be expressed as:

$$x_D \leq 1. \quad (\text{C.5})$$

Where x_D is the percentile in the long term (generalised) load effect distribution corresponding to a return period of D-years. Techniques for establishment of the long-term load effect distribution are discussed separately in F.

C 500 ULS Analysis Procedure

501 Separation of global response into components due to functional and environmental loading is an additional key issue for ULS analyses, which require due consideration of analysis strategy as well as response post processing.

502 The basic force output from global time domain analyses are simultaneous time series of bending moments and effective tension. These response quantities contain contributions due to functional as well as environmental loading. Separation of these quantities into components requires that the static configuration due to functional loading is determined separately. The following analysis sequence can be applied:

1) Static analysis - functional loading.

The purpose of the 1st step in the analysis sequence is to establish the static equilibrium configuration due to functional loading (i.e. effective weight and nominal floater position). The analysis is typically started from an initial stressfree configuration with incremental application of functional loading to reach the final solution. The static force output is two axial bending moments and effective tension due to functional loading:

$$\begin{aligned} \vec{M}_F &= [M_{yF}, M_{zF}] \\ T_{eF} & \end{aligned} \quad (\text{C.6})$$

2) Static analysis - environmental loading.

This analysis is restarted from 1) considering additional loading due to steady current and mean floater offset due to environmental actions.

3) Dynamic time domain analysis - environmental loading.

This analysis is restarted from 2) considering additional relevant dynamic environmental loading on the system (e.g. loading due to wave action and floater motions, possible slug flow etc) The force output is simultaneous time histories of two axial bending moment and effective tension:

$$\begin{aligned} \vec{M}(t) &= [M_y(t), M_z(t)] \\ T_e(t) & \end{aligned} \quad (\text{C.7})$$

503 The referred global response quantities are assumed to contain the total response, i.e. dynamic components from environmental loading as well as static components due to functional and environmental loading. This is in accordance with the storage and output conventions applied in the majority of tailor made computer codes for slender structure analysis

In fact, this analysis sequence is convenient for application of static and dynamic loading and is used in the vast majority of design analyses. The distinction between static and dynamic environmental loading is always a key issue that must be evaluated carefully in view of the actual concept (e.g. static vs. dynamic current and LF floater motions). The only additional effort needed from the analyst is hence separate storage and treatment of the static response due to functional loading.

C 600 Post processing procedures

601 The post processing to compute the generalised load effect based on output from the ULS analysis procedure described in the previous section can be summarised in the following steps:

1. Establish response components due to environmental loading:

$$\vec{M}_E(t) = \vec{M}(t) - \vec{M}_F \quad (C.8)$$

$$T_{eE}(t) = T_e(t) - T_{eF}$$

2. Establish design values

$$M_d(t) = \frac{\left\| \gamma_F \vec{M}_F + \gamma_E \vec{M}_E(t) \right\|}{\sqrt{\left(\gamma_F M_{yF} + \gamma_E M_{yE}(t) \right)^2 + \left(\gamma_F M_{zF} + \gamma_E M_{zE}(t) \right)^2}} \quad (C.9)$$

$$T_{ed}(t) = \gamma_F T_{eF} + \gamma_E T_{eE}(t)$$

3. Establish time history of the generalised load effect

$$g(t) = g(M_d(t), T_{ed}(t), \Delta p, R_k, \Lambda) \quad (C.10)$$

602 SLS and ALS LRFD capacity checks can be based directly on time series for resulting moment and effective tension given as output from the global analyses. Consistent treatment of correlation requires that steps 2) and 3) in the post processing procedure discussed in the previous section is considered.

C 700 Computer implementation

701 The key to efficient LRFD capacity checks for combined loading is a computer implementation of the procedures described in the previous sections. The main technical features needed in to perform capacity checks in a stationary design condition can be summarised as:

- Separation of global load effects into E- and F-components
- Generate time series of the generalised load effect
- Processing results from regular/irregular dynamic analysis
- Analyse several E-,F- safety factor combinations
- Evaluate utilisation by non-Gaussian extreme value statistics
- Evaluate statistical confidence in extremes
- Evaluate contribution from P-,F-,E- loads
- Efficient communication with FE global analysis program
- Graphical presentation of results as a function of location along the riser.

Guidance note:

The following combinations of partial coefficients need to be checked for LRFD ULS conditions

g_f	g_e
1.1	1.3
1.1	0.77
0.91	1.3

- end - of - Guidance - note -

702 A computer program with the described functionality is capable of performing all relevant capacity checks for combined loading automatically with a minimum of input from the analyst. Application examples are presented by Sødahl et al (2000)

D. Implementation of the WSD design format

D 100 General

101 Practical implementation of the WSD design format for combined loading is simpler when compared to the LRFD ULS design checks because no separation of the load effect into F and E components is required. Implementation of the WSD design format is hence similar to the LRFD SLS and ALS design checks as discussed in section C 602. A brief introduction to implementation of WSD design checks is however given in the following for completeness.

D 200 Implementation in design analyses

201 The generalised load effect for the WSD design format for combined loading can be expressed as:

$$g(t) = g(M(t), T_e(t), \Delta p, R_k, \eta) \quad (C.11)$$

Where M , T_e , Δp and η denote bending moment, effective tension, local differential pressure and usage factor, respectively. The generalised load effect can hence be computed directly from the effective tension and bending moment components given as output from the global analyses. The resulting bending moment is computed as:

$$M(t) = \sqrt{M_x^2(t) + M_y^2(t)} \quad (D.12)$$

202 Evaluation of acceptance criteria based on the generalised load effect is identical as outlined in sections C 300 and C 400 for the LRFD approach

E. Short-term extreme load effect estimation

E 100 General

101 For a design storm approach, the extreme load effect can be estimated as the expected- or most probable largest response peak for the specified duration of the design

condition. This approach applies to SLS, ULS, and ALS design conditions.

102 Output from irregular time domain analyses using the analysis/post processing procedure as described in section B are time traces describing one realisation of the (generalised) load effect. The probabilistic distribution of the load effect process is in general is non-Gaussian. Furthermore, the duration of the simulated time record will in many situations be shorter than the specified duration of the design condition due to practical limitations related calculation time on the computer. Thus, extrapolation is often involved in practical estimation of characteristic extreme load effect. The process of obtaining extreme load effect estimates from time domain analyses will typically involve the following issues :

- Envelope statistics.
- Estimation of extreme values from non-Gaussian load effect time series
- Estimation of simulation length required to obtain extreme load effect estimates with sufficient statistical confidence

E 200 Envelope statistics

201 Response envelope is defined as extreme response values (minimum and/or maximum) attained during the time domain simulation as a function of location along the structure. This concept is very useful to establish design values in case of deterministic loading (e.g.. regular wave loading).

202 A more careful interpretation is however needed for application of the envelope concept in for application in a design storm approach. Envelopes from irregular time domain analyses will represent realisations of the extreme load effect for the duration considered in the time domain simulation. For prediction of characteristic extreme response it is hence required that the simulation time must be identical to the duration of the design condition (e.g. 3 – 6 hours). Furthermore, the extremes predicted in this way will have low statistical confidence as they only represent the extreme load effect found for one realisation.

203 Improved statistical confidence can be achieved by considering the average envelope found by averaging over several realisations. The average envelope will hence represent expected extreme load effect along the structure, which is the wanted output from short-term global response analysis. The statistical uncertainty can be expressed in terms of the standard deviation of the estimated expected extreme value, s_T :

$$\sigma_T = \frac{\sigma_E}{\sqrt{N_R}} \quad (\text{C.13})$$

where N_R is the number of realisations and s_E is the standard deviation of the extreme response estimated from all realisations. This “brut force” approach will yield unbiased extreme response estimates at any location along the structure, but is in most situations too time consuming to be of practical use. It can however be applied for simple systems

and for verification of more sophisticated statistical methods for prediction of extreme response based on one realisation.

E 300 Extreme response estimation

301 The main steps involved in statistical processing of stochastic load effect time histories to produce characteristic extreme load effect can be summarised as:

- Select probabilistic distribution model (i.e. parametric probabilistic model for individual response peaks or extreme peak for a given duration)
- Estimate parameters in the selected model based on the available response time history realisation
- Accept/reject the selected model (e.g. by use of engineering judgement or formal statistical hypothesis test)
- Compute estimate of characteristic extreme load effect based on the fitted model (i.e. percentile in fitted peak distribution or expected extreme peak value)
- Quantify statistical uncertainty of the estimated characteristic extreme load effect.

302 The major challenge is often related to selection of an adequate probabilistic distribution model for the individual peaks of the load effect process. Special attention must be placed on description of the upper tail of the distribution, which is of vital importance for estimation of extreme values. The choice of distribution model is complicated by the fact that the non-Gaussian response characteristic in general is strongly system and excitation dependent. A significant variation of the non-Gaussian response characteristics must in addition be foreseen along the riser. The choice of a proper distribution model will hence depend on the riser system, excitation level as well as location along riser. In most practical applications, the choice of probabilistic model is (at least to some extent) empirical, based on previous experience and physical knowledge of the dynamic behaviour of the actual riser system of concern (see also Appendix A for a discussion of governing nonlinearities). Simple parametric models (e.g. Normal, Rayleigh, Weibull, Exponential) are frequently applied.

303 The selected parametric model is fitted to the simulated peak sample using an appropriate statistical estimation technique (e.g. method of moments, probability weighted moments, maximum likelihood, regression, etc), For a more detailed discussion, reference is made to statistical textbooks, e.g. Bury (1975). A problem often encountered in practical applications is that fitted parametric model fails to describe the ‘true’ upper tail behaviour resulting in biased extreme value prediction. Special estimation techniques (tail fitting techniques) have been designed to improve the fit in the upper tail region at the expense of a somewhat increased statistical uncertainty (Sødahl and Larsen 1992).

304 Mathematical arguments in terms of limiting asymptotic distributions can in addition be applied to establish models for extreme peaks within a specified time window (e.g. Gumbel extreme value distribution, see Gumbel

1958) and for peak excesses over high thresholds (e.g. generalised Pareto distribution, see Davison and Smith 1995).

E 400 Statistical uncertainty and simulation planning

401 A fundamental problem related to estimation of characteristic extreme load effect is that statistical uncertainties are introduced because estimates are based on simulated time series realisations of finite lengths. Different realisations will consequently give different estimates of the extreme load effect. The estimation variability can be expressed in terms of the probabilistic distribution of the applied estimator, commonly denoted the sampling distribution. The sampling distribution can hence be applied to express the confidence of the estimated characteristic extreme response as a function of simulation length for each particular estimator of concern. This information can be applied directly in practical planning of computer simulations to estimate the simulation length needed to give estimates of characteristic extreme response with a specified confidence (Sødahl and Larsen 1992). The sampling distribution will also be the basis for selecting the most efficient estimator among several possible candidates.

402 The exact sampling distribution is in general very difficult to establish for finite samples and is in practical calculations normally approximated by the Gaussian distribution. This assumption is justified by theoretical results showing that the sampling distribution of most estimators of practical interest will approach the Gaussian distribution asymptotically as a function of sample size (see e.g. Cramer (1971) for moment based estimators). The sampling distribution can consequently be completely described by the mean value and variance of the estimator. Approximate techniques (e.g. asymptotic expressions) or numerical simulation techniques (e.g. bootstrap estimation) assuming a sample of independent stochastic variables is normally used to establish the variance. The independence assumption is normally an acceptable approximation for the peak sample.

403 For moment based estimators (i.e. estimators that can be expressed as a function of sample moments) the following relation between simulation length t_s and standard deviation of the estimator σ_T can be established by asymptotic approximations:

$$\sigma_T = \frac{c}{\sqrt{t_s}} \quad (\text{C.14})$$

where c is a (unknown) constant.

404 The following procedure can be applied for practical planning of simulations to obtain a target confidence specified in terms of the standard deviation σ_T^c :

- Perform time domain analysis with initial duration t_s^i
- Estimate extreme response and associated standard deviation of the estimate σ_T^i based on the initial duration t_s^i

- If target confidence is not obtained (i.e. $\sigma_T^i > \sigma_T^c$) the increased simulation length t_s^c needed to fulfil the confidence requirement can be estimated as:

$$t_s^c \geq t_s^i \left(\frac{\sigma_T^i}{\sigma_T^c} \right)^2 \quad (\text{C.15})$$

An important consequence of this equation is that an increase of the simulation length with a factor of 4 is required to reduce the standard deviation with a factor of 2.

F. Long-term load effect statistics

F 100 General

101 The long-term load effect distribution is a result of the combined wind, wave and current action on the coupled floater/slender structure system i.e. a probabilistic description of the response from the long-term environmental action. The long-term environmental loading process can be divided into time intervals with stationary conditions, denoted short-term conditions. It is further assumed that each short-term condition can be completely described by a limited number of environmental parameters (Waves will for example typically be described by significant wave height, peak period, spreading, mean direction etc). The long-term response distribution can hence formally be expressed as:

$$F_X(x) = \int_{\mathbf{M}} w(\mathbf{M}) F_{X|\mathbf{M}}(x | \mathbf{m}) f_{\mathbf{M}}(\mathbf{m}) d\mathbf{m} \quad (\text{C.16})$$

where :

$F_X(x)$	Long-term distribution of load effect peaks
\mathbf{M}	Vector of parameters describing short-term environmental conditions
$w(\mathbf{M})$	Weight function accounting for variation in load effect mean level crossing frequency
$F_{X \mathbf{M}}(x \mathbf{m})$	Short term distribution of load effect peaks for a stationary environmental condition (i.e. conditional on \mathbf{M})
$f_{\mathbf{M}}(\mathbf{m})$	Distribution of environmental parameters

102 The main challenge related to this approach is to establish the short-term load effect distribution $F_{X|\mathbf{M}}$ as nonlinear irregular time domain analysis in general will be required to give an adequate description of the response process.

103 Discrete approximations to this general formulation form the basis for approximate techniques for assessment of the long-term load effect distribution in practical applications. These methods have in common that simplifications are introduced in the long-term load effect description to enable practical computations. Simplifications are typically based on rational conservative assumptions regarding system behaviour with respect to e.g.

environmental directionality, wave/current correlation, floater position, operation of the system etc.

Guidance note:

The relative importance of waves, current and floater motions to the response of deep-water riser systems is strongly system specific. Floater type, station keeping system, riser configuration and boundary conditions will determine how the external loading is transformed into deformations and internal reaction forces in the riser. A significant variation in response characteristics along the riser must also be anticipated. Waves and floater motions will always be crucial for the response in the upper part of the riser. The situation is more complex in lower parts of deep-water riser systems. Floater offset and current are expected to be governing for the global response in lower parts of tensioned risers. Wave induced floater motions will normally be of some importance all along compliant riser configurations. Possible simplifications and conservative assumptions introduced to ease the design process of deep-water risers must therefore always be evaluated very carefully for each riser concept of concern. As an example, the commonly applied discrete formulation for environmental statistics described in terms of a H_s - T_p wave scatter diagram can be expressed as:

$$F_X(x) = \sum_{i=1}^N w(H_s, T_p)_i F_X^s(x | H_s, T_p)_i P(H_s, T_p)_i \quad (C.17)$$

Where:

N	Number of discrete sea states in the wave scatter diagram
$w(H_s, T_p)_i$	Weight factors accounting for variation in level crossing frequency
$P(H_s, T_p)_i$	Sea state probability
$F_X(x)$	Long-term distribution of load effect maxima
$F_X^s(x H_s, T_p)$	Short term distribution of load effect maxima

- end - of - Guidance - note -

F 200 Response surface approach

201 The response surface approach can be thought of as a direct numerical approximation to the general formulation as defined by Eq. (C.13). The computational efforts involved in such techniques are establishment $F_{X|M}$ by global load effect analyses in a limited number of carefully selected stationary environmental conditions considering irregular wave excitation. Interpolation/extrapolation techniques can then subsequently be applied to establish $F_{X|M}$ for all relevant environmental conditions required for assessment of the long-term load effect distribution. See e.g. Farnes & Moan (1993) for a flexible riser application example and Sødahl et al (2000) for a SCR application example.

202 The response surface approach can be formulated in the following steps:

1. Select a limited number of basic 'representative' seastates (i.e. combined environmental conditions).

These seastates will serve as 'interpolation points' and should hence be selected very carefully

2. Perform global response analysis for the basic seastates considering irregular time domain analysis.
3. Establish probabilistic models for the short-term load effect distributions for all basic seastates. Fitting a parametric model (e.g. Weibull distribution) to the simulated sample of load effect peaks is a typical procedure.
4. Establish short-term distributions for all relevant seastates by interpolation/extrapolation techniques using results obtained by analysis of the basic seastates as interpolation points.
5. Establish long-term response distribution by use of the discrete approximation to the general formulation defined in F 101.

203 The response surface will hence enable computation of the long-term load effect distribution considering a possible non-Gaussian short-term load effect characteristics. For practical application, it is however crucial that acceptable precision can be obtained by use of relatively few basic seastates (e.g. 5 or less).

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APPENDIX D VERIFICATION OF GLOBAL ANALYSIS MODEL

Contents

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- A 100 Objective
- A 200 Introduction

B. Verification of theoretical models

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- C 200 Spatial discretisation
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D. References

A. General

A 100 Objective

101 The purpose of this Appendix is to give an introduction to principles for verification of the computer model applied in global static- and dynamic finite element analysis, ref. Section 4.

A 200 Introduction

201 The computer model of a riser system represents two fundamentally different types of approximations to the physical system:

- Theoretical models;
- Numerical approximations;

202 The theoretical models represent the fundamental assumptions in terms of idealised models for the physical system. Examples of theoretical idealisations are environmental models (e.g. wave spectrum, Airy wave kinematics etc), load models (e.g. Morison equation, soil model etc) and models for structural behaviour (e.g. global cross-sectional models, Rayleigh structural damping, solution strategy etc.).

203 Furthermore, numerical approximations of the theoretical models are needed to facilitate computer solution. The numerical approximation will typically involve spatial discretisation of the structure into a finite number of elements as well as time- and/or frequency discretisation of the dynamic loading.

204 Hence, the key issue involved in verification of the computer model is to ensure that the theoretical models and numerical approximations represent the real physical behaviour of the riser system. As discussed in Appendix A C 200 the required accuracy is closely linked to the purpose of the analyses (e.g. feasibility studies, early design, detailed design, and final verification)

B. Verification of theoretical models

101 Global analyses should in general be performed with well-documented and verified computer codes for analysis of slender structures. Furthermore, accumulated experience expressed in terms of recommended practice for modelling and analysis should always be consulted.

102 However, it is crucial to have a basic physical understanding of the applicability and limitations in commonly used theoretical models. This is of particular importance for a critical assessment of modelling and analysis of new concepts and to ensure that adequate results are obtained when simplified modelling and analysis strategies are applied.

103 Any use of simplified analysis strategies will in general require benchmark validation by comparison to more advanced analysis procedures. Examples of typical situations are given in the following:

- Dynamic analyses should be considered to verify quasistatic assumptions;
- Linearized time domain analyses should be validated by nonlinear time domain analyses;
- Frequency domain analyses should be validated against time domain analyses;
- Verification of combined use of global and local quasistatic response models by comparison to a complete response model (e.g. quasistatic model for bend stiffener response);
- Floater/slender structure coupling effects should always be assessed by coupled analysis and/or model tests for deep-water mooring systems. This is of particular importance for turret moored ships at deep water locations;
- De-coupled floater motion analysis should be supported by coupled floater motion analysis when significant coupling effects are identified;
- Effects from simplified treatment of LF floater motions in terms of an additional offset should be evaluated for deep water concepts. Statistical correlation as well as effects from LF response on WF response (e.g. LF variation of effective tension) should be addressed. Such studies should at least be carried out for new deep-water concepts;
- Regular wave analyses should always be verified by irregular analyses. This is in particular important for systems that may be subjected to resonance dynamics;
- Many riser concepts are sensitive to wave loading in the splash zone. The effect of disturbed kinematics due to the presence of the floater should be carefully evaluated. Simplified modelling in terms of adjustments of hydrodynamic coefficients must be evaluated by more advanced techniques considering transfer functions for wave kinematics consistent with the floater motions;
- Any structural modelling simplifications to gain computational efficiency should be validated against a

more comprehensive structural model (e.g. omission of bending stiffness, simplified modelling of components, use of average of cross-sectional properties, simplified modelling of boundary conditions etc);

104 Analytical verification should be performed whenever possible to verify modelling and input parameters. Examples of simple analytical checks are given in the following:

- Verification of static effective tension distribution of top tensioned risers. The effective tension distribution of top tensioned risers can be found by accumulation of effective weight along the riser. This check represents a verification of the mass (pipe, components, internal fluid etc), buoyancy modelling (pipe, additional buoyancy components etc) and tensioner modelling of the system;
- The static configuration of single line compliant riser configurations can be verified by use of catenary equations disregarding the effect of bending stiffness. The catenary configuration solution will in most situations represent a close approximation because the effect of bending stiffness to the overall static configuration normally is negligible. Simple equilibrium iteration is however required in obtaining the static configuration (e.g. using the so-called 'shooting' approach). The primary purpose of this check is to verify mass and buoyancy modelling, but it will also give a verification of the shape of the static configuration;
- Eigenmodes of top tensioned risers can be verified by analytical calculations. Approximate solutions are given in terms of closed form expressions for tensioned beams and cables with uniform cross-sectional properties.

105 It has been experienced that surprisingly many modelling mistakes can be traced back to a few common problem areas. Two important examples are discussed below:

- Input of floater motion transfer functions in terms of amplitude and phase angle (or alternatively on complex form) as function of wave frequency and direction related to a local floater coordinate system. Definition of amplitude, phase angle, wave direction and floater coordinate system differ from program to program. Conversion between different definitions is usually required to apply output from hydrodynamic floater motion analysis (e.g. diffraction/radiation approach) as input in global riser analyses. Such operations should be performed very carefully with emphasis on thorough verification. Floater terminal point motion (i.e. motion of a point on the floater at some distance from origin of vessel coordinate system) generated in global riser analysis should in particular be verified by analytical calculations for different wave directions and floater directions. Animation showing floater motions, waves and riser deflections is a very useful tool for verification of floater motions;
- Buoyancy can be treated in terms of effective tension as discussed in Appendix A or alternatively by integration

of the hydrostatic pressure acting on the outer riser surface. Both formulations are correct and will hence give the same riser response when applied correctly. The latter formulation will however require a very careful modelling of the exposed outer area for complex riser systems with variable outer diameter (e.g. Spar risers, systems with attached buoyancy elements etc). It is therefore recommended that use of computer programs based on pressure integration for representation of hydrostatic pressure should be validated against other codes using the effective tension formulation.

106 Independent analyses of selected critical conditions are in addition highly recommended as a part of the design process of riser systems. The independent analyses should in principle always be carried out using a different recognised computer program. Furthermore, it is crucial to utilise information from model tests as well as full-scale measurements whenever possible for validation, calibration and enhancement of computer analysis of riser systems.

107 Sensitivity studies are also recommended to investigate the influence from uncertain system parameters (e.g. equivalent multipipe model, hydrodynamic coefficients in moonpool, soil data etc). The main purpose should be to quantify model uncertainties, support rational conservative assumptions and identify areas where a more thorough investigation is needed to achieve an acceptable modelling (e.g. calibration against model test).

C. Verification of numerical procedures

101 Numerical approximations will typically involve spatial discretisation of the structure into a finite number of elements as well as time- and/or frequency discretisation of the dynamic loading. Investigation of convergence in the solution by repeated analyses considering successive refinement of the discretisation is the basic principle to verify that the discretisation is adequate. The discretisation is considered adequate when the change in response between two successive discretisation is acceptable seen in relation to the purpose of the analyses. In this situation, there will be no practical gain by further refinement of the discretisation.

C 200 Spatial discretisation

201 Repeated static and dynamic analyses considering successive refinement of the element mesh can be applied to assess the adequacy of the spatial discretisation. Special attention should be given to the following parts of the riser system:

- Areas with high curvature (e.g. hog and sag bend);
- Contact areas (touch down, hull supports);
- Terminations to fixed structures;
- Areas with high load intensities (e.g. splash zone);
- Areas with significant change in cross-sectional properties (e.g. taper-joint, bend stiffener etc);

- Areas with change in element lengths. The relative change in length between adjacent elements with uniform cross-sectional properties should not exceed 1:2. A lower relative change may be required in case of non-uniform cross-sectional properties;

202 The convergence should be assessed for all relevant response quantities. This is because the rate of convergence normally will be different for different response quantities (e.g. slower convergence is normally observed for shear forces and bending moments when compared to effective tension).

203 The convergence study must be performed for the actual element used in the analyses. This is because e.g. beam elements based on conventional displacement formulation may display a significantly different numerical behaviour when compared to hybrid elements used in a mixed formulation. Furthermore, static as well as dynamic analyses should be considered in the evaluation studies.

C 300 Frequency discretisation

301 Floater motion transfer functions are represented in terms of amplitude and phase angle as function of a number of discrete wave frequencies and directions. The discrete frequencies and directions must be selected carefully to obtain an adequate description of the floater motions:

- The frequencies should be selected to cover the resonance peaks in vessel motion transfer functions (e.g. heave, roll and pitch resonance frequencies);
- Possible cancellation frequencies should be identified and covered by the discrete representation. (relevant for e.g. semi-submersibles and TLP's);
- The frequency range should cover relevant frequencies in the wave excitation. It should also be clarified how the actual computer program handles possible excitation outside the frequency range of the floater motion transfer function (this is a well known source to erroneous excitation);
- Discretisation of wave direction with a spacing in the range of 15-30 deg. is normally sufficient to give a good representation of the floater motions;

302 Results from frequency domain analysis are given in terms of auto- and cross-spectral densities at a number of discrete frequencies. The frequency spacing will hence be decisive for the variance and covariance found by integration of the corresponding response spectra. The adequacy of the frequency discretisation can be assessed by repeated analysis considering successive denser frequency spacing.

C 400 Time discretisation

401 Numerical time integration is applied in time domain analyses to produce discrete response time-series. Unconditional stable, single step integration procedures such as Newmark- β and Hilber-Hughes- α methods are frequently applied. The latter approach is normally preferred in variable time step algorithms due to explicit control of numerical damping to suppress possible high frequency

noise introduced by change of time step. Choice of time step is crucial for the stability and accuracy of direct time integration methods, some aspects are discussed in the following:

- The time step required to obtain a stable numerical solution is to a large extent governed by the highest eigenmode present in the discrete structural model. This is because all eigenmodes need to be integrated accurately to obtain a stable solution (i.e. also modes that are of no significance for the response description) Typical time step is in the range of 0.1- 0.4s for numerically well-behaved systems;
- Nonlinear analyses will in general require a shorter time step to obtain a stable numerical solution when compared to linearized analyses. This is in particular the case for numerical sensitive systems, e.g. systems with significant displacement dependant nonlinearities such as low tension problems including snap loading, instability problems, contact problems and significant nonlinear material behaviour (e.g. moment-curvature hysteresis);
- Variable time step integration methods may introduce high frequency noise when applied to numerically sensitive systems. It is therefore recommended to apply constant time step algorithms when analysing numerically sensitive systems. Use of variable time stepping procedures should at least be validated against constant time step algorithms when unphysical noise is detected in response time series;
- Quality checks of response time histories should always be considered to identify possible unphysical noise reflecting an inaccurate numerical solution. The overview statistics discussed in Appendix A is a very useful tool for detection of possible unphysical response peaks. Identified suspicious locations along the riser should be subjected to closer examination by spectral and statistical analyses as well as visual inspection of the response time histories;
- Study of convergence considering successive refinements of the time discretisation is a useful exercise to determine the required time step to obtain an adequate numerical solution.

402 Time domain analyses considering stochastic wave loading will typically require generation of discrete time histories for floater motions and wave kinematics according to a specified wave spectrum. The load time histories are represented in terms of a finite number of harmonic components. The amplitude of each harmonic component is normally computed from the specified spectral representation of the load process, while the phase angle is assumed to follow a uniform probabilistic distribution over the interval $(0-2\pi)$. Important aspects regarding load discretisation is discussed in the following:

403 The generation of load time histories can be carried out very efficiently by use of the FFT (Fast Fourier Transform) technique using equi-distant frequency representation of the load process. The main advantage of this approach is that almost no additional cost is related to use of many frequencies to describe the load processes. This

is of particular importance to describe the relevant frequency content of vessel motion transfer function and wave spectrum as well as the response process in case of resonance dynamics. The repetition period of the generated load time history is also uniquely determined by the frequency spacing of the harmonic components (see Appendix A). The main drawback is however that time series must be generated prior to the simulation at fixed locations along the riser. Interpolation in time and space is hence necessary during the simulation. The spatial interpolation should in particular be considered carefully to obtain an adequate representation of the loading close to sea surface. Variable spacing of interpolation points (i.e. points where load time histories are pre-generated) along the riser is normally considered to obtain efficient analyses. Benchmark validation by successive increase of number of interpolation points is recommended to verify the spatial interpolation. A time step in the range of 0.25-1s is typically sufficient to facilitate adequate time interpolation of WF excitation.

404 Direct accumulation of harmonic components representing floater motions and wave kinematics can alternatively be performed during the simulation to overcome the interpolation problem related to the FFT approach. The main advantage is that wave kinematics can be calculated at instantaneous spatial position allowing for consistent representation of wave kinematics in case of large riser displacements (e.g. combined LF and WF floater motions). This approach is however far more time consuming than the FFT approach and will only be applicable when relatively few frequencies are considered for representation of the load processes (typically 100-200). These frequencies must hence be selected very carefully to give an adequate representation of the loading (e.g. resonance peaks in the vessel motion transfer function and peak period in wave spectrum). Furthermore, use of variable frequency spacing is required to cover the relevant

frequency range with as few harmonic components as possible. Several strategies have been proposed, see e.g. Garrett et al (1995) and McNamara and Lane (1984). Benchmark validation by successive increase of number of frequencies is recommended.

405 An additional practical problem related to use of variable frequency spacing is that it is more complicated to assess the repetition period of the generated time histories. Approximate closed form expressions are available for some algorithms. Judgements based on the auto-correlation function estimated from the generated realisation can alternatively be applied to assess the repetition period (Garrett et al 1995).

406 The quality of the generated floater motions and wave kinematics depends on the ability of random number generator to produce statistically independent phase angles. The numerical behaviour of the random generator may depend on the actual computer used in the analyses. Quality checks of generated wave realisations are recommended in connection with new computer installations to ensure that the generated realisations are Gaussian. Statistical properties of the process and individual peaks should be considered for several realisations with rather long duration (e.g. 3-6 hours).

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APPENDIX E VIV ANALYSIS GUIDANCE

Contents

A. General

A 100 Objective

B. Fatigue Assessment

B 100 Simplified Assessment of Fatigue Damage

B 200 Multi-modal Response Analysis Based on Empirical Models

B 300 Methods Based on Solution of the Navier-Stokes equations

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A. General

A 100 Objective

101 This Appendix proposes a four-step method for assessment of Vortex-Induced riser response amplitudes and corresponding fatigue damage. These steps of increasing complexity is defined as follows:

- Simplified assessment of fatigue damage;
- Multi-modal response analysis based on empirical hydrodynamic coefficients (and tests);
- Computational Fluid Dynamics solving the Navier-Stokes equations;.
- Laboratory test.

102 The fundamental principle is that for cases where Vortex-Induced Vibrations (VIV) are likely to represent design problem, refined assessment methods preferably supplemented with tests are required.

Guidance note:

Often, the main design focus is to evaluate if the fatigue capacity is sufficient. Accordingly, a simplified (i.e. conservative) VIV analysis will suffice if the resulting fatigue damage is within the tolerated limit. If the simplified analysis indicates insufficient fatigue capacity, more sophisticated should be applied. The method should be chosen according to the specific case investigated.

- end - of - Guidance - note -

B. Fatigue Assessment

B 100 Simplified Assessment of Fatigue Damage

101 A simplified estimate of the induced fatigue damage can be computed by neglecting the influence of the waves, assuming undisturbed current velocities to apply. The

following procedure can subsequently be applied (B 102- B 106).

102 Identify the planes of vibration for the relevant mode shapes in relation to the specified current directions.

Guidance note:

For rotationally symmetric riser systems, the cross-flow vibration will generally be perpendicular to the current direction. For non-symmetric systems, the cross-flow vibration is assumed to occur in the plane of the relevant mode-shapes

- end - of - Guidance - note -

103 Identify dominant mode shapes and natural frequencies as follows:

- a) Determine the natural frequencies and mode shapes for bending in the cross-flow direction based on analytical models or by numerical FEM analysis.
- b) Define a band of local vortex shedding frequencies f_s along the riser using:

$$f_s = S_t \frac{U}{D} \quad (\text{E.1})$$

Where U is the local tangential flow velocity and D is the outer riser diameter. S_t is the Strouhal number where upper and lower bound values should be checked (Typically $S_t = 0.14$ to 0.25)

- c) For each mode, check for which parts of the riser the natural frequency for the mode is within the limits of the local shedding frequency.
- d) Identify the most likely mode shapes to be excited by VIV and select the one with the highest curvature for a unit modal amplitude. Typically, this will be the mode with the highest frequency among the “probable modes”

104 For a given flow velocity compute the vibration amplitude for the anticipated mode according to Sarpkaya (1979):

$$\frac{A}{\gamma D} = \frac{0.32}{\sqrt{0.06 + (2\pi \cdot S_t^2 \cdot K_s)}} \quad (\text{E.2})$$

Where K_s is the stability parameter, and γ is the mode participation factor, see e.g. Blevins (1990).

105 Compute corresponding stress range:

$$S = A \text{ SCF} \cdot E \cdot \kappa \cdot (D-t) \quad (\text{E.3})$$

where E is the modulus of elasticity and SCF is a stress concentration factor. κ is the curvature of the mode shape $\phi(s)$ at the point (s, $\phi(s)$) to be calculated as:

$$K(x) = \frac{\partial^2 \phi}{\partial s^2} \left(1 + \left(\frac{\partial \phi}{\partial s} \right)^2 \right)^{-3/2} \quad (\text{E.4})$$

Guidance note:

If a finite element model is applied, the stresses corresponding to unit mode shape amplitude is first computed based on the stiffness matrix for the relevant element. The resulting stress range is subsequently obtained by multiplication with 2 A SCF.

- end - of - Guidance - note -

106 The fatigue damage is estimated by application of the relevant SN-curve as:

$$D_F = \frac{f_n \cdot T_L}{a} \cdot S^m \quad (\text{E.5})$$

where f_n is the frequency of the relevant mode, T_L is the design life of the riser, S is stress range and m and a are constants defining the SN-curve, see Appendix B.

For screening purposes a 1-year velocity with associated velocity profile is considered conservative. Otherwise, a weighted summation of computed damage over the long-term current distribution for velocities and direction must be performed.

B 200 Multi-modal Response Analysis Based on Empirical Models

201 If significant VIV induced fatigue damage is likely, more thorough calculations should be conducted. The next level of refinement is typically methods for multi-modal response analysis based on empirical or semi-empirical values of the hydrodynamic coefficients. One way of achieving this is by application of a generalisation of the procedure described above. There are also two other main approaches for calculating the response:

- Calculate modal response in the frequency domain. This approach can incorporate general current profiles. A correlation function for the loading process at two points along the riser is introduced. Subsequently, a double integration is performed. The parameters entering the calculation of load and response generally requires calibration with model field data.
- Calculate response in the time domain. Here one must have a considerable database of cross-section tests giving force coefficients, frequencies and phase angles for various combination of incident velocity and cross-section vibration. In the end such a simulation would hopefully stabilise or maybe repeat, and a response spectrum can be retrieved.

Guidance note:

For vertical risers in well-known environmental conditions recognised semi-empirical programs may be applied, see e.g. SHEAR7 (Vandiver & Li, 1996). Larsen and Halse (1995) conducted a comparison between programs showing considerable discrepancies concluding that at present no generally accepted program exist for calculation of VIV response. The excitation is directly dependent on the response.

Jumps from one mode to another may happen. Proper force coefficients for vibrations including more than one frequency are still lacking.

- end - of - Guidance - note -

B 300 Methods Based on Solution of the Navier-Stokes equations

301 The analysis based on solution of the full Navier-Stokes equations implies a set of two-dimensional fluid-flow analysis for sufficiently many cross-sections along the riser, also including modelling of the dynamic boundary conditions. The direct solution of the complete flow equation is until now restricted to low Reynolds numbers (no turbulence in the near wake). However, for marine risers the wake will be turbulent, requiring very small time-steps or a good turbulence model. Even if this approach at present stage is very time consuming and possibly not correctly modelled for high Re, it is likely that this will be a feasible approach in the future.

302 For compound multi-pipe riser geometries, the computations generally become increasingly complex and time consuming. Validation of the numerical results by sensitivity studies with respect to key parameters should accordingly be performed. Comparison with results obtained from full-scale or model experiments is also essential for calibration and fine-tuning of the numerical algorithms.

C. Methods for reduction of VIV

101 If the calculated VIV-response is a problem, there are two main approaches:

- Modify the properties of the riser, i.e., tension, diameter, structural damping.
- Introduce vortex suppression devices.

C 200 Modification of Riser Properties

201 There are several different ways of reducing the amplitude of vortex induced vibration. It is usually possible to avoid the resonant cross-flow region when the highest reduced velocity is below 3, i.e. below the resonant region. To be well above the resonant area is much more complicated. There will always be a higher natural mode with a frequency that corresponds to f_s . However, according to Vandiver (1993), the presence of shear flow in the region of the higher modes greatly reduces the probability for lock-in.

202 A different approach is to increase the reduced damping. Blevins (1990) states that a reduced damping greater than 64 reduces the peak amplitudes to less than 1 % of the diameter. In marine applications, the reduced damping is usually lower than one and it is very seldom possible to increase the damping to such an extent.

C 300 Vortex suppression devices

301 A second possibility is to add vortex suppression devices to the cylinder. Zdravkovich (1981) classifies the

means of suppression to three categories according to the way it influence the vortex shedding:

- surface protrusions (wires, helical strakes etc.) triggering separation;
- perforated shrouds, axial slats etc. (breaking the flow into many small vortices); and
- near wake stabilisers, preventing the building of the vortex street.

In Blevins (1990), eight different devices are shown, and comments on their use and effects are given. Common for all (except the ribboned cable) is that they increase the cost of the riser, and that they will complicate handling during installation. Some of the devices also reduce the drag coefficient, especially the streamlined fairing. However, in most cases the in-line drag coefficient is increased rather than being reduced by introducing vortex suppression devices.

D. References

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APPENDIX F FRAMEWORK FOR BASIS OF DESIGN

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A. General

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B. Design basis

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- B 200 General design requirements
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A. General

A 100 Objective

This Appendix defines the items normally to be included in the design basis document.

A 200 Application

Design basis shall be prepared for all risers.

B. Design basis

B 100 General

101 A design basis document shall be created in the initial stages of the design process to document the basis criteria and analysis methodology to be applied in the structural design of the riser system.

102 When the design has been finalised, a summary document containing all relevant data from the design and fabrication phase shall be produced, i.e. a Design, Fabrication and Installation (DFI) résumé.

103 This section presents the essential of the information that must be available to the designer, in order to be able to design the riser according to this standard. This information is normally included in a design basis document.

104 Typical information needed to perform a riser design includes as a minimum:

- general riser system design requirements;
- functional requirements of the riser system;
- operational requirements of the riser system;
- internal fluid data;
- environmental data;
- floater data;
- interface requirements and equipment/component data;
- structural analysis methodology including load cases to be considered;
- verification procedures;

— miscellaneous.

B 200 General design requirements

201 The operator should specify project specific design requirements, e.g.:

- riser location;
- general requirements;
- description of the riser system including extent, main interfaces, configuration, boundary conditions, main dimensions and main components;
- choice of applicable design codes, standards and regulations;
- nominal and minimum internal diameter of equipment bores interfacing with the riser;
- length of each component type;
- number off, for each component type;
- required service life;
- testing ;
- fire protection ;
- material selection, coating, corrosion protection and corrosion allowances.

B 300 Internal fluid data

301 The operator should specify all relevant internal fluid parameters. As relevant, the parameters listed in Table F-1 should be specified. For uncertain data, the parameters should be specified as realistic ranges (min/normal/max). Expected variations in the internal fluid parameters over the service life should be specified.

302 If temperature and pressure is correlated, extreme combinations of temperature and pressure may be provided in the form of a design envelope diagram.

303 If rapid decompression of internal gas may occur, the corresponding adiabatic temperature drop inside should be calculated by the supplier, and reflected in the minimum design temperature.

Table F-1 Internal fluid parameters	
<i>Parameter</i>	<i>Comment</i>
Internal pressure	The following internal pressures should be specified: <ul style="list-style-type: none"> — maximum internal pressure including operating, design and incidental pressure with possible pressure profile through service life ; — mill and system test pressure requirements ; — minimum internal pressure (including vacuum condition if applicable).
Temperature	The following temperature should be specified: <ul style="list-style-type: none"> — operating temperature or temperature profile through service life ; — design maximum temperature ; — design minimum temperature ;
Fluid composition	Including produced fluids, injected fluids, exported fluids, and continual and occasional chemical treatments (dosages, exposure times, concentrations and frequency) ; <ul style="list-style-type: none"> — all parameters which define service conditions, including partial pressure of H₂S (sour) and CO₂ (sweet) ; — fluid density range corresponding to relevant pressure and temperature ; — fluid/flow description including fluid type and flow regime. ; — sand or particle erosion data ;.
Service definition	Sweet or sour in accordance with fluid composition.
Fluid/flow description	Fluid type and flow regime including slugs. Annulus fluids for multipipe systems
Flow rate parameters	Flow rates, fluid density, viscosity.
Thermal parameters	Fluid heat capacity.

B 400 Environmental data

401 The operator should specify all relevant environmental parameters. As relevant, the parameters listed in Table F-2 should be considered. Combined wind, wave and current conditions should be specified for relevant return periods (e.g. 1, 10 and 100 year return periods).

402 For temporary (retrievable) risers, the operator should specify the required range of environmental conditions (weather window) and planned field locations for which the riser should be suitable.

403 For environmental conditions at the limits of the weather window, it should either be possible to safely retrieve the riser, or it should sustain being hang-off throughout a design storm specified by the operator.

Table F-2 Environmental parameters	
<i>Parameters</i>	<i>Comment</i>
Location	Geographical data for planned fields of operation.
Water depth	Design water depth (minimum and maximum), tidal variations, storm surge and subsidence.
Seawater data	Density, pH value, and minimum and maximum temperatures.
Air temperature	Minimum and maximum during storage, transportation, installation and operation.
Soil data	Description, shear strength or angle of internal friction, friction coefficients, seabed scour and sand waves (soil/well and/or soil/pipe structure interaction characteristics). To be used for analysis/design riser base foundation, soil restraint for conductors and soil/structure interaction evaluation for touch down region for catenary risers.
Marine growth	Maximum values and variations along length of thickness, density and surface roughness.
Current data	Current velocity as a function of water depth, direction and return period, and including any known effects of local current phenomena.
Wave data	In terms of significant and maximum wave heights, associated periods, wave spectra, wave spreading functions and wave scatter diagrams as function of direction and return period.
Wind data	Wind velocity as function of direction, height above water level and return period.
Ice	Maximum ice accumulation, or drifting icebergs or ice floes.
Earthquake data	Ground motions described by means of spectra or time series.

B 500 Data for Floater and Station-keeping System

501 The operator shall specify all data for the floater and station-keeping system of relevance for design and analysis of the riser system.

502 The following general floater data should be included as relevant for the actual installation:

- Main hull dimensions;
- Detailed hull geometry, draughts, mass, radii of gyration etc required to perform hydrodynamic motion/excitation analysis of the floater;
- Detailed moonpool geometry, if relevant;
- Location of riser supports and riser supporting structures/devices (e.g. tensioner, moonpool supports etc)
- Specification of possible interference areas, including other risers, mooring lines, platform columns, floater pontoons, keel, surface equipment and deck, surface jumper and deck, etc. and definition of allowable interference/clashing if any.

503 Floater motion characteristics should normally be specified in the design basis. The following information is required for documentation of the floater motion characteristics:

- WF floater motion transfer functions in 6 degrees of freedom with a clear cut definition of amplitudes and phase angles as well as wave directions;
- The floater motion transfer function shall be given for relevant loading conditions (i.e. draughts);
- The actual water depth at the location and together with the slender structure restoring force for the actual mooring/riser system design shall be applied in calculation of WF floater motion transfer functions;
- The floater attached coordinate system used as reference for floater motion transfer functions shall be documented in terms of origin (i.e. motion reference point) and directions of coordinate axes. ;
- DP system performance (e.g. position tolerances and capability curves), if relevant
- Mean position and second order motions for relevant design conditions including intact as well as damaged conditions due to e.g. mooring line breakage shall be specified;

504 The design basis document may include relevant data for evaluation of the global performance of the installation. The following additional information is required to conduct coupled and /or de-coupled station-keeping analyses

- WF and LF transfer functions for hydrodynamic excitation on the floater.
- Frequency dependent added mass and damping for the floater.
- Wind- and current coefficients for the floater.
- Detailed description of the tethers/mooring system. For slack/semi-taut/taut mooring systems this will typically include lay-out pattern of the mooring lines and detailed mooring line composition (e.g. material data, description of possible clump weights/buoys, suspended line lengths, location of anchors and floater attachment points etc)
- DP system characteristics in case of DP assisted mooring systems
- Detailed description of the riser system
-

A clear cut definition of must be provided for transfer functions and coefficients (e.g. reference coordinate system, directions, amplitudes and phase angles etc) to allow for implementation of these data in the actual software for station-keeping analysis.

B 600 Riser system and interfaces

601 The customer should provide the required information on any interfaces between riser pipe and adjacent structures, equipment and component data.

602 An overall lay-out of the riser system should be provided together with a clear definition of scope of design, i.e. specification of which parameters/components of the riser system that are subject to design (typical examples are wall thickness, material quality, buoyancy modules, stress joints etc). Indications of preferred solutions should be given to the extent possible. Examples of information that may be included in the design basis document are:

- Riser configurations;
- Arrangement of risers, in case of more than one riser ;
- Riser joints including cross section data, annulus content, riser joint length, connectors, attachments etc;
- Description of buoyancy modules such as air-cans, mid-water arch and distributed buoyancy modules;
- Description of additional external lines , umbilical etc;
- Description of structural components of relevance for the actual installation (e.g. stress joints, flex joints, mechanical connectors, tension joint, ball joints emergency disconnect package, etc)

603 A general description of the top interface between riser system and adjacent structure should include information, such as:

- Floater support boundary conditions;
- geometry, stroke, pulling capacity, load/displacement characteristics (linear/nonlinear) and failure tolerance of tensioner systems, if any;
- design of temporary and permanent riser top suspension systems (spiders, etc.);
- surface equipment like surface flow tree, jumpers, etc.

604 A general description of the bottom interface and subsea equipment should be included in the design basis document. The following information may be included as relevant for the actual installation:

- wellhead datum relative to sea level;
- seafloor conditions including characteristic soil properties (e.g. stiffness, friction coefficients etc);
- conductor stiffness and soil restraint;
- subsea template dimensions and stiffness ;
- subsea equipment like BOP, subsea tree, EDP, LMRP, LWRP, etc.

605 The operator should provide information on the permissible loading (e.g. pressure, tension and bending moment) of the wellhead equipment and the top suspension, to which the riser is connected.

606 For temporary top tensioned risers, the maximum allowable disconnect angle of the emergency disconnect package (EDP) should be defined by the operator for input to the operating condition limits for the riser analysis.

607 For risers equipped with flex-joints, the maximum permissible deflection angle should be defined for the relevant tension and pressure ranges.

B 700 Analysis methods and load cases

701 The intended procedures to be adopted in the design of the risers shall be documented. All applicable limit states for all relevant temporary and operational design conditions shall be considered. The following should be included:

702 Design criteria for all relevant temporary phase conditions including, as relevant:

- limiting pressure, functional and environmental load criteria and design load combinations (cases) ;
- essential design parameters and analytical procedures associated with temporary phases e.g. transportation, lifting/handling, installation, retrieval, connection and disconnection ;
- relevant ALS criteria ;
- riser abandonment.

703 Design criteria for all relevant operational phase conditions including, as relevant for the actual installation:

- limiting pressure, functional and environmental load criteria and design load combinations (cases) ;
- essential design parameters and procedures associated with operational phases e.g. top tension, vessel offset, internal pressure and related internal fluid density;
- relevant ALS criteria, e.g. tensioner failure, drive/drift off, collision, explosion, fire, dropped objects etc;
- relevant SLS criteria for the riser pipe and structural components

704 A general description of analysis models to be utilised, including description of :

- global analysis model(s) including modelling for wave and current loading and floater motions;
- local analysis model(s);
- load cases to be analysed.

705 A general description of the structural evaluation process, including:

- description of procedures to be utilised for considering global and local responses;
- description of procedures to be utilised for combining global and local responses;
- criteria for limit state checking;
- description of fatigue evaluation procedures (including use of design fatigue factors, SN-curves, basis for stress concentration factors (SCF's), etc.) ;
- description of procedures to be utilised for code checking.

B 800 Miscellaneous

801 A general description of other essential design information, including:

- in-service inspection criteria general philosophy for inspection, maintenance and repair/replacement;
- Procedures/scope for verification of the riser design (e.g. testing and independent review/analyses of the design);
- weak links (if relevant).