GUIDANCE NOTES ON

SUBSEA HYBRID RISER SYSTEMS

JANUARY 2017

American Bureau of Shipping
Incorporated by Act of Legislature of
the State of New York 1862

ABS Plaza
16855 Northchase Drive
Houston, TX 77060 USA

Foreword

These Guidance Notes describe suggested practice for the design, materials, testing, manufacturing, installation and maintenance of hybrid riser systems to be classed or certified by ABS. These Guidance Notes are to be used in conjunction with other Rules and Guides published by ABS as specified herein, in particular the ABS *Guide for Building and Classing Subsea Riser Systems*. During the preparation of these Guidance Notes, ABS recognized that industry participation is a vital factor both to the rapidly progressing nature of this technology, and for the success of developing an appropriate standard which satisfies practical classification requirements. ABS appreciates the industry's input in the development of these Guidance Notes.

These Guidance Notes reflect the latest technology developments and industry practice for hybrid riser systems for deepwater installation. These Guidance Notes indicate detailed guidance for hybrid riser systems from configuration selection, engineering design to offshore installation. This does not exclude the use of other practices for a hybrid riser system, provided that relevant industrial design codes are followed, sound engineering practice is implemented, and justification for the use is adequately documented. Riser design engineers are encouraged to consult fabrication and installation specialists to establish the presence of constraints that will affect the design.

These Guidance Notes become effective on the first day of the month of publication.

Users are advised to check periodically on the ABS website www.eagle.org to verify that this version of these Guidance Notes is the most current.

We welcome your feedback. Comments or suggestions can be sent electronically by email to rsd@eagle.org.

Terms of Use

GUIDANCE NOTES ON

SUBSEA HYBRID RISER SYSTEMS

CONTENTS

This Page Intentionally Left Blank

SECTION 1 Introduction

1 Overview

The principal elements of a subsea hybrid riser system are a vertical, or catenary, steel riser(s) tensioned by a near subsurface buoyancy tank, and a flexible jumper connecting the riser(s) to a floater. The vertical, or catenary, riser(s) may be anchored to the seabed using a foundation pile or connected to a flowline end termination (FLET) directly.

A hybrid riser system may be installed before or after the Floating Production Installation (referred to herein as an FPI, or floater) is moored on site; (e.g., a Floating Production Storage and Offloading (FPSO) installation). The riser's own weight is supported by the buoyancy tank, resulting in lower reactions on the floater. The flexible jumper allows the riser to be substantially decoupled from the floater's motions, which makes the riser fatigue response typically insensitive to the floater's motions.

A hybrid riser system configuration combines the features of tensioned and compliant risers in an efficient manner. Most proposed designs are based on combining a self-supporting vertical riser column (e.g., by means of a buoyancy tank) with a flexible jumper at the upper end for connection to a floater. However hybrid risers tend to be very complex structural systems with special design challenges for both in-situ conditions as well as during the installation phase.

Hybrid riser systems are a field-proven concept; they have been installed in the Gulf of Mexico, offshore Brazil and offshore West Africa. Hybrid riser systems have been installed in water depths ranging from 1,500 ft. to over 8,600 ft.

Hybrid riser systems can be associated with any floater type. Typically such systems have been used with floating production installations (FPIs) as this takes advantage of one of the hybrid riser system's best aspects, which is its ability to decouple the rigid riser system from the FPI's motions. This decoupling can reduce the necessity of using a vessel with enhanced motion-performance.

3 Description of Hybrid Riser Systems

3.1 General

Although there are different versions of hybrid riser systems, and their configurations have been modified through the years, the key technical benefit of this concept remains that the major rigid vertical, or catenary, riser is isolated from the FPI using an upper flexible jumper as a connection. The rigid riser is thus substantially decoupled from FPI motion.

So far, the hybrid riser system concepts that have been developed are as follows:

- Hybrid Riser Tower (HRT)
- Single Line Hybrid Riser (SLHR)
- Tension Leg Riser (TLR)
- Hybrid 'S' Riser System (HySR)
- Hybrid Catenary Riser (HCR)

3.3 Hybrid Riser Tower Type (or Hybrid Tower Riser)

The riser tower consists of a center core tubular surrounded by production, water injection, and service lines internal or external to the bundle, either fully enclosed or attached on the periphery of the syntactic foam buoyancy module.

The vertical column of the riser tower normally consists of a bundle of steel risers. A buoyancy tank at the top provides the required tension, and syntactic buoyancy units along the length reduce the wet weight and may also provide insulation if riser pipes are enclosed within. The upper end of the vertical column is connected to the FPI by multiple flexible jumpers.

The tower type has been used for deepwater fields mainly in West Africa, although the first riser tower was installed in the Gulf of Mexico. All these riser towers were fabricated onshore, towed to sites and upended.

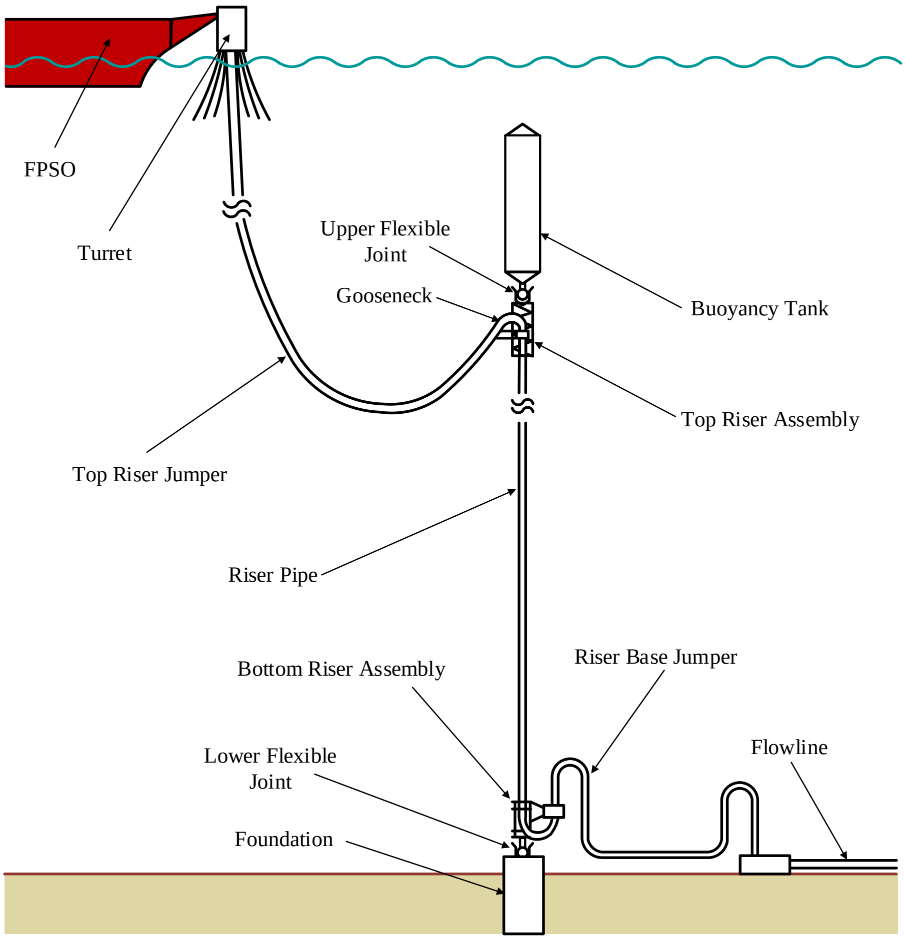
A typical HRT consists of the following components:

- Top Flexible Jumper(s)
- Buoyancy Tank
- Top Riser Assembly (TRA including Gooseneck Assembly)
- Continuous Riser Bundle Section
- Bottom Riser Assembly (BRA)
- Bottom Connector (e.g., latch type connector)
- Riser Tower Anchor
- Rigid Jumper Spool connection to FLETs

3.5 Single Line Hybrid Riser Type

A single line hybrid riser (SLHR) consists of a vertical rigid pipe anchored to the seabed via a foundation (e.g., suction pile) and tensioned by means of a near-surface buoyancy tank that provides the required uplift force. For the SLHR, one flexible jumper connects the rigid riser via a gooseneck to the FPI. The connection of the riser to seabed is by means of mechanical connector (e.g., latch type connector or taper joint). A riser base jumper, either flexible or rigid, connects BRA and FLET. A typical SLHR concept is illustrated in Section 1, Figure 1. Such a vertical rigid riser pipe can be installed using either J-lay or Reel-lay. There are several different names of SLHR, for example, single line (or leg) offset riser (SLOR), single top tension riser (STTR), single line free standing hybrid riser (SLFSHR), free standing hybrid riser (FSHR), and single line (or leg) hybrid riser. SLHR broadly includes the pipe in pipe (PIP) hybrid riser system as well.

FIGURE 1
Illustration of an SLHR



A typical SLHR is composed of the following components, as shown in Section 1, Figure 1 above:

- Top riser jumper (or jumpers for PIP)
- Umbilical (optional)
- Top riser jumper connector
- Buoyancy Tank (BT)
- Tether Chain/Flexible joint
- Top Riser Assembly (TRA including Gooseneck Assembly)
- Upper Tapered Stress Joint (UTSJ), if required
- Riser Joint/Buoyancy Modules/Coating/Insulations
- Inner riser joints, centralizers, bulkhead/injection forgings for PIP
- Lower Tapered Stress Joint (LTSJ), if required
- Bottom Riser Assembly (BRA)
- Foundation
- Riser Base Jumper (RBJ)
- Riser base jumper connector

3.7 Other Hybrid Riser Types

There are some other hybrid riser concepts such as Tension Leg Riser (TLR), Hybrid Catenary Riser (HCR), etc. However, so far, only one buoyancy supported riser (BSR) system has been installed.

5 Applicability

Except for HRT, SLHR and BSR systems, other hybrid riser concepts have not yet been deployed in offshore field development. Though these Guidance Notes are meant to be applicable to all types of hybrid risers, focus is given to the SLHR system.

7 Alternatives

7.1 General

ABS is at all times ready to consider alternative arrangements and designs which can be shown, through either satisfactory service experience or a systematic analysis based on sound engineering principles, to meet the overall safety, serviceability, and long-term strength standards of the Rules and Guides.

7.3 National Standards

ABS will consider special arrangements or design of subsea hybrid riser systems which can be shown to comply with standards recognized in the country provided that the proposed standards are not less effective.

9 Definitions and Abbreviations

9.1 Definitions

Bill of Material. A list of raw materials, sub-assemblies, intermediate assemblies, sub-components, parts and the quantities of each needed to manufacture an end product.

Bottom Connector. A mechanical device used to connect bottom adjacent components in the riser system to create a structural joint resisting applied load.

Bottom Riser Assembly. The assembly structure to connect the bottom riser string, riser base jumper and foundation pile.

Buoyancy Modules. Units of low density materials, usually foamed polymers, strapped or clamped to the exterior of riser joints, to reduce the submerged weight of the riser.

Buoyancy Tank. A buoyant structure attached to the top of the riser system anchored to the seafloor, keeping the riser in tension and in place.

Coiled Tubing Intervention. A typical well intervention, which can be a cost/time effective solution for well intervention operations.

Continuous Riser Bundle Section. A structure, which has multiple risers that are bundled together.

Design Life (Service Life). Time, usually expressed in years, that the system (or considered component or structural detail) will be exposed to loads or other demands after installation at the operating site.

Dog House. An assemblage including insulated material designed to maintain the thermal integrity of the system at the point of connection.

Dynamic Amplification Factor (DAF). A dimensionless number which describes by how many times the static responses (deflections and stresses) should be multiplied when dynamic effects are considered.

Engineering Criticality Assessment (ECA). An analytical procedure based on fracture mechanics principles that allow determination of the maximum tolerable sizes for imperfections in fusion welds.

Fatigue Life. (a) The minimum required Fatigue Life is the Design Life multiplied by a specified Fatigue Design Factor (FDF) that accounts for matters such as criticality, ease of inspection and repair, etc. (b) Calculated Fatigue Life is the quantity, usually expressed in years, obtained using the S-N curve method referred to in these GNs. The calculated Fatigue Life available for the Design Life should account for significant fatigue damage occurring before service (i.e. from installation or transit). The calculated Fatigue Life should equal or exceed the minimum required Fatigue Life.

Foundation Pile. A steel structure anchored to the seafloor and attached to the bottom of the riser system, to provide adequate axial and lateral support, as well as to satisfy the serviceability and installation requirements.

Fusion Bonded Epoxy (FBE). Fusion bonded epoxy, also known as fusion-bond epoxy powder coating (commonly referred to as FBE coating), is an epoxy-based powder coating that is widely used for the corrosion protection of: steel pipe used in pipeline construction, concrete reinforcing bars (rebar), and on a wide variety of piping connections, valves etc.

Gas Lift. An artificial lift technique of raising a fluid such as water or oil by introducing bubbles of compressed air, water vapor or other vaporous bubbles into the riser. Riser base gas-lift is a method that has been proven to work in subsea developments for production enhancement.

Glass Syntactic Polyurethane (GSPU). A type of thermal insulation which is made from Syntactic Polyurethane.

Gooseneck Assembly. The assembly structure to connect the TRA and the top flexible jumper. It may include the riser induction bend, the flexible jumper stiffener and the subsea connector.

Hazard and Operability (HAZOP). A method of assessing and evaluating potential hazards to personnel or equipment.

Hazard Identification (HAZID). A systematic critical examination of facilities to identify any potential hazards and the consequential effects on the facility as a whole.

Knockdown Factor. The term knock-down factor refers to the reduction in fatigue life in a corrosive environment (e.g., sour service), as compared to the fatigue performance in air.

Load and Resistance Factor Design (LRFD). Load and Resistance Factor Design (LRFD), commonly associated with Limit State Design (LSD), refers to a design criteria format used in structural engineering. A limit state is a condition of a structure beyond which it no longer fulfills the relevant design criteria.

Lower Tapered Stress Joint. Typically, a forged piece with a tapered shape that connects the standard riser pipe and the BRA.

Metal-To-Metal (MTM) Seal. Type of seal using resilient metal seals for applications involving high temperatures, high pressures or vacuum, or corrosive chemicals.

Minimum Bending Radius (MBR). Measured to the inside curvature, is the minimum radius one can bend a pipe, tube, sheet, cable or hose without kinking it, damaging it, or shortening its life.

Minimum Separation. The minimum separation is defined as the minimum surface-to-surface distance between the upstream and downstream riser pair.

Riser Base. The bottom end of the riser system which connects to the foundation pile.

Riser Base Jumper. A short piece of pipe, either flexible or rigid, connected between the lower end of each individual riser and the relevant FLET or manifold.

Riser Joint. A joint consisting of a tubular member(s) middle section that is welded or mechanically connected to adjoining riser joints.

ROV Hot Stab. A running tool which an ROV may connect directly to subsea equipment to hydraulically operate the equipment.

Stem Pipe. A large steel pipe in the center of a buoyancy tank that transfers the weight of SLHR to each bulkhead of the buoyancy tank, which can also be called the central pipe or core supporting pipe. ‘Stem Pipe’ can also be used to describe the piece of pipe at the bottom of the TRA or top of the BRA, which is installed in conjunction with, and is therefore considered as an integral part of, the TRA/BRA.

Stress Concentration Factor (SCF). The local peak stress at geometric discontinuities (including welds) divided by the nominal stress in the pipe wall.

Tension Leg Riser (TLR). One type of hybrid riser utilizing conventional steel catenary riser (SCR) and flexible pipe technology with a mid-water buoy tethered to the seabed.

Tie-back Connector. A type of hydraulically operated subsea connector which has metal-to-metal sealing.

Top Flexible Jumper. A flexible pipe connecting the TRA and a floater, such as an FPSO.

Top Riser Assembly (TRA). The assembly structure including gooseneck assembly to connect the tether chain/flexible joint, top flexible jumper and UTSJ.

Universal Transverse Mercator (UTM). A conformal projection using a 2-dimensional Cartesian coordinate system to give locations on the surface of the Earth. It is a horizontal position representation (i.e., it is used to identify locations on the Earth independently of vertical position), but differs from the traditional method of latitude and longitude in several respects.

Upper Tapered Stress Joint (UTSJ). A forged piece with a tapered shape that connects the TRA and the standard riser pipe.

Weld-on Connector. One type of pipe connector for which the male and female parts of the connector are welded on to ends of a standard pipe.

Working Stress Design (WSD). A design method wherein the structure is designed such that the stresses developed due to service loads remain within specified limits through the use of factors of safety.

Wye-piece Forging. A forged piece having a Y shape.

9.3 Abbreviations

ABS	American Bureau of Shipping
AISC	American Institute of Steel Construction
ALS	Accidental Limit State
ANSI	American National Standards Institute
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASTM	ASTM International
BPVC	Boiler and Pressure Vessel Code
BRA	Bottom Riser Assembly
BT	Buoyancy Tank
CFD	Computational Fluid Dynamics
CoG	Center of Gravity
CP	Cathodic Protection
DAF	Dynamic Amplification Factor
DBD	Design basis document
DBM	Distributed Buoyancy Module
DFI	Design, Fabrication and Installation
DGPS	Differential Global Positioning System
DVRT	Differential Variable Reluctance Transducer
ECA	Engineering Criticality Assessment
EPS	Early Production System

FBE	Fusion Bonded Epoxy
FE	Finite Element
FEA	Finite Element Analysis
FJ	Flexible Jumper
FLET	Flowline End Termination
FLS	Fatigue Limit State
FOS	Factor of Safety
FPI	Floating Production Installation
FPS	Floating Production System
FPSO	Floating Production Storage and Offloading
FSHR	Free Standing Hybrid Riser
GoM	Gulf of Mexico
GSPU	Glass Syntactic Polyurethane
HAZID	Hazard Identification
HAZOP	Hazard and Operability
HCR	Hybrid Catenary Riser
HLV	Heavy Lift Vessel
HRT	Hybrid Riser Tower
HySR	Hybrid 'S' Riser System
ID	Internal Diameter
ISO	International Organization for Standardization
ITP	Inspection and Testing Plan
JONSWAP	Joint North Sea Wave Project
LRFD	Load and Resistance Factor Design
LTSJ	Lower Tapered Stress Joint
LVDT	Linear Variable Differential Transducer
MBR	Minimum Bending Radius
MLPP	Multiple Layer Polypropylene
MR	Material Requisitions
MRU	Motion Reference Units
MSST	Maximum Soil Setup Time
MTM	Metal-To-Metal
MTO	Material Take Off
MWL	Mean Water Level
NACE	NACE International
NDE	Non-Destructive Examination
OD	Outside Diameter
PO	Purchase Order

PP	Polypropylene
PR	Performance Requirement
PSL	Product Specification Level
QA	Quality Assurance
QC	Quality Control
RAO	Response Amplitude Operator
RBJ	Riser Base Jumper
ROV	Remotely Operated Vehicle
SAE	Society of Automotive Engineers
SCF	Stress Concentration Factor
SCR	Steel Catenary Riser
SIT	System Integration Test
SLFSHR	Single Line Free Standing Hybrid Riser
SLOR	Single Line (or Leg) Offset Riser
SLS	Serviceability Limit State
SMYS	Specified Minimum Yield Strength
STC	Stress Transfer Coefficient
STTR	Single Top Tension Riser
TLP	Tension Leg Platform
TLPE	Three Layer Polyurethane
TLPP	Three Layer Polypropylene
TLR	Tension Leg Riser
TRA	Top Riser Assembly
TSA	Thermal Sprayed Aluminum
TSJ	Tapered Stress Joint
TTF	Top Tension Factor
ULS	Ultimate Limit State
UTM	Universal Transverse Mercator
UTSJ	Upper Tapered Stress Joint
VIM	Vortex Induced Motion
VIV	Vortex Induced Vibration
WA	West Africa
WD	Water Depth
WSD	Working Stress Design
WT	Wall Thickness

SECTION 2 System Design

1 General

In general, hybrid riser design and analysis are to be in accordance with the criteria given in the ABS *Guide for Building and Classing Subsea Riser Systems (Riser Guide)* (or API STD 2RD) and relevant specifications.

Global analyses for normal and extreme environmental conditions are to be conducted to demonstrate compliance with the relevant specifications and industry codes. Fatigue strength (considering waves, VIM, VIV and installation conditions) and clearance/clashing responses are all to be assessed.

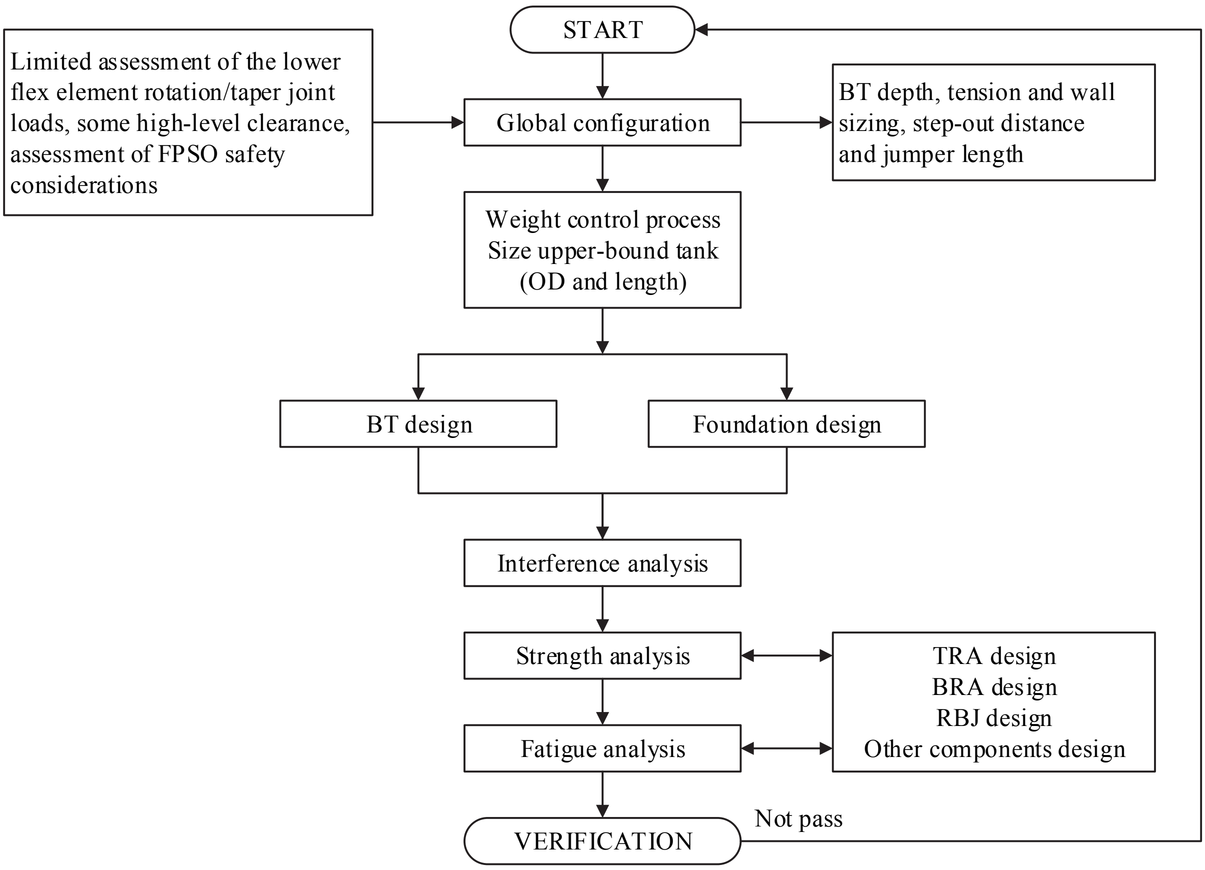
The detailed component design may be performed using finite element analysis (FEA).

3 Design Flowchart

Considering the complexity of the system and its sensitivity to fabrication and installation, a proven procedure for hybrid riser system design should be pursued.

The flowchart in Section 2, Figure 1 shows a suggested procedure and major issues to be considered during a typical engineering design of a deepwater hybrid riser applicable for all types of floaters.

FIGURE 1
Suggested Hybrid Riser Design Flowchart



5 Design Basis Data

At the beginning of the design and analysis process, an overall project design basis document is often written to denote the essential parameters and the acceptance criteria for a fit-for-purpose design and analysis of the hybrid riser system. The input to the basis of design is:

- *Metocean and Geotechnical Data:* Water depth and geotechnical data, wind, wave and current data dictate the selection of a production platform as well as the hybrid riser response; soil data dictates foundation design
- *Reservoir Data:* Pressure, temperature, and product contents affect the riser pipe wall sizing, and material selection. Reservoir data also affects the outcome of flow assurance calculations and thus the riser insulation requirements. High temperatures may result in yield strength de-rating
- *FPI Data:* Floater motion characteristics, major particulars, riser termination locations, floater offsets corresponding to different conditions, operating philosophy
- *Riser System Data:* Number and function of risers, diameters, thermal insulation requirements, subsea layout; manufacturer/ vendor supplied data
- *Design Requirements:* Design philosophy, applicable design codes and standards, design acceptance criteria, design constraints
- *Analysis Requirements:* Software selection and verification, types of analysis, analysis methodology, load case matrix, and validation of analysis results

The hybrid riser system design basis is often updated throughout the life of the project due to new flow-assurance information gathered during the drilling campaign, improvement of metocean hind-cast model, or other developments along the course of the project. Keeping the latest revision and distribution of the basis of design should be considered essential to the design.

The following aspects should be specifically considered when selecting a hybrid riser concept for a specific field development:

- Ability to withstand all design loads and load combinations for in-situ, as well as temporary conditions
- Capacity to perform its function for the specified service life
- Use of materials conforming to corrosion control requirements
- Flow assurance – avoidance of blockage or other flow impediments – maintenance of delivery temperature and minimum no-touch cool-down duration to minimize risk of hydrates/wax
- Access and smooth passage for intervention tools
- Means for integrity monitoring and inspection
- Access for pigging
- Ability to transfer high pressure fluids (oil, gas, water) between flowlines and FPI
- Fabrication considerations
    - Fabrication yard location and assembly (for riser tower)
    - Fabrication limits
- Installation considerations
    - Overall installation methodology
    - Tow route selection and duration (for riser tower)
    - Deployment of buoyancy tank and hookup
    - Installation of riser foundation pile/anchor

7 System Design

7.1 System Requirements

The design of each of the various riser system components from the seabed to the FPI should consider the following:

- Containment of hydrocarbons and control fluids throughout the design life under defined startup, normal, and shut down operations and accidental or damaged floater conditions
- Compliance to accommodate the environmental and operating conditions, hydrodynamic loadings, FPI motions and excursions that the riser system is subjected to throughout the riser system's life
- Thermal insulation performance and process remediation systems for the flow assurance performance requirements of the production system
- Protection from external and internal corrosion effects without introducing detrimental conditions, such as hydrogen embrittlement, that could affect riser system materials
- Strength, fatigue and corrosion resistance for the intended service to satisfy the required margins against failure due to cracking, leakage, rupture, collapse, yielding or buckling under the design conditions
- Reliability and redundancy of the buoyancy system for the riser system's life under defined startup, normal and shut down operations and accidental or damaged conditions
- Long-term polymer material 'aging' properties due to hydrostatic pressure, temperature and mechanical loading exposure during the riser system's life
- Clearances from other structures, risers, umbilical, mooring lines, and components in the floater's turret area
- Consistency with all agreed interface requirements for the FPI connections, hang offs, the flowlines and any directly-connected BRA and jumpers
- Hang-off loads within the identified capacity values under all operating conditions identified through HAZID and HAZOP processes (e.g., loss of Buoyancy tank compartment)
- Safe and reliable installation issues should be addressed (e.g., hybrid riser system pull-down, jumper pull-in through turret, jumper connection at TRA)

7.3 Global Configuration

Initial considerations in hybrid riser design include the following:

- Functional requirements
- Metocean criteria
- FPI excursions
- Subsea field layout
- Riser Installation methodology
- Field interference
- Flexible jumper performance
- In-place performance (standby and operating)

Controlling parameters governing the global configuration design of a hybrid riser system include the following:

- Depth from MWL to the top of the buoyancy tank
- Riser foundation offset to riser hang-off location at the FPI
- Flexible jumper length and departure angles at FPI and riser ends

- Connection between buoyancy tank and riser top
- Connection between riser end or BRA and pile/FLET
- Flowline routing
- Other detailed considerations that can affect global configuration including FLET/BRA/RBJ orientations, TRA/BRA concept and RBJ design.

9 Components Design

9.1 General

Compared with other types of deepwater riser concepts, there are some unique engineering design features of a hybrid riser system. Key design considerations of a hybrid riser system include the following:

- Global Configuration
- Riser base offset to the FPI
- Flexible jumper length
- BT Design
- Functional requirement: vertical access, gas lift, disconnection
- Global-Local interface design
- Installation method

Additionally, specific concerns for the following three components of SLHR are as follows:

- RBJ – complexity and coupling with BRA and global analysis
- BT – large pressure vessel
- BRA/TRA – complex fabricated structures with multiple interfaces and functions

Due to the complexity of the system, hybrid riser design can require increased consideration of the interdependency between procurement, fabrication, and installation. The installation method may have significant impact on the design of some components including BT, TRA, BRA, TSJ and the foundation pile. Early input about the installation is recommended to make the riser system more “installation friendly”.

Structural/load bearing members of the riser system should be designed to:

- Support all the loads produced by the BT, flexible jumpers and other riser assembly structures during each stage of the installation and operating phases of the riser system; and
- Meet the relevant mechanical and process fluid compatibility requirements, and should be suitably designed to account for all dynamic and transient load cases.

9.3 Riser String

9.3.1 Production Riser

A production riser should be designed to meet relevant mechanical and process fluid compatibility requirements. The riser should be insulated so that produced fluids retain their heat and remain free of hydrates and wax deposition.

API 5L X65 or X70 material is commonly selected for a production riser. A lower material grade such as API 5L X60 can be considered for sour service conditions. A higher material grade can be considered for non-welded connectors though not for permanent production applications (e.g., emergency response system).

The riser design should demonstrate that welds for dynamic service meet the required fatigue performance, and the non-destructive examination (NDE) methods used should be able to detect the minimum allowable defect or other characteristics needed to achieve the design life.

Insulation materials should retain adequate mechanical and thermal performance over the riser's design life to comply with thermal requirements.

Individual riser line pipe sections should meet the requirements of API 5L, and should be in general connected by welded joints. In a special case, mechanical connectors (e.g., weld-on connector) may be acceptable to connect the line pipes.

9.3.1(a) Pipe-in-Pipe. The pipe-in-pipe design may require a pipe hanger at the top and a bulkhead at the bottom to form the junction between inner and outer sections. The pipe-in-pipe system may enable fluid interaction between inner and outer sections (e.g., for gas lift injection into a production bore) and accordingly specific requirements should be included in the design, such as the size, position and orientation of injection holes. Centralizers may be required over the length of the inner riser to reduce buckling tendency of the inner pipe and the spacing of centralizers can be determined through analysis. Additional sealing and other interface requirements may need to be provided. Qualification testing may be required to verify these key design requirements.

The PIP design analysis should consider all the loading conditions, the appropriate tension distribution between pipes based on installation procedure, pipe and tension tolerances, fluid content and variations over the life of the field, to provide sufficient strength and fatigue performance. Specific interface components, such as bulkheads, should be adequately designed based on detailed FEA.

9.3.2 Gas and Water Injection Risers

Gas injection/export or water injection risers are typically deployed from the FPI. These risers can be manufactured from carbon steel material grades. Individual riser line pipe sections should be connected by welded joints.

Assessment from flow assurance should document that the riser is not at risk over time, since water injection could be subjected to hydrogen embrittlement or a higher level of H_2S content over time.

External corrosion protection should be in accordance with the criteria referred to in these Guidance Notes.

9.3.3 Gas Lift Risers

If PIP production risers are not selected, then a dedicated gas lift riser may be required with subsea manifolding to achieve the same function.

Insulation materials are to retain adequate mechanical and thermal performance over the riser's design life to comply with thermal requirements.

Injection points are provided either on the flowline termination (i.e., upstream of the riser base spool) or on the BRA.

9.3.4 Oil and Gas Export Risers

Produced and processed oil may be stored for offloading to a tanker or may be exported via a subsea pipeline network. Produced and processed/dried gas may be injected back into the reservoir or may be exported via a subsea pipeline network.

If either product is exported, export risers may be required. Design considerations are similar to the gas injection risers.

9.5 Top Flexible Jumper

The flexible jumper should be designed to be post-installed on the riser after the installation of the vertical hybrid riser in the field. The flexible jumper may be installed after the arrival of the FPI or be pre-installed and clamped along the riser length while waiting for FPI to arrive on site (stand-by modes). The flexible jumper should also be replaceable without the need to retrieve the entire string or remove any structural or buoyancy elements.

Process fluids should be transferred to/from the FPI by means of flexible jumpers configured in an appropriate manner to avoid undue loading on the top of the hybrid riser system and to avoid clashing. Jumpers should be designed for dynamic service for at least the design life of the vertical riser under the specified design conditions.

Dynamic analysis of the flexible jumper should be performed to provide the FPI designer and the flexible jumper manufacturer with: the interface loadings and their applied directions under the applicable metocean conditions, FPI motions and FPI excursions to provide a robust strength and fatigue resistance for all interface components of the jumper.

Consideration should be given to the study of interference between a flexible jumper and the FPI hull/appurtenances (e.g., lift/dump hoses), in addition to the interference between the flexible jumper and any adjacent umbilical, flexible jumper or mooring line. The hybrid riser system should be designed to avoid any interference that can bring potential damage to the system, such as impact or abrasion.

Damage to the outer sheath of the flexible jumper during installation can result in a reduced service life. Flexible jumpers should be fitted with protection at potential clashing points to reduce damage risk.

The risk of VIV damage to the internal carcass generated by gas flow through a flexible riser should be assessed.

9.7 Buoyancy Tank

Once installed, the riser should be designed to be self-supporting by means of the BT. The BT can be manufactured with individual compartments connected by a ballasting system of pipes and valves. This enables buoyancy load or its position in the water column to be adjusted following installation or during operation.

BT design should take account of the following key factors; including:

- Design Life
- Load transfer paths between the BT and the riser structure
- Stresses from hydrostatic pressure, extreme and fatigue loading and sloshing loads
- Loss of buoyancy over the design life due to partial or complete flooding of one or two compartments of the BT
- Additional weight and drag forces induced by marine growth, particularly at the upper end of the riser structure
- Additional weight due to riser pipe fabrication tolerances and base tension tolerance caused by weighing and deballasting inaccuracy
- Fatigue loads, especially at the connection between the BT and the TRA
- Fatigue of structural and piping welds due to pressure variations (e.g., caused by wave, tide, setdown due to current, liquid sloshing inside compartment)
- Fatigue of girth weld due to riser VIV for connector at bottom of BT (if applicable)
- ROV impact on ROV panel and outer shell of BT
- Impact due to dropped objects
- Global and pitting corrosion due to microbial action in the presence of residual seawater and oxygen (depending on purity of Nitrogen used to de-ballast the compartment) remaining in each compartment at the end of installation
- Collapse loads on air filled central pipe

In addition the following factors from a HAZID study should be considered in the design:

- Additional weight from accidental failure of the flexible jumper at the FPI, resulting in jumper hanging vertically from the riser gooseneck interface (or designed to remain like this during stand-by operations)
- Feasible combinations of the above factors should also be considered
- Handling points for installation and padeyes for secondary buoyancy elements to be added in emergency situations

The BT can be designed on the basis of the following functional requirements:

- To support the hybrid riser dead weight
- To provide sufficient pulling tension for the dynamic equilibrium of the hybrid riser
- To minimize the angle at the riser lower assembly by limiting the maximum offset of the riser due to FPI excursion even in the loss of one compartment condition
- To support the jumper, the jumper supporting structure, the rigid goose neck and associated structures
- To provide appropriate partition of the compartments to meet in-place damaged stability requirements

In addition the following facilities should be incorporated in the design:

- Pressurizing/ballasting/deballasting system
- Tension monitoring system (with sufficient accuracy to detect leaks/compartment failure)
- ROV connectable device for nitrogen injection and control panel
- Transportation supports
- Connections for sea fastening
- Lifting and up-ending device for fabrication/transportation/installation

9.9 Top Riser Assembly

The TRA should provide a safe and reliable means of connecting the lower end of a flexible jumper spanning from the FPI to the top of the riser. The connection system should take into account predicted load conditions, interface requirements with the flexible jumper/TRA and subsea intervention. More than one jumper is required for a PIP system with associated additional connection equipment and piping.

Provision should be made at the upper end of a riser to enable fluids to be transferred to/from the FPI by means of dedicated flexible jumpers. The TRA incorporates the load transfer path(s) to the BT. Each load path should be analyzed for the predicted applied loads, both individually and in combination.

The TRA should be designed to enable the flexible jumper(s) to be safely installed and replaced (if needed), by divers or Remotely Operated Vehicle (ROV), during the life of the riser. The TRA should also be designed to accommodate the loads induced by installation guides, winches and support structures.

Pigging requirements (if applicable) should be considered when bend radii are selected and in handling ID transitions between piping, forgings and connectors.

For a production system, provision may be required for hydrate remediation (access forgings, valves and connection points) with associated structural support. For a PIP system, additional piping and forgings are required to inject the gas lift fluid into the PIP annulus.

9.11 Bottom Riser Assembly

The BRA should provide the transition from the vertical pipe section to the RBJ. Pigging requirements (if applicable) should be considered when bend radii are selected.

Key considerations for a gas lift system located at the BRA of the PIP hybrid risers are as follows:

- Thermal performance and proper insulation of the system
- Reliability of the non-redundant components incorporated in the system

- Material selection for components and piping and their compatibility
- Selection of seals and materials
- Access for underwater intervention
- Availability of space to incorporate the gas-lift system in the frame of the BRA
- Accommodation of anticipated loads both during installation and operation.

Due to potentially high collapse pressures in deep-water applications, ovalization and thinning of the piping should be assessed through detailed FEA.

For production systems, a method for injecting gas lift fluids into the production bore may be required. The source of these fluids can be:

- An annulus (in the case of a PIP riser), in which case a (passive) perforated bulkhead can be implemented
- A dedicated gas lift riser, in which case a valve assembly and injection forging will be required either on the BRA or on the flowline termination.

9.13 Foundation Pile

A latch type riser base connector or a lower taper joint can be used to connect the riser to the foundation.

Installation tolerances, which account for positional accuracy, orientation and verticality requirements should be considered in the foundation design. These tolerances should be listed in the riser's Installation Manual.

Dynamic load conditions during foundation installation, riser system installation, life of field operations and decommissioning should be determined and considered in the foundation design. Accidental cases should be considered and additional inclination should be accounted for when determining tolerances on the installation of the foundation.

9.15 Riser Base Jumper

Depending on the particular field application, installation requirement and required lead time, the RBJ can be rigid or flexible. The RBJ should be designed to provide the connection between the lower end of each individual riser and the relevant FLET or manifold. The RBJ should be configured to provide the necessary flexibility to cater to pressure and thermal effects (flowline and RBJ itself), as well as the motions of the hybrid riser, slugging loads and other mechanical effects, and to meet the installation tolerance requirements. The RBJ should also be designed in consideration of the proposed installation sequence, whether prior or after hook-up of the flexible jumpers to the TRA.

Due to the susceptibility to high fatigue loading, the fatigue performance of the rigid RBJ should be fully evaluated. Both the weight and inertial effects should be considered in slugging evaluation, particularly where multiple tight (3D/5D) bends are incorporated in the design, and the weld should be in accordance with welding requirements for the RBJ.

A production RBJ should be insulated so that the production fluids retain their heat and remain free of hydrates and wax deposition in accordance with the flow assurance performance requirements. Pigging requirements (if applicable) should be considered when bend radii are selected.

9.17 Connectors

Connectors typically have the following applications in a hybrid riser system:

- Gooseneck connection to flexible jumper
- BT connection to TRA
- BRA connection to foundation pile
- FLET/BRA connection to RBJ

Particular attention should be given to the connections. A single point of failure should be avoided. The connection between BT and TRA should be designed with a contingency in case of load path failure. The same principle should apply to the bottom connection if there is BRA connecting to a pile.

Subsea hydraulic connectors, if used, should be designed and tested in accordance with ANSI/ASME B31.8 or ANSI/ASME B31.4, as applicable. All hydraulic connectors, hubs and ancillary equipment should be designed in accordance with API Spec. 6A and 17D with Product Specification Level (PSL) 3G, Performance Requirement (PR) 2 for function testing with temperature in accordance with project requirements.

Hydraulically operated components should be flushed in accordance with SAE AS4059 Class 6B to 6F hydraulic fluid cleanliness, and should be designed to operate in SAE AS4059 Class 12B to 12F.

Connectors should be designed to use pressure energized metal-to-metal (MTM) seals, field replaceable without recovering the connectors to the surface. Non-metallic seals should only be used as backup seals. The hardness of the MTM seals should be less than the hardness of the connector and hub seal surfaces.

External seal tests should be performed at an agreed pressure differential. A one-off qualification test should be performed on each gasket size to determine the external pressure capability of each seal type. Each seal should be tested to at least the hydrostatic head pressure at the design water depth.

Connection hubs should include a reaction can or ring that provides passive guidance and orientation, facilitates passive latch engagement, and protects the seal gasket preparation on the hub from impact from the connector. Connectors are to be designed to resist unintentional release.

Connectors should be designed to prevent damage to any control lines from dropped objects, handling, installation, and intervention, etc.

Subsea flooding caps should be provided with all male hubs. Flooding caps should:

1. Be field installable and retrievable;
2. Incorporate a test port for venting, injecting or monitoring the sealed cavity; and
3. Incorporate a field-operated ball valve for flooding operations.

Suitable redundancy should be provided in the design of the connections to prevent catastrophic failure of the riser system due to a single point failure.

11 Design Criteria

The design criteria for the design and analysis of the hybrid riser system should include the following:

- Industry codes, standards, and specifications to be used in the design
- Minimum design life requirement
- Transportation and installation
- Minimum bend radius versus effective tension envelope for flexible jumpers
- Fatigue curves, stress concentration factors and ECA for typical welds and connectors
- Interference criteria in terms of diameters between risers or the permissible impact energy
- Material loss allowances and mitigation measures
- Operational requirements – cool down time, start up and shut down cycles, water injection, and gas lift requirements
- Inspection and maintenance criteria
- Thermal insulation requirement from flow assurance

The system design should satisfy the ABS *Riser Guide* or API STD 2RD as a primary design code while codes and standards listed in Subsection 2/19, “Applicable Codes and Standards” of these Guidance Notes should be used to address individual components.

13 Flow Assurance

Flow assurance criteria should be specified. Thermal insulation coating should be provided for a hybrid production riser, which is defined by:

- U-value requirement, and
- Cool down time requirement

For irregular pressure containing component (e.g., TRA and BRA), CFD can be a useful tool to determine thermal coating requirements.

Providing a Dog House is a common practice to provide thermal insulation for connectors, which could be used to tie a riser string to its base.

Slugging-induced internal fluid pressure fluctuations should be considered when the normal transporting flow rate is below the slug-free flow rate limit or at the restart/shutdown scenarios. The slug-free flow rate limit depends on the pipe size, fluid properties, flowline geometry, back pressure, and flow temperature. The RBJ vibrating failure and lifespan should be evaluated based on the sustainable internal fluid pressure fluctuation magnitude and frequency with an appropriate safety factor; see the *Riser Guide*.

15 Material Selection

15.1 General Considerations

Material selection for a hybrid riser system should consider the following:

- Weight sensitivity leads to an increased use of higher material grades: this is permitted provided the other material related criteria are met
- Material compatibility between connected components should be considered to avoid dissimilar material interaction issues
- Material suitability should consider the ease of availability at fabrication yard
- Casting material should not be used
- Either internal cladding or lining should be considered based on the reservoir data

15.3 Specifications

Material specification should comply with recognized industrial standards, as indicated in Section 2, Table 1.

TABLE 1
Material Specification Standards

Standards	*Title*
API SPEC 5L	Specification for Line Pipe
API SPEC 2B	Specification for the Fabrication of Structural Steel Pipe
API SPEC 2H	Specification for Carbon Manganese Steel Plate for Offshore Platform Tubular Joints
API SPEC 2Y	Specification for Steel Plates, Quenched-and-Tempered, for Offshore Structures
API SPEC 2W	Specification for Steel Plates for Offshore Structures, Produced by Thermo-Mechanical Control Processing
AWS D1.1/D1.1M	Structural Welding Code – Steel
API STD 1104	Welding of Pipelines and Related Facilities
API SPEC 5CT	Specification for Casing and Tubing

In addition, material testing requirements specified by ASTM should be applied.

17 Coating and Corrosion Control

17.1 Thermal Insulation Coating

The most commonly used thermal insulation system for a hybrid riser system is an external thermal coating.

When selecting a thermal insulation coating, the following items should be considered:

- Properties of the materials/layers within insulation and field joint
- Documented properties with acceptance criteria being generally based on retention of acceptable insulation properties at end of the riser's design life
- Impact of installation methods on coating (e.g., coating reliability)

External insulation may have a detrimental effect on a riser's dynamic response, due to increased drag loading and reduced weight/drag ratio. Manufacturing and installation requirements also impose limitations on the maximum thickness of insulation that can be applied.

The most commonly used thermal insulation systems are:

- Multilayer Polypropylene (MLPP)
- Glass Syntactic Polyurethane (GSPU)

17.3 Corrosion Coating

External corrosion protection of the hybrid risers should be achieved using a combination of corrosion resistant coatings and sacrificial anodes.

Design and selection of riser cathodic protection system should be compatible with cathodic protection systems of the floater and nearby subsea systems (e.g., riser foundation pile or FLET).

Attention should be paid to provide electrical continuity from the flexible jumper all the way down to the foundation and that sufficient anodes are installed on the riser, either concentrated at the top or the bottom or using bracelet anode depending on the length of the riser.

Special consideration should be given to the protection of riser sections interfacing with ancillary components.

The most commonly used corrosion coatings are:

- Fusion Bonded Epoxy (FBE)
- Three Layer Polypropylene (TLPP)
- Three Layer Polyethylene (TLPE)

17.5 Corrosion Protection

17.5.1 Internal Corrosion Protection

Internal corrosion protection should be considered for all riser components where internal corrosion may occur. Internal corrosion protection methods may be based on corrosion resistant materials, protective coatings, corrosion allowance; and where appropriate, sacrificial cathodic protection systems.

17.5.2 External Corrosion Protection

External corrosion protection should also be considered by using corrosion resistant materials, protective coatings, corrosion allowance, and where appropriate, sacrificial cathodic protection (CP) systems.

Any sacrificial anodes, if used, should be mounted on the riser system structure, not on the riser string.

Corrosion protection of the FPI and riser systems may not be fully independent. Consideration should be given to the influence of the FPI hull's CP (impressed current or equivalent) system on the riser's CP system.

Due account should be taken in the design of the CP system of the mixture of materials present in the structure such that the long term performance of any such materials should not be degraded due to the influence of the CP system.

System components should be designed to be in direct electrical contact with each other. Where coatings or elastomers are present that prevent direct electrical contact, appropriate electrical straps should be installed to provide for electrical continuity.

17.5.3 Cathodic Protection Design

The riser's cathodic protection system can be a sacrificial type incorporating Al/Zn/In anodes. The cathodic protection designs for each component should be integrated to maintain mutual compatibility and compatibility with all materials and coating systems. Cathodic protection for the riser pipe and jumpers is supplied by anodes mounted on end structures such as the TRA and the BRA. Attenuation modeling should be performed to verify that the entire length of each riser section receives cathodic protection from end-structure mounted anodes.

Cathodic protection for the buoyancy tank, TRA, riser base assembly, foundation pile and other hybrid riser appurtenances should be designed in accordance with NACE SP0169. The cathodic protection design for the riser joints, TSJs and RBJ is to be in accordance with BS EN 12496 and ISO-15589-2. The cathodic protection design life should take into account the riser's design life. The design should consider the interface of the riser and the vessel as well as the riser and the subsea production system.

19 Applicable Codes and Standards

Due to the complexity of hybrid riser systems, different design standards are used to address individual components, while the system design should satisfy ABS *Riser Guide* or API STD 2RD as a primary design code.

Typical design codes and standards used for hybrid riser are listed in Section 2, Table 2 below. It is noted that the list is not all inclusive. Additional design standards can be added for special project requirements, and local governmental regulations.

TABLE 2
Design Codes, Standards and Specifications

Document	*Title*	*Applications*
ABS Riser Guide	Guide for Building and Classing Subsea Riser Systems	Primary, General
API STD 2RD	Dynamic Risers for Floating Production Systems	Primary, General
AISC	Steel Construction Manual	General
NACE SP0169	Control of External Corrosion on Underground or Submerged Metallic Piping Systems	General
ASME	Boiler and Pressure Vessel Code (Section VIII, Div. 3)	Structural Design
API RP 2SK	Design and Analysis of Station Keeping Systems for Floating Structures	Foundation Pile Design
API RP 2GEO	Geotechnical and Foundation Design Considerations	Foundation Pile Design
ABS Buckling Guide	Guide for Buckling and Ultimate Strength Assessment for Offshore Structures	Foundation Pile & BT Design
API RP 2A-WSD	Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress Design	Foundation Pile & BT Design
ISO 19900	Petroleum and natural gas industries — General requirements for offshore structures	BT Design
ISO 19901-6	Petroleum and natural gas industries – Specific requirements for offshore structures – Part 6: Marine operations	BT Design
BS PD 5500	Specification for unfired fusion welded pressure vessels	BT Design

TABLE 2 (continued)
Design Codes, Standards and Specifications

Document	*Title*	*Applications*
ABS Fatigue Guide	Guide for the Fatigue Assessment of Offshore Structures	Fatigue Analysis BT Design RBJ
ABS Pipeline Guide	Guide for Building and Classing Subsea Pipeline Systems	RBJ
API RP 1111	Recommended Practice for the Design, Construction, Operation, and Maintenance of Offshore Hydrocarbon Pipelines (Limit State Design)	RBJ
ASME B31.4	Pipeline Transportation Systems for Liquids and Slurries	RBJ
ASME B31.8	Gas Transmission and Distribution Piping Systems	Temperature De-rating & RBJ
EN 12496	Galvanic anodes for cathodic protection in seawater and saline mud	CP Design
AWS D1.1/D1.1M	Structural Welding Code – Steel	Welding

21 Documentation

21.1 General

For classing risers according to these Guidance Notes and the *Riser Guide*, the documentation to be submitted to ABS should include reports, calculations, specifications, procedure, drawings, manuals, and other documentation that demonstrate the adequacy of the design of the subsea hybrid riser system. Specifically, required documentation can include the items listed in this Subsection.

21.3 Plans and Specifications

Plans and specifications depicting or describing the arrangements and details of the major items of the hybrid riser system should be submitted for review or approval in a timely manner. These include:

- Site plan indicating bathymetric features at the proposed site, and other important features related to the characteristics of the sea floor
- Structural plans and specifications for risers, their supports and coating
- Schedules of nondestructive testing and quality control procedures
- Specifications and plans for instrumentation and control systems and safety devices

When requested by the Owner, the Owner and ABS will jointly establish a schedule for information submittal and plan approval. This schedule, to which ABS will adhere, as far as reasonably possible, is to reflect the fabrication and installation schedule and the complexity of the riser system as they affect the time required for review of the submitted data.

21.5 Information Memorandum

An information memorandum about the riser system should be prepared and submitted to ABS. ABS will review the contents of the memorandum to establish consistency with other data submitted for the purpose of obtaining classification or certification.

An information memorandum should contain the following:

- A site plan indicating the general features at the site, and the field location of the riser system
- Environmental design criteria, including the recurrence interval used to assess environmental phenomena
- Plans showing the general arrangement of the riser system
- Descriptions of the safety and protective systems provided
- Listing of governmental authorities having authority over the riser system

- Brief description of the monitoring system proposed for use
- Description of manufacturing, transportation and installation procedures

21.7 In-Place Design Engineering Documents

21.7.1 Functional Requirements and Site Specific Conditions

Functional requirements of the hybrid riser system should be submitted.

An environmental condition (metocean) report should be submitted, describing anticipated environmental conditions after installation, as well as during transportation and installation. Items to be assessed should include, as appropriate, wind, waves, current, temperature, tide, marine growth, water, ice conditions, earthquakes and other pertinent phenomena.

In the site investigation report, geotechnical data acquisition and integrated geoscience studies according to API RP 2GEO should be included to determine soil properties, soil conditions, and geotechnical hazards and constraints across the site if applicable.

21.7.2 Design Data and Calculations

Design basis/premise report should be submitted for the riser system that describes the material data, and methods of analysis and design that were employed in establishing the design. The estimated design life of the risers should be stated. Typical deliverables include the following:

- Hybrid riser system design premise/basis report
- Riser material selection and wall thickness sizing report
- Global configuration design report
- Riser CP design report
- Riser thermal performance design report (if needed)
- Flexible jumper design reports (cross-section, configuration)
- Riser component design reports (including gooseneck, TRA, BRA, stress joint, other permanent structures)
- Riser foundation design reports
- Riser full scale fatigue testing reports, if necessary
- Riser ECA study report
- RBJ design report
- RBJ ECA study report (if rigid)
- Riser monitoring system design report
- Riser component repair or replacement procedure reports

21.7.3 Analysis Reports

The following analysis reports should be submitted, as applicable:

- Hybrid riser global strength/response analysis report
- Interface loads for component design report
- VIV and VIM analysis report
- FPI motion fatigue analysis report
- Component strength analysis reports (including gooseneck, TRA, BRA, stress joint, other permanent structures)

- Component fatigue analysis reports (including gooseneck, TRA, BRA, stress joint, other permanent structures)
- Flexible jumper motion and fatigue report
- RBJ strength and fatigue analysis reports
- Riser foundation analysis reports (geotechnical and structural)
- Buoyancy tank system analysis report

21.7.4 Drawings

As a minimum the following drawings should be submitted:

- Riser global configuration drawings (different phases)
- Riser cross section and anode dimension drawing
- Buoyancy tank drawings (general arrangement and local details)
- Riser foundation pile drawings (general arrangement and local details)
- RBJ drawings (general arrangement and local details)
- Riser component drawings (general arrangement and local details)
- Riser monitoring system drawings (general arrangement and local details)
- Riser component inspection, monitoring and repair procedure drawings (general arrangement and local details)

21.7.5 Specifications

The following specifications should be produced and submitted, as applicable:

- Riser line pipe specification
- Riser welding and NDE specification
- Riser component material specification
- Riser component fabrication specification
- Riser thermal insulation coating specification
- Riser corrosion coating specification
- Riser field joint coating specification
- Riser stress joint specification
- Riser forging specification
- Riser VIV suppression device specification (if needed)
- Riser pipe full scale fatigue testing specification
- Buoyancy tank fabrication and testing specification
- Riser foundation pile fabrication and testing specification
- Riser connector functional specification
- Riser component fabrication and testing specifications
- Flexible jumper fabrication and testing specifications
- RBJ fabrication and testing specifications
- Foundation pile fabrication and testing specifications

21.9 Fabrication Documents

For hybrid riser component fabrications, the following types of documents should be submitted, as applicable:

- Component Fabrication QA/QC plan
- Component Fabrication HSE plan
- Component fabrication plan
- Component qualification procedure
- Welding procedure qualification plan
- ITP procedure/plan
- FAT procedure
- Component storage and transportation plans
- Component fabrication record book
- Riser SIT plan/procedures

21.11 Installation Engineering Documents

With regard to the installation procedures, calculations and analysis of installation procedures should be submitted for review. These calculations should demonstrate that the anticipated loading from the selected installation procedures does not jeopardize the strength and integrity of the risers and their foundations.

21.11.1 Installation Design and Analysis

- Riser installation analysis report
- Buoyancy tank installation analysis report
- Riser foundation pile installation analysis report
- Flexible jumper installation analysis report
- RBJ installation analysis report
- Riser component installation analysis report
- Riser installation aids design reports
- Riser installation rigging design reports

21.11.2 Installation Manual/Procedure

Installation manuals should be prepared to demonstrate that the methods and equipment to be used will meet the specified requirements. A manual/procedure should be submitted describing procedures to be employed during the installation of risers as well as its structural component and should include, as applicable the following:

- Riser pipe installation/deployment procedure
- Riser buoyancy tank installation procedure
- Riser foundation pile installation procedure
- Flexible jumper installation procedure
- RBJ installation procedure
- Riser component installation procedures (including gooseneck, TRA, BRA, stress joint, other permanent structures
- Riser installation contingency plan
- Riser pre-commissioning procedure/plan
- Riser post-installation test procedure/plan

21.11.3 Installation Specification

Riser installation equipment specifications

21.13 Operation, Maintenance and Repair Documents

21.13.1 Operation

An operations manual should be prepared to provide a detailed description of the operating procedures to be followed for expected conditions. The operations manual should include procedures to be followed during start-up, operations, shutdown conditions and anticipated emergency conditions. This manual should be submitted for record and file.

21.13.2 Maintenance

A maintenance manual providing detailed procedures to denote the continued operating suitability of the riser system should be submitted for record and file.

21.13.3 Repair

Riser component repair or replacement procedure reports.

21.15 As-built Documents

The results of surveys and inspections of the risers should be given in a report which, as a minimum, should include the following details:

- Description and location of any major damage to a riser along with information regarding how such damage was repaired; and
- The result of the inspections of the riser tie-in, documenting compliance with the pertinent plans and specifications.

As appropriate, results of additional inspections, which may include those for the proper operation of corrosion control systems, other suitable means and the testing of alarms, instrumentation and safety and emergency shutdown systems, should be included.

SECTION 3 Local Design

1 Buoyancy Tank

As one of the most critical components of the hybrid riser system, the buoyancy tank is used to provide appropriate tension for the system. Protection of the buoyancy tank connection to the riser system should be maintained during all phases. Redundancy of the buoyancy tank connection system should be considered in the design.

The offset of the buoyancy tank to the FPI should be sufficient to avoid catastrophic failure, such as loss of the buoyancy tank constraint due to tether chain/flexible joint failures.

1.1 General Principles

The following principles should be followed during the design of the buoyancy tank:

- BT should keep riser string under tension in any conditions including the flexible jumper free hanging on veritical riser system during installation condition.
- BT should be compartmented.
- The number of chambers/compartments should be selected to maintain high efficiency (higher upthrust to weight ratio) of the BT.
- The volume of each compartment should be designed so that in case of flooding of one or two compartments, the bottom tension of the riser is still positive and will not generate excessive rotation at the latching mechanism.
- One redundant compartment should be reserved by flooding seawater and preferably located at the bottom of the BT.

The overpull should consider the flexible jumper free hanging as a normal installation case to provide flexibility during installation, which may be the governing case for BT overpull determination. Typically, overpull varies from 1.4 to 1.9 in this case, depending upon functional requirements.

Closed form BTs are recommended and all compartments are suggested to be pressurized with nitrogen and sealed by ROV hot stab after installation offshore. The pressure difference between the external wall and internal wall of the compartment is suggested to be in the range 2-4 bars.

A central support pipe, if any, could be used as the load bearing member, which can penetrate through the BT compartments. Typically, the central support pipe should be sized in such a way that it can provide the buoyancy equivalent of at least one compartment.

1.3 Design Considerations

The major design parameters and their impact on the BT performance (buoyancy, buckling behavior, and maximum stress) can be demonstrated using recognized software. Decisions about major BT design parameters depend on the following factors:

- Functional requirements
- Ease of fabrication (e.g., compartment standardization)
- Installation requirements
- Buckling behavior and maximum stress
- Material sizing, fabrication, transportation constraints

Sufficient attention should be paid to fabrication issues, including the following:

- *BT Shell Plate Rolling Diameter Capacity:* The capabilities of the fabricator need to be taken into account.
- *BT Bulkhead:* Stiffeners are typically needed on flat bulkhead plating; welding procedures for those stiffeners should be considered; domed type bulkhead may be considered per project requirement.
- *BT Padeyes:* Welding and NDE of very thick padeyes (if any) should be specially considered.
- *BT Shell Thickness:* A minimum wall thickness of the shell is to be considered for fabrication to avoid flattening effect. Often a minimum shell thickness of $^{1}/_{2}$ inch is suggested.
- The pressure retaining parts of the buoyancy tank should be designed in accordance with recognized standards, such as ASME Pressure Vessel Code (Section VIII, Div. 3) or BS 5500.

3 Riser Foundation Pile

3.1 Driven Pile

The design of the driven pile is to follow Section 9 of API RP 2A-WSD "Foundation Design", API RP 2GEO and API RP 2SK.

3.3 Suction Pile

3.3.1 General

The riser can connect to a suction pile via a latch or tie-back type connector at the seabed foundation. The suction pile should be designed to withstand the maximum loads from the vertical riser system in current and severe storm under operating condition. The pile design should also consider transportation, installation and removal, if any. Both pile capacity and crown displacements should be evaluated for all stages. These piles should function with minimal maintenance for the service life of the riser system.

3.3.2 Design Process

The design process can comprise the following:

- Global sizing of the suction pile based on provided soil information to verify the adequacy of the pile capacity under all design loading conditions
- Global sizing of the suction pile to verify the induced pile displacement satisfies the serviceability requirements
- Global sizing of the suction pile to verify that the embedment suction pressure is acceptable for the available soil strength
- Global sizing of the suction pile to verify that the extraction pressure is acceptable for the available soil strength in case pile removal is required
- Structural design of suction pile for maximum installation loads with upper bound soil strength properties
- Structural design of suction pile and padeye for fatigue loadings
- Structural design for lifting, handling and transportation
- Design of appurtenances for installation and recovery
- Sizing of appurtenances and installation aids (e.g., vent openings, padeyes, support for pump interface, anode design, etc.)

The suction pile should be designed so that the induced vertical displacement and lateral deflection do not exceed the acceptance criteria of the hybrid riser system. In addition, the suction pile should be designed so that the accumulated cyclic displacement is within certain limits that will not cause significant deterioration of the uplift resistance. The pile top seals should remain functional until reconsolidation of the soil provides adequate skin friction.

3.3.3 Sizing – Geotechnical Design

The geometry (length and diameter) of the foundation pile should be designed to provide adequate axial and lateral capacity, as well as to satisfy installation and removal requirements. The suction pile design should be performed in accordance with API RP 2SK and API RP 2GEO using recognized geotechnical analysis program and FEA software packages.

The allowable capacity in WSD method is determined by dividing the net capacity by a factor of safety (FOS), see Section 5, Table 2. The safety factor accounts for uncertainties in soil properties, anticipated loads, and the consequences of failure.

The uplift and lateral capacities are the most critical aspects of suction pile design. In deriving the appropriate suction pile uplift capacity, the following effects should be considered:

- Local scour and other minor geo-hazard issues
- Installation tolerances (pile mis-verticality and mis-orientation)
- Soil disturbance due to padeye and chain
- Set-up effect
- The interaction between the vertical load and the lateral load
- The soil creep effect under long-term sustained loading
- The soil cyclic degradation effect based on the dynamic loading
- If the reference site is within a seismic zone, potential of soil liquefaction and its effects
- When lateral deflections associated with cyclic loads at or near the mudline are relatively large, considerations should be given to reducing or neglecting the soil-pile adhesion through this zone.

3.3.4 Sizing – Structural Design

The suction pile structure should be designed to withstand the maximum loads applied by the vertical riser and equilibrated by the soil reactions, the maximum negative pressure required for pile embedment, the maximum internal pressure required for pile extraction, and the maximum loads imposed on the pile during lifting, handling, transportation, launching, lowering, and recovery etc.

The WSD method in API RP 2SK should be used in the structural design of the suction piles, wherein calculated stresses in all components of the structure should not exceed specified values. The structural components of the suction pile should be designed in accordance with the applicable provisions of API RP 2A-WSD, AISC *Steel Construction Manual* and the ABS *Guide for Buckling and Ultimate Strength Assessment for Offshore Structures (Buckling Guide)*. In general, cylindrical shell elements are to be designed in accordance with API RP 2A-WSD; the ABS *Buckling Guide*; or API Bulletins 2U for circular shells and for flat plate elements in accordance with API Bulletin 2V. Other structural elements can be designed in accordance with API RP 2A-WSD or AISC *Steel Construction Manual*, as applicable. Alternative codes should only be considered acceptable if the safety levels and design philosophy implied in API RP 2SK are adequately met.

3.3.5 Miscellaneous Appurtenances and Cathodic Protection

The suction pile design includes sizing and Bill of Material call-outs for appurtenances such as:

- Vent valves in the pile top used to minimize pile instability and pumping action when the pile approaches the seabed
- ROV landing appurtenances and suction outlet
- Pile top cap positioning equipment receptacles
- Receptacle and locking mechanism of the bottom connector on the pile top
- Pressure gauge and associated fittings
- Bullseye-type level gauge

- Surface coating on the surface areas exposed above the mudline and not active in load transfer
- Markings required to monitor pile penetration and pile orientation
- Markings to distinguish individual piles
- Cathodic protection anodes

Vent valves should have an ROV-friendly means of closure. A protection flange above the valve should accommodate a contingency cover plate. Both the internal and external faces of the suction pile shaft that penetrate the soil should not be painted or cleaned. Anode layout should accommodate ROV and pump equipment footprint.

5 Top Riser Assembly (TRA)

The TRA is typically a welded truss structure usually comprised of tubular members. Temporary support saddles, sea fastening and upending padeyes should be provided as required.

The TRA interfaces with:

- The buoyancy tank via a tether chain/flexible joint
- The flexible riser jumper via a subsea diverless connection, if required
- The rigid riser pipe via a structural connection or a tapered stress joint

TRAs for production hybrid risers may also require means to allow access to the riser bore for hydrate remediation operations.

5.1 Design

The TRA is positioned between the upper rigid riser pipe and the buoyancy tank. The TRA should be able to withstand installation and operational loads, including loading induced from direct wave and current action on the riser and those from vessel motion transmitted through the flexible riser jumper. The critical load cases are summarized as follows:

- Loads during fabrication:
  - General handling and lifting
- Transportation and installation:
  - Barge transit and transfer to field
  - Upending the TRA
  - TRA support on the installation vessel
  - Flexible jumper installation
- Operational loads, including:
  - Loading from the riser tension
  - Riser lateral motions induced from direct wave, current action and vessel movement
  - Internal pressure and temperature
- Fatigue loads due to:
  - First and second order motions of the hybrid riser
  - VIV of the hybrid riser
  - VIV of the Buoyancy Tank
  - Operational temperature and pressure cycles
  - Slugging loads
- Loads due to ROV impact

7 Bottom Riser Assembly (BRA)

The BRA is typically a welded tension frame constructed from large diameter tubular and plate members. Temporary support saddles, seafastening and upending padeyes should be provided as required.

The BRA interfaces with:

- The foundation via a flexible joint or taper joint
- The riser base jumper via a subsea connector
- The rigid riser pipe via a structural connection or a tapered stress joint

Production BRAs may require insulation to meet flow assurance requirements.

7.1 Design

The BRA is positioned at the base of the lower rigid riser pipe and provides the structural connection to the foundation. The BRA frame and piping should be able to withstand loads during:

- Fabrication:
  - Erection
  - General handling and lifting
- Transportation and Installation:
  - Upending the BRA
  - BRA support in the installation vessel
  - Determination and adjustment of BRA heading
  - Riser 'stabbing' into base foundation
  - Potential riser 'lay-down' as contingency for abandonment
  - ROV impact
  - Riser base jumper installation
- Operation:
  - Hybrid riser tension
  - Hybrid riser lateral motions induced by:
    - Direct wave
    - Current action
    - Vessel movement
  - Loads from the riser base jumper
- Hybrid riser induced fatigue loads:
  - First and second order motions
  - VIV
  - VIM of the buoyancy tank
- Riser base jumper induced fatigue loads:
  - VIV
  - Slugging
- Operational temperature and pressure cycles (BRA piping only)

SECTION 4 System Global Analysis

1 General

The objectives of a hybrid riser analysis should be as follows:

- To obtain the riser global response by applying environmentally-induced effects to the hybrid riser system;
- To demonstrate that the design complies with pertinent acceptance criteria; and
- To provide input for component designs.

1.1 Analysis Tools

Recognized riser analysis software should be used for the hybrid riser analysis. Some software has been developed specifically for riser analysis and some are generic FEA tools.

Considering the complexity of a hybrid riser system and software availability, it is typical that riser specific software is used for global response analysis, and generic FEA software is used for detailed and local component analysis and design evaluation.

There are also some purpose-developed programs to handle particular issues (e.g., interference). Such specialized software should be suitably verified prior to being implemented into analysis.

1.3 Loads and Load Case Matrix

A hybrid riser system will experience the following loads which are to be taken into account in the analysis:

- Environmental loads (wave, current, wind)
- Vessel motion loads (static, dynamic)
- Pressure and temperature loads (internal, external)
- Functional loads (weight, content, buoyancy)
- Accidental loads (dropped objects, partial tension loss, etc.)
- Other loads (e.g., coil tubing intervention)

A detailed loading condition matrix should be developed based on API STD 2RD detailing the combinations of the above loads that are to be used for design, taking into account the following when setting up the load case matrix.

- Different combinations of metocean data
- Vessel in intact or damaged condition
- Riser operating temperatures and pressures
- Range of fluid content
- Mooring line loads from vessel intact or damaged condition
- Buoyancy tank loads from intact or damaged condition
- FPSO turret buoy loads in the connected or disconnected condition, if applicable.

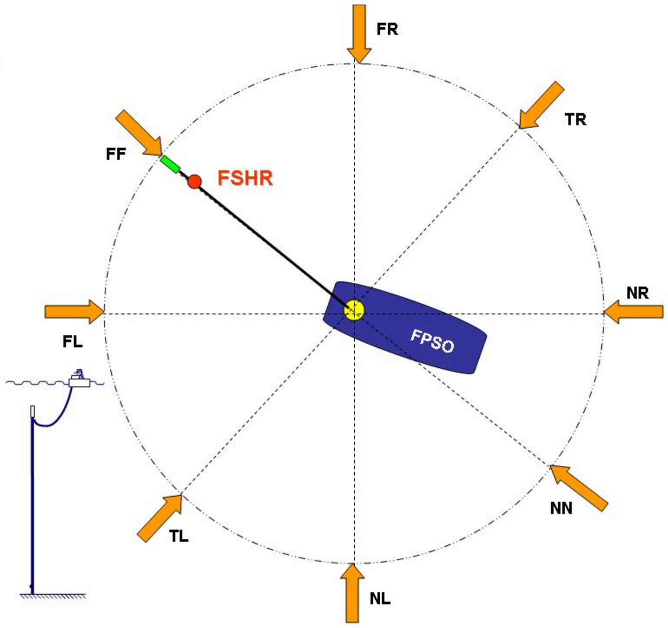
- FPI position with respect to hybrid riser plane (near, far, transverse, quartering) as shown in Section 4, Figure 1, “Vessel Position Definition” below (NN: near-near, FF: far-far, NL: near-left, NR: near-right, FL: far-left, FR: far-right, TL: Transverse-left, TR: transverse-right)
- Positional tolerances (vessel, riser, effect of re-spudding of foundations)

Global design per API STD 2RD considers SLS, ULS and ALS while local FEA may well consider Operating, Extreme, Survival, hydro-testing and temporary conditions. Other recognized standards like API RP 2A, 17B, Spec 17J, 17D etc. are followed for specific components. Code mapping should be carried out to map the global analysis matrix to these standards to verify adherence to code. This is likely to be Operator and region specific and include an element of risk assessment. An (incomplete) example of an approach is shown Section 4, Table 1 below.

TABLE 1
An (incomplete) Example of Code Mapping

Pressure	*Environment*	*FPSO Mooring/ Buoyancy Tank Status*	*Rigid Pipe (ULS/ALS)*	*Flexible Jumper (API RP 17B, Spec 17J)*	*Local FEA Acceptance Criteria*
Operating	100-year	Intact	ULS	Recurrent Operation	Operating
Design	100-year	Intact	ULS	Extreme Operation	Extreme
Design	100-year	Damaged Mooring	ALS	Accidental Operation	Survival
Design	1-year	Damaged Tank	ALS	Accidental Operation	Survival

FIGURE 1
Vessel Position Definition



1.5 Rationale of Riser Selection for Analysis

Proper selection of a representative riser from multiple hybrid risers for riser analysis is acceptable, and at least one of each riser type and size should be analyzed. The selection should consider the following items to establish the worst case:

- Water depth
- Horizontal distance between hybrid riser bases and riser hang off location at the FPI
- Rigid base jumper plane close to the plane or transverse to the plane of the flexible jumper, whichever is worse
- Omni-directional wave approach
- Omni-directional current approach (e.g., loop current in GoM)

Any discrepancies between the selected hybrid riser and its analysis model, if applicable, should be justified by sensitivity analyses.

3 Global Strength Analysis

The strength analysis should be performed with the following objectives:

- To determine the hybrid riser global configuration, including RBJ
- To confirm that the hybrid riser design satisfies strength criteria under all operational, extreme, accidental, survival and hydrotest loadings specified in the load case matrix
- To provide interface loads as input for component design

The ABS *Riser Guide* or API STD 2RD is the primary design standard for hybrid riser global strength analysis. For hybrid risers installed in the GoM, WSD method is typically preferred.

Riser segments can be modeled using beam elements or equivalent. The mesh needs to be successively refined and results are to be compared until it is demonstrated to be suitable.

3.1 Analysis

3.1.1 Wave

Regular wave analysis may be used for screening purposes to identify the governing load cases for each load condition. The regular wave analysis should be carried out until the riser dynamic response has stabilized. A simplified approach may be used by calculating vessel response spectra to given wave spectra and determining likely maximum responses and then calibrating regular waves/selecting appropriate irregular waves.

Irregular-wave, time-domain analysis should then be performed for the selected load condition. The JONSWAP spectrum is recommended for the irregular wave, time-domain analysis, unless specified otherwise in the metocean data report (e.g., multi-peak spectra). The extreme riser responses are to be obtained from evaluation of the most probable extremes in an at least 3-hour storm.

Where regular wave analysis is used, load cases critical to riser response or design should be identified from the regular wave cases, and further analyzed using an irregular wave approach to determine if there is any undue conservatism due to the analysis approach.

Where irregular waves are used, sufficient care should be taken to acquire a realistic representation of the storm-based statistics. Uncertainty about wave period should be considered along with wave direction, vessel heading, and vessel draft. Special attention should be given in case of multi-peak spectra.

3.1.2 Current

Current directionality should be considered conservatively. In some cases considering currents to be co-linear can be non-conservative, particularly in regions of the world where surface currents are largely unrelated to deep currents.

Hydrodynamic coefficients should be carefully selected to acquire conservative estimation of drag and inertia forces from both current and wave loading.

3.1.3 Tension

Riser tension is applied by the buoyancy tank. Care should be taken to verify that the correct tension distribution is captured accounting for changes in fluid density, buoyancy, material loss and tolerances over the life of the field.

For a PIP riser, the effects of differential pressure and temperature between the inner and outer pipes should be assessed considering the range of tension distributions included in the detailed load case matrix. The calculation should include consideration of the installation method (e.g., inner pipe pull-out/pre-tensioning operations; the presence of fluid during installation; etc.). The strength response of the inner pipe is highly dependent on the level of tension applied.

3.1.4 Load Case Mapping

An important output from global response analysis is the interface loads at the location of individual components. These loads should be obtained early in design and appropriate margins should be added to the FEA output. These extreme interface loads are inputs to local component design, such as the TSJ, and the TRA, via load case mapping.

3.3 Analysis Procedure

The global strength may be analyzed using a multi-stage analysis procedure consisting of three static (or quasi-static) steps followed by a dynamic run that is the strength analysis.

1. *Hybrid riser neutral position (weight equilibrium) – Static Analysis:* The “neutral position” considers the riser and the flexible jumper system with content filled when it is subjected only to gravity and hydrostatic loads (i.e., no current, no wave and no vessel offset).
2. *Apply vessel offset on hybrid riser system – Quasi-Static Analysis:* From the previous Step 1, the hybrid riser system is subjected to the effects of vessel offsets.
3. *Current loadings on hybrid riser system – Quasi-Static Analysis:* From the previous Step 2, the hybrid riser system is further subjected to the effects of the current loadings.
4. *Apply wave loadings and vessel motions on the hybrid riser system – Dynamic Analysis:* From the previous Step 3, the hybrid riser system is further subjected to the effects of wave loadings.

Step 4 is actually the hybrid riser strength analysis in time domain which includes the functional (e.g., gravity, buoyancy, temperature, pressure, vessel offset, etc.) and environmental loadings (current and wave actions).

All the strength results (e.g., loadings and motions output) will be obtained at Step 4.

3.5 Sensitivity Analyses

Sensitivity analyses should be carried out to determine the effects of practical variations in riser configuration with time and uncertainties in design parameters. Parameters considered should include the following:

- Riser VIV drag coefficient amplification and BT VIM drag coefficient amplification
- Manufacture weight tolerances and installation tolerances of all riser components
- Variable rotational stiffness of the bottom connector
- Variable hybrid riser base tension with tolerances
- Effect of FLET/Manifold settlement and flowline expansion/contraction over RBJ
- Tolerance on measurements, fabrication and installation of the RBJ

Expected extremes of the parameters listed above should be incorporated into the riser models. Previously identified critical load cases should be analyzed to quantify the effects of parameter changes on response.

5 Global Fatigue Analysis

5.1 General

Riser design fatigue life is predicted using cumulative damage calculations. The cumulative damage is based on contributions from vessel first and second order motions, VIV responses, BT VIM, installation and transportation. The fatigue damage from each contributing mechanism should be factored by the appropriate safety factors prior to combination to determine the combined fatigue life. Typical fatigue loadings are:

- Riser VIV and BT VIM
- Vessel motion (wave)
- Installation
- Transportation (e.g., towing)
- Start-up and shut-down (pressure/temperature cycles)
- Slugging

5.3 Global Motion Fatigue Analysis and Procedure

5.3.1 Analysis Considerations

The objective of motion fatigue analysis, using appropriate (e.g. non-linear, time domain) FEA software should be to determine the fatigue life of the hybrid riser system and related components due to first order (wave frequency) and second order (vessel low frequency) motions considering in-place conditions.

Motion fatigue analysis can also provide the fatigue loadings and motion histograms for the design of the affected components. Fatigue performance of the buoyancy tank, tether chain/flexible joint, TRA, gooseneck assembly, BRA and RBJ should then be addressed in the components' local analyses.

Stress histograms at the riser welds and other critical welded connections can be generated for further ECA to establish the allowable weld defect acceptance criteria.

Fatigue damage of the hybrid riser system caused by first order and second order vessel motions should be analyzed utilizing a time-domain methodology. The metocean data for all floater fatigue bins, including H_s, T_p, wave direction, other parameters of wave spectrum (e.g., JONSWAP peakedness parameters), current surface velocity and direction, and percentage of occurrence are usually utilized in the analysis. Vessel heading should be considered particularly for turret-moored systems. Fatigue analysis should consider applicable wave directions (relative to riser) and vessel headings (relative to wave). Probabilities should be consolidated for at least eight, evenly spaced compass directions for each fatigue sea state to achieve the cumulative bin probability. Condensed fatigue bins should be analyzed to capture the overall wave-induced fatigue for the system.

For each fatigue sea state, an appropriate simulation time should be selected based on demonstrated convergence. Fatigue damage should be calculated for the entire hybrid riser system across at least eight points on the pipe's circumference based on rain-flow counting technique.

Bi-modal or tri-modal wave spectra should be used to capture the proper wave characteristics when specified in the metocean data report.

5.3.2 Global Motion Fatigue Analysis Procedure

The metocean definition for all wave fatigue load cases, including H_s, T_p, wave direction, current surface velocity and direction, and percentage of occurrence is usually presented in the design basis metocean report.

The vessel motion can be given in the form of time traces in six degrees of freedom given at the CoG of the vessel or RAOs with second order motions provided separately as RMS with period/time traces. These motion data can combine first order and second order vessel responses. Motions are transferred to the riser hang-off location through rigid body transformation.

The current profiles associated with the surface currents are based on the metocean data. These profiles may or may not be applied in the motion fatigue analysis. Condensed fatigue sea states, with the intention of saving simulation time and being conservative, can be used.

Time-domain analysis with the rainflow cycle counting method is suggested because it accounts for nonlinearities, and low and wave frequency motions. A suggested procedure for motion fatigue analysis is as follows:

1. Generate the wave scatter diagram from the metocean data as a number of bins defined in grid directions.
2. Combine adjacent sea state bins to form directional condensed scatter diagram with 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.
3. Fatigue damage in each selected sea-state is obtained by counting the stress cycles in the simulated stress time histories through the rainflow counting method. The total wave fatigue damage is the sum of the individual fatigue damage for all the representative blocks.

5.5 Global Vortex Induced Vibration (VIV) Fatigue Analysis and Procedure

The analysis of VIV fatigue for the hybrid riser should be performed, using appropriate (e.g., non-linear, time domain) FEA program with accompanying modal analysis software and specialty VIV assessment software, with the following objectives:

- Identify the placement of VIV suppression devices using an interactive procedure.
- Determine the VIV fatigue damage.
- Provide fatigue bending moment histograms for the fatigue design of components. Stress histograms at the riser welds and welded connections will be generated for further ECA to set inspection criteria for key components.

The VIV-induced fatigue damage should be analyzed based on the nominal installation tolerances and the nominal components weight. The model for performing VIV fatigue analysis should include the integral components of the hybrid riser system, very similar to the modeling for strength analysis.

5.5.1 Computer Modeling

Hybrid riser VIV fatigue analysis should be carried out using pertinent, recognized software. The possibility of flexible pipe VIV should be discussed with the supplier.

The analysis software is used to get the riser’s nominal shape and tension distribution along the riser. The flexible jumper, RBJ and the other components should also be included in the model in order to consistently assess their effects on hybrid riser responses.

The modal frequencies, modal shapes, and modal curvatures both in-plane and out-of-plane of the hybrid riser are generally required as input to VIV analysis program. Proper QA/QC should be performed to verify the correct modal response will be used for further analysis. In general, the jumper-/RBJ-/components-driven modes are excluded from the modes considered in the VIV analysis.

VIV analysis program is used for predicting the VIV fatigue damage rate for each of current event flowing in the plane of the riser and the plane normal to the riser. The total VIV fatigue damage is then obtained by summing the damages from each current bin.

5.5.2 VIV Directions

VIV fatigue damage can be calculated assuming 100% of current heading in the plane of the flexible jumper (in-plane), and 100% of current heading perpendicular to the plane of the flexible jumper (out-of-plane). Comparing the VIV-induced fatigue damage for both in-plane motion and out-of-plane motion at each location along the whole riser, the shorter fatigue life is selected as the VIV fatigue life at that location.

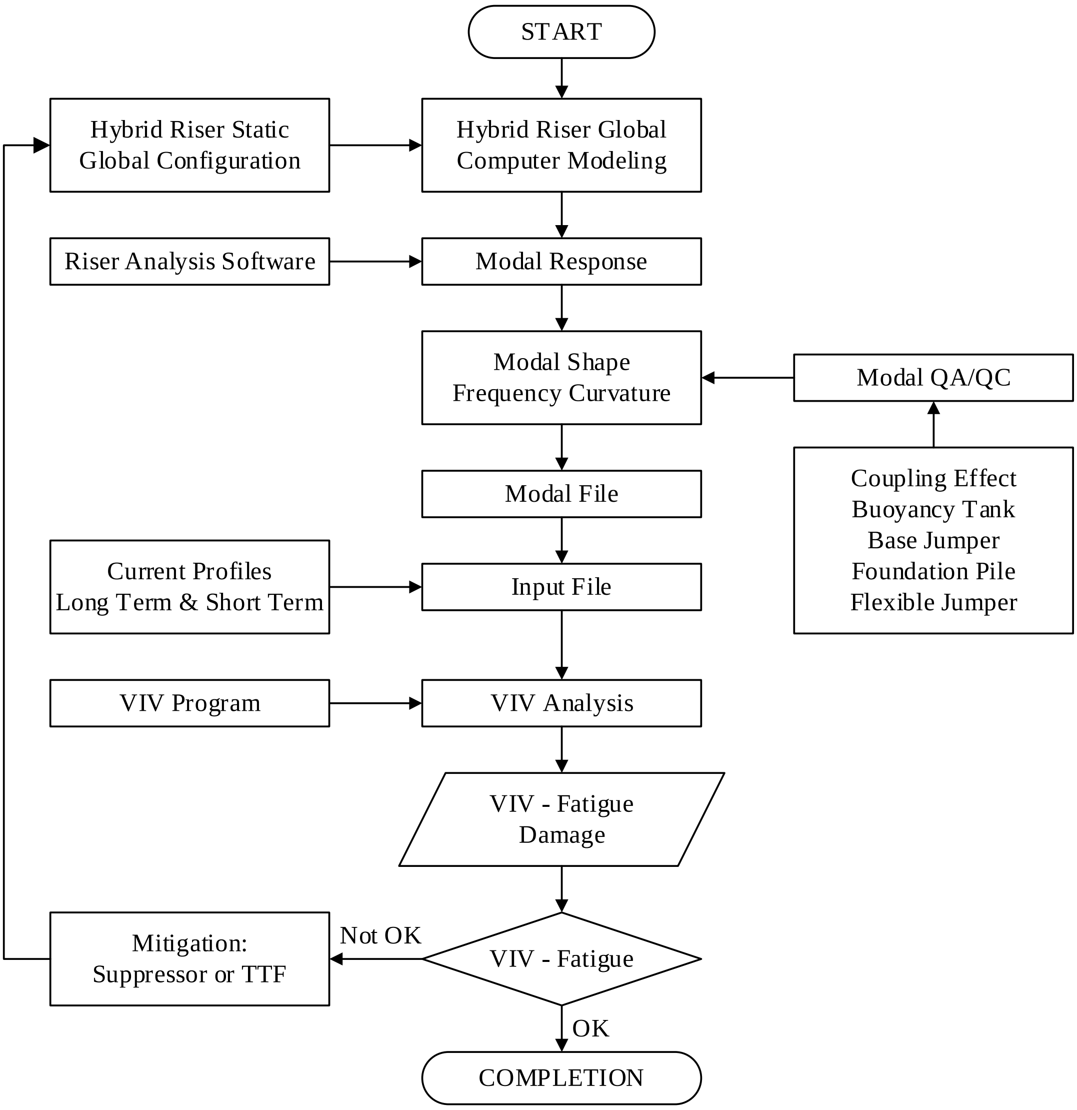
5.5.3 Global VIV Analysis Procedure

The following two cases should be considered in hybrid riser VIV analysis:

- Long term VIV fatigue
- Short term (extreme) VIV fatigue

The flowchart in Section 4, Figure 2 shows a sample procedure and major issues that should be considered during a typical VIV fatigue analysis of a deepwater hybrid riser system applicable for all types of floaters.

FIGURE 2
Hybrid Riser VIV Fatigue Analysis Flowchart



A general VIV fatigue analysis procedure is outlined below:

1. FEA software is used to get the riser's nominal shape and tension distribution along the riser.
2. Modal analysis software is then used to extract modal frequencies, modal shapes, and modal curvatures both in-plane and out-of-plane for the hybrid riser system.

3. QA/QC of modal response results is conducted.
4. The results of the modal analysis software are utilized by VIV fatigue analysis program to predict the VIV fatigue damage rate for each of the current profiles.
5. The total VIV fatigue damage is obtained by summing the damages from each current bin.

5.5.4 Sensitivity Analysis

The following sensitivity studies on input parameters may be performed for the riser VIV analysis:

- Structural damping coefficient
- Stiffness of latch type/mechanical connector
- Modal excitation cut-off parameters

5.7 Buoyancy Tank (BT) Vortex Induced Motion (VIM) Fatigue Analysis and Procedure

5.7.1 Analysis

A free standing riser with a buoyancy tank at the top (not possessing flexible jumpers) can be considered as an upside down pendulum in the flow. The fundamental period (mode 1) can be calculated similar as for a mathematical pendulum. VIM is mode 1 riser system VIV due to periodic vortex shedding at the leeside of the buoyancy tank.

VIM originates when fluid passing the buoyancy tank causes low pressure eddies (or vortices) to form downstream of the body. These vortices are shed periodically at frequencies that are fluid velocity dependent. Vortex shedding induces loading on the body primarily normal to the direction of current flow. If the frequency of excitation of the vortices is close to, or the same as, a natural frequency of the structure, resonance occurs. Consequently, large amplitudes of oscillation may be induced when interaction between the flow (usually current) and structural motion causes lock-in. During lock-in, the buoyancy tank resonates and makes the riser undergo cyclic ranges of tension and curvatures that can cause fatigue damage.

VIM of the buoyancy tank has implications for the fatigue life of the riser pipe and the connection system (e.g., tether chain) attached to the buoyancy tank. Considering the potential impact of VIM on the fatigue lives of riser string, tether chain, and top riser assembly, VIM fatigue should be properly addressed in riser system design and analysis documents.

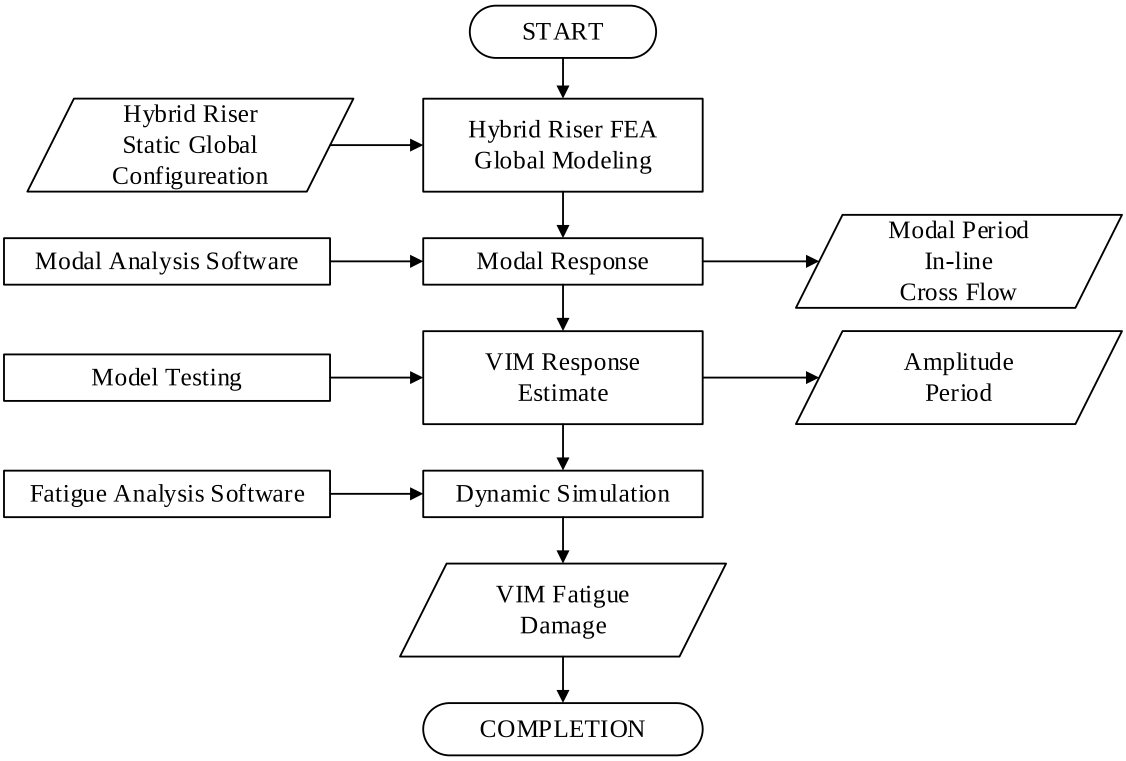
Transverse VIM occurs when the vortex-shedding period is close to the natural period of the Mode 1 riser. It takes place in the direction perpendicular to the current following approximately a sinusoidal pattern. The transverse A/D ratio is normally defined as the ratio of single amplitude (A) to the BT diameter (D).

In-line VIM occurs in the direction of the current and is affected by the transverse VIM. The magnitude of the in-line A/D is typically 10% to 25% of the transverse A/D. However, in-line motion is generally at twice the frequency of the cross-flow motion. Therefore, the fatigue damages contributed from both in-line and transverse VIM should be considered.

5.7.2 BT VIM Fatigue Analysis Procedure

The flowchart for BT VIM analysis is shown in Section 4, Figure 3:

FIGURE 3
BT VIM Fatigue Analysis Flowchart



The following procedure is suggested for evaluating the VIM response of the buoyancy tank:

1. Database preparation, which includes the riser and current information.
2. Performance of modal response analysis to obtain the hybrid riser's natural periods for the movements transverse and parallel to the flexible jumper's plane.
3. Using the natural periods from Step 2, a possible method is to perform calculation based on model testing results (or equivalent) to obtain VIM amplitude (*A*/*D*) for both cross-flow and in-line VIM.
4. In conjunction with the obtained amplitudes and natural periods, dynamic VIM is analyzed for each current bin. The dynamic response of the hybrid riser is captured and analyzed for a sufficient number of cross-flow VIM oscillations. Using the obtained tensile and bending response, fatigue life can be calculated along the hybrid riser with a rainflow counting technique.

5.9 Riser Base Jumper (RBJ) Fatigue Analysis and Procedure

5.9.1 VIV Fatigue Analysis

VIV fatigue analysis of the RBJ should be performed separately from that of the hybrid riser itself (as discussed previously), but should be carried out with a similar approach. The RBJ can be considered as an independent component, as its modal response is independent of the riser response. The procedure described for the VIV analysis of the hybrid riser should be considered for the RBJ, although care should be taken to verify that mode shapes and curvature are accurately captured should the RBJ design be 3-dimensional and/or have seabed interaction.

5.9.2 Riser-VIV Induced Motion Fatigue Analysis

The effects of the riser experiencing VIV may also adversely affect the response of the RBJ; thus negating the independence of riser and RBJ responses assumed above. Some of the modes of the riser that are excited through VIV may be in the region of the main RBJ modes. In this event, the resulting motions of the riser will generate excitation of the RBJ. This may lead to excessive fatigue damage and should be considered for the RBJ design. As a first step the modes of the riser that are potentially being excited should be compared to the main modes of the RBJ. If an overlap is observed, the motions of the riser under VIV, at the elevation of the BRA, should be extracted and implemented in a forced-excitation model of the hybrid system (including the RBJ) that will be assessed through a time-domain analysis. Stress cycles can then be extracted and, considering the probability of occurrence of each riser VIV mode, the fatigue damage along the RBJ may be determined.

5.9.3 Pressure & Temperature Fatigue Analysis

During the life of the field, the flowlines will experience a number of shut-down cycles, which will result in a variation in pressure and temperature condition within each flowline. These variations will cause expansion of the RBJ pipe, and expansion and contraction of the pipelines, which may result in displacement of the FLET. These variations will induce fatigue damage along the length of the RBJ and should therefore be considered. A static evaluation of the maximum change in pressure and temperature in the RBJ, combined with the expected flowline expansion/contraction during shutdown, should be considered in order to determine the maximum stress cycles along the system. When considered with the expected number of shutdowns during the field life, the resultant fatigue damage may be determined.

5.9.4 Slugging Induced Vibration Fatigue Analysis

Slugging originates when the produced fluid, typically formed of water, oil, and gas separates into a distinct mass of liquid (the “slug”, mostly comprised of oil and water) and a pocket of gas in the subsea pipeline system. This fluid will travel at a particular speed through the pipeline, the RBJ, and the riser and will have the following effects:

i) The variation between slug pocket and gas bubble will result in a density and weight variation in the system.

ii) When passing through a bend, the change of flow direction will generate a centrifugal force on that bend.

The first effect will typically affect the suspended section of the RBJ, as the length of the slug pocket and gas bubble are similar to the RBJ, and cyclic weight variation may induce fatigue in the system. Systems with increased flexibility are more likely to experience larger variations in displacements, which could result in adverse fatigue effect on connecting ends.

The second effect will be prominent mostly for tight bends (3D or 5D) in a rigid system, with large bend angles, such as the BRA bend or any of the RBJ bends. This fluid inertia effect can induce resonance in the system and lead to increased fatigue damage.

Both effects should be considered simultaneously, as either may be dominant depending on the flexibility/rigidity of the system, and may be assessed with global analysis software.

5.11 Fatigue Analyses in Sour Service Environment

When carbon steel pipe is used in sour service conditions, the S-N curve is recommended to be developed from tests simulating the service conditions. In absence of such tests, a standard S-N curve in the ABS *Guide for the Fatigue Assessment of Offshore Structures (Fatigue Guide)* may be used with a suitable knockdown factor for sour service. Considering that sour service knockdown is generally more severe for the low stress cycle/high stress range, the knockdown factor may be expressed in a linear variation (log-log scale) with a larger factor for low cycles and a smaller factor at high cycles. Full scale fatigue tests simulating the service conditions with the same riser pipe and welds are recommended to verify the fatigue analysis of the critical welds in sour service conditions.

7 Interference Analysis

7.1 General

The hybrid riser should be analyzed to assess potential interference scenarios between: risers, flexible jumpers, umbilicals, FPI mooring lines and appurtenances. It is possible that the global configuration may have to be modified to avoid clashing. To facilitate this, system arrangement should be evaluated to identify governing pairs, vessel scenarios and environmental conditions under which clashing is likely to occur.

The proposed interference analysis approach should analyze governing adjacent pairs and calculate the minimum separation for the free stream current. For a given current, the minimum separation over the length of the upstream-downstream pair is used as the basis for the clashing. The effects of different current incident angles and through-depth variation also should be investigated.

7.3 Load Cases

Screening studies to evaluate interference likelihood can be done using approximate methods, as various current angles and current angles that vary with depth should be investigated. The interference analysis can be simplified with conservative assumptions and careful selection of the riser pairs prone to interference. The comprehensive layout model should be analyzed for a number of load cases covering a range of tension combinations between adjacent risers (i.e., fluid densities and buoyancy tank status). Governing pairs and associated minimum separation should be determined based on the screening studies. The effects of wake on drag and lift forces, VIV and dynamics should be considered in the interference analysis for the governing pairs. Mitigation measures are recommended if the analysis shows that clashing is possible.

Installation tolerances for the riser foundations and allowance for re-spudding in the event of a failed foundation installation should be included when defining the field layout. Allowances should be included within the interference analysis to demonstrate acceptable clearance can be achieved when these are taken into account.

7.5 Minimum Separation

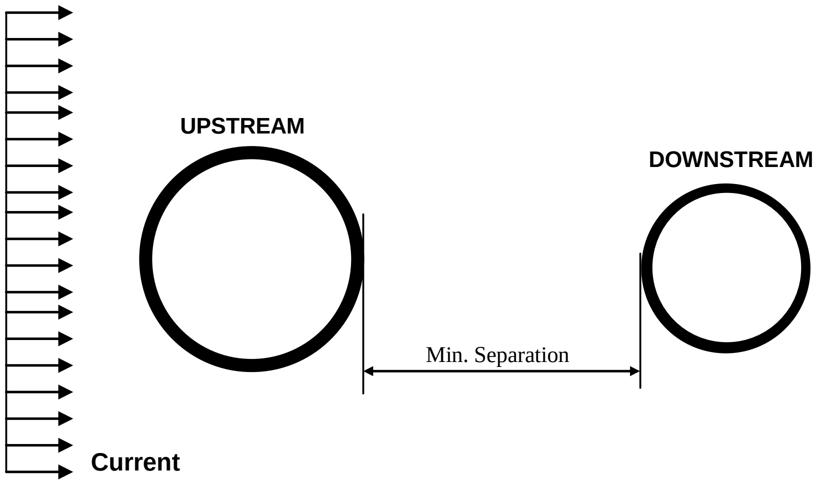
The separation between pairs is a measure of the likelihood of clashing. The minimum separation is defined as the minimum surface-to-surface distance between the upstream and downstream pair as illustrated in Section 4, Figure 4. The minimum separation should be stated as clearly as possible (e.g., 10 ft) for all operational and extreme conditions including coating and suppression device of the lines in the pair. If the minimum separation of the pair in the current is less than the minimum separation, clashing should be considered highly likely.

Clashing may be acceptable for flexible jumpers in extreme or survival events provided:

- Clashing occurrence is expected to be low
- Impact energies can be shown to be acceptable
- Appropriate inspection plans are in place

Due to the large potential energy stored in a buoyancy tank at depth, additional acceptance criteria may be required to eliminate or minimize the duration that the riser tower can spend below the production facility. This also includes the consideration of the statistical distribution of the facility’s position (e.g., heading analysis for an FPSO).

FIGURE 4
Minimum Separation Definition



7.7 Interference Analysis Approach

The interference analysis may consist of four major steps.

i) Generate the global model of the field including all the risers, mooring lines and umbilicals.

ii) Identify the governing pairs of lines which are susceptible to clashing. The minimum separations between every line and its nearest line are to be computed for necessary load cases. At least eight evenly spaced current directions should be analyzed for each load case to check the primary current direction for interference. For the governing current direction, nominal vessel/buoy position, minimum and maximum vessel/buoy offsets in a minimum of eight evenly spaced directions should be used to identify the associated minimum separation position for the vessel/buoy.

iii) Calculate the minimum separation between the identified pairs from step two considering the effects of VIV, wake and dynamics with sufficient refinement on current directions.

iv) Establish clashing mitigation methods for these pairs.

Clashing analysis should take wave effects as well as drag amplification due to VIV into account. In a pair of up and down stream lines, the drag and lift coefficients of the downstream line depend on the distance between the two lines and the direction of the current in terms of the wake effect. The drag of the upstream line is also affected by the proximity of the downstream line. Taking wake effect into consideration, the lift coefficient of the downstream and upstream lines and the drag amplification due to riser VIV are calculated by suitable software. Those two parameters along the upstream-downstream pair are then used for simulation of the deflections of the lines.

The line properties, sizes, suppression devices, buoyancy modules, contents weight, top angles, etc. along with the current profiles are input to the analysis software. Minimum surface-to-surface clearances are estimated by analysis. All appurtenances and components like fairing, TRA, etc., are to be considered in the calculation of the minimum surface-to-surface clearance as appropriate.

7.9 Interference Analysis Procedure

Effects of wake, VIV and dynamics in interference analysis can be determined using appropriate Riser and VIV analysis software. The primary procedure is outlined below:

1. Create analysis model to obtain the respective mode-shapes and static configuration.

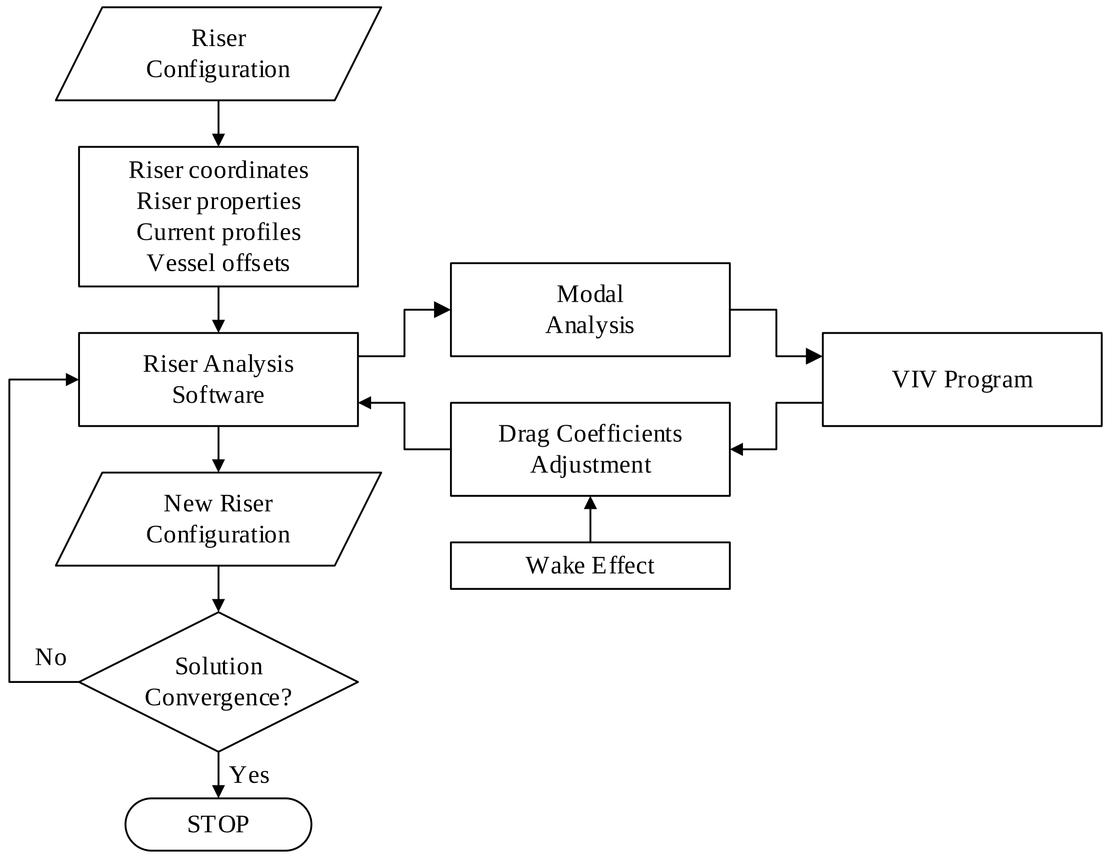
2. Create input data of upstream and downstream pairs for VIV analysis software using mode-shapes obtained in Step 1.

3. Use Riser analysis software to calculate the loads on the upstream and downstream pair considering:
   - The free stream current at each elevation
   - The free stream drag given in the input
   - The amplification in the drag coefficient due to VIV
   - The adjustment in the drag coefficients because of the proximity of the downstream riser
   - The vessel motions effects.
4. Use Riser analysis software to calculate the loads on the downstream riser using the similar parameters as for the upstream riser, considering the wake current of the upstream riser.
5. Use VIV analysis software to calculate the VIV for each riser from the current and the modal shapes and obtain the VIV amplitudes.
6. Use the loads on the risers to calculate new riser configurations in Riser analysis software. The new configurations are updated and compared to the previous ones until the differences are acceptable.
7. Use the final riser configurations to calculate the spacing between the risers along the length of the risers to evaluate the possibilities of riser clashing.

Steps 1 through 7 should be repeated for the governing current incident angle and vessel offset to capture the worst angle of incidences and identify the minimum separation for the main pairs.

The above methodology is illustrated in the Section 4, Figure 5 below.

FIGURE 5
Interference Analysis Flowchart



7.11 Sensitivity Study

Sensitivity analyses should be conducted for the following parameters of the most likely interfering pair. These analyses may only be conducted for the most pertaining load cases.

- Reduced weight of upstream line
- Increase in drag coefficient for upstream line
- Vessel offset variations
- Base tension tolerance

9 Analysis Modeling

9.1 General

The general modeling considerations for a hybrid riser are described in this Subsection. Analysis modeling should be consistent for the strength and fatigue analyses. Finite element analysis (FEA) models should include all the major hybrid riser components including BT, flexible jumper, gooseneck assembly, top riser assembly, riser pipes, VIV suppression devices, as well as boundary condition definitions at top and bottom ends and seabed properties. The FEA models should be sufficiently detailed in critical areas to achieve realistic stress results.

Components of the hybrid riser can be modeled by beam elements, or equivalent. The element meshes need be suitably graded so that response in critical areas (e.g., tapered stress joint) is accurately identified. Mesh refinement should be applied to areas of high loading, high curvature and significant changes in geometric properties. Von Mises stress envelopes along the riser may be used to justify the mesh as suitable.

9.3 Floater Motion

Motion RAOs at the center of gravity (CoG) of the FPI or time traces of the FPI motion are normally used to simulate FPI motion in waves. Corresponding motion at the hang off location of the hybrid riser system can be obtained by coordinate transfer from the floater motion at CoG via rigid body assumptions. These motions are the boundary conditions of the top of the flexible jumpers.

9.5 Riser Pipe

The riser pipe is discretized based on the spatial variation of physical properties of the riser. In general, coarser meshes can be applied in the regions where the stress is not of interest (e.g., middle section), while finer meshes are essential for accurately determining stresses in the top and bottom regions.

Standard riser joints of the hybrid riser system can be modeled as beam elements or equivalent. Coatings are considered and the diameters in computer model are adjusted accordingly. The weight in the computer model should include the weight of the pipe and the anodes.

The hydrodynamic coefficients depend on a number of parameters. The values of the drag and inertia coefficients should follow API 2A-WSD.

9.7 Flexible Jumper

The flexible jumper can be modeled as beam elements or equivalent with suitable properties. Analysis can be performed considering fixed connections at both ends of the jumper (i.e., oriented with respect to FPI hang-off angle and gooseneck angle). Bend stiffener parameters (size, mass and stiffness) can be used at both ends of the jumper. The verification of the bend stiffener parameters should be carried out by the supplier with the required data (e.g., the range of curvature at the end connections, tensions and number of tension cycles). Marine growth should be included in the analysis model of the flexible jumper. Drag coefficients of the flexible jumper should be based on data supplied by the manufacturer. No structural damping should be included unless fully justified. Uncertainties in stiffness (both sheath and stick-slip) should be considered carefully and conservatively.

9.9 Buoyancy Tank

The BT can be modeled as beam elements, or equivalent, with the principal dimensions (diameter & height) and dry mass as designed to provide required up-thrust buoyancy. The void and flooded compartments should be modeled individually. To model flooded BT compartments, the mass of the applicable series of compartments are increased to include the mass of the contained water. Tangential added mass should be included. The drag diameter should reflect the presence of auxiliary equipment on the exterior surface of the BT, if applicable. The effects of BT surface roughness, aspect ratio, and cross-flow VIV should be considered in selection of drag coefficients.

9.11 Foundation Pile

The foundation pile, if any, may be included in the global analysis model to achieve a more realistic response; and the pile can be modeled by beam elements, or their equivalents. The lateral interaction of the pile with soil below the seabed can be modeled using *p-y* curves as a function of depth. Inclination tolerances should be considered.

9.13 Buoyancy Tank-Riser Connection

Depending upon the connection system between the BT and the top of the riser, computer modeling could be different. If tether chain, cable, and/or fiber rope is used, they can be modeled as a series of beam elements, or equivalent, between two ends of each line. The load spools (if any) at the end of the tether chain, cable, and/or fiber rope can also be modeled as short beam elements, or equivalent. The properties of the short beam element at the two ends may be obtained from a local detail FEA of the connections. For a flexible joint connection, nonlinear flexible joint stiffness values supplied by the flexible joint manufacturer should be used in the model.

9.15 Top Riser Assembly

The top riser assembly (TRA) incorporates the gooseneck spool, which transmits bending loads to the riser via the flexible jumper connection. Attention should be paid to the overall geometry including center of gravity, center of buoyancy, jumper load application point, etc. Even though the local behavior of the TRA may not be included accurately in a global model, its effect on the global response should be reasonably determined through sensitivity study.

9.17 Bottom Riser Assembly

If a latch type connector is used at the bottom of the vertical riser, the latch type connector can be modeled using an articulation element, or equivalent. Nonlinear flexible joint stiffness values, supplied by the flexible joint manufacturer, should be defined in the model.

If a mechanical connector (e.g., tie-back connector) is selected, it can be modeled as fixed in the computer model with its structural properties properly considered.

9.19 Use of Corrosion Allowance

Forces and moments within the riser components can be calculated considering the uncorroded condition. For plain round pipe, the von Mises equivalent stresses should be calculated in accordance with the ABS *Riser Guide* or API STD 2RD {i.e., considering the minimum wall thickness (manufacturing tolerance and corrosion allowance) for the burst and collapse pressure check}. Otherwise, nominal wall thickness can be used for the radial and axial stresses.

For fatigue, 50% of the corrosion allowance should be taken into account when calculating the stress cycles. This procedure is a way to account for the gradual loss of pipe wall thickness and the resulting change in alternating stress over the life of the riser.

Anti-corrosion and insulation coatings should be accounted for. These coatings can cause an increase in mass and hydrodynamic diameter but are assumed not to contribute to the structural stiffness of the pipe.

Nominal pipe properties without corrosion should be used for performing all riser analyses. Corrosion allowance specified in the *Riser Guide* is considered during the post-processing of the analysis results, i.e.:

- Fully corroded pipe is used for stress check
- 50% corrosion allowance is used for fatigue analysis.

SECTION 5 Analysis of Components

The input to component analyses comes from system global analysis. Typically, component analysis is performed using generic FEA software. Typically, the design criteria for components are different from those used in global analysis.

1 Buoyancy Tank

1.1 General

This Subsection describes a methodology for the analysis of buoyancy tanks for a hybrid riser system. The BT analyses include the following:

- Static analysis
- Strength and fatigue analysis for operating and extreme conditions
- Strength and fatigue analysis for transportation conditions
- Strength and fatigue analysis for installation conditions

1.3 Load Cases for Buoyancy Tank (BT) Analysis

Load cases for BT analysis can be as follows:

TABLE 1
Summary of Load Case Matrix for BT Analyses

Type Number	*Load Description*
1	Static stress check: simple sling lifting at both ends of BT
2	Buckling check
3	Strength analysis: In-place
4	Strength analysis: Transportation
5	Strength analysis: Installation
6	Fatigue analysis: In-place dynamic from current, wave and tide
7	Fatigue analysis: In-place dynamic from VIM and sloshing
8	Fatigue analysis: Transportation dynamic
9	Fatigue analysis: Installation dynamic

The BT analysis should at least encompass the following design tasks:

- Strength analysis for operating conditions: The strength is to be analyzed to confirm that the BT design satisfies the acceptance criteria for transportation, installation, and operational conditions, as defined in the load case matrix. API RP 2A-WSD and ISO 19900 should apply.
- Fatigue analysis: Fatigue should be evaluated to confirm that the BT design will have a calculated fatigue life longer than its design life. A safety factor (Fatigue Design Factor) of 10 is suggested; therefore the BT should have an accumulated damage of less than or equal to 0.1 at the end of its service. Both API RP 2A-WSD and the ABS *Fatigue Guide* should apply, as appropriate.

1.5 Buoyancy Tank Strength Analysis and Procedure

1.5.1 General

The strength analysis is performed to confirm that the BT design satisfies the acceptance criteria for transportation, installation, and operating conditions, as defined in the load case matrix.

The BT is designed to withstand environmental loads determined from the data in the design basis, which includes the transportation and installation requirements.

The strength analysis should comprise the following activities:

i) Global sizing of the BT based on the installation method and capability

ii) Strength analysis of BT for maximum in-place loads

iii) Strength analysis of BT for lifting, handling and transportation

iv) Strength analysis of BT for installation

v) Buckling check of BT for in-place, lifting, handling and transportation

1.5.2 In-place Loading Condition

The in-place loading condition can be defined as shown in Section 5, Figure 1 with the top of BT (e.g., 50-200 m under MWL). All the compartments except the lowest can be filled with nitrogen.

Damage, or failure, of the buoyancy tank pressure containing components is not expected over the operational life of the buoyancy tank since the components are designed for expected loading conditions. Normally, the expected loading conditions consider the buoyancy tank in neutral, draw-up and draw-down positions.

However, the following potential accidental scenarios should also be considered:

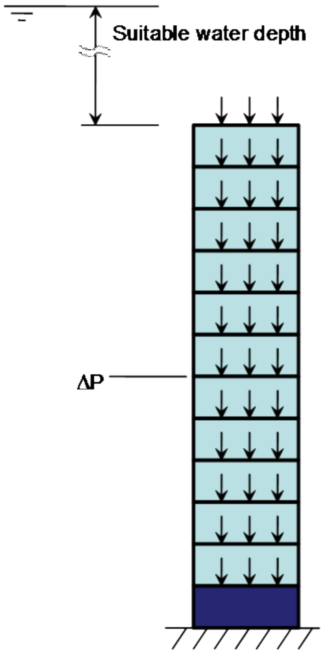
i) FPI and support vessel operations in the field should be considered to establish the likelihood of dropped objects on the BT.

ii) Likelihood of collision damage to the BT from vessel hull and appurtenances, trailing wires from installation vessels and ROVs should be assessed. Impact energy should be calculated for possible collision scenarios.

iii) Likelihood of a pressure breach because of corrosion should be fully evaluated, and design and fabrication procedures should prevent corrosion.

Likelihood of flooding of compartment(s) due to small or substantial cracks in structural members (outer shell, bulkhead, central pipe, etc.) should be evaluated. The structural members should be designed for accidental collapse or burst conditions which may arise due to a breach.

FIGURE 1
In-Place Loading Condition for BT Strength Analysis



1.5.3 Fabrication Loading Condition

Consideration should be given to loads occurring during handling and lifting of sections of the buoyancy tank in the fabrication yard. Temporary handling and lifting aids may be welded to the tank, and resulting stress levels in BT outer shell should be assessed.

On-shore hydrotest condition should be considered. Due consideration should be given to the differential pressure occurring across bulkheads between a flooded and empty compartment during the hydrotest. The hydrostatic head also needs to be taken into account when the BT is in a horizontal or vertical orientation during the hydrotest.

1.5.4 Transportation Loading Condition

Transportation of the BT includes lifting it at the fabrication yard and lowering it onto the transport vessel or onto the sea surface, depending on the shipping method. Cradles may be used to support the BT during installation and the BT may be loaded out from the fabrication yard with cradles attached.

During transportation, the worst scenario acceleration of the BT should be determined by considering the sea-states and the operating condition of the transport vessel. A quasi-static FEA is suggested to be carried out to check the stress level.

If there is more than one identical BC on the deck of the vessel, the location producing the worst accelerations should be considered.

For sea transportation of the BT, stress levels for the cradles should also be checked.

1.5.5 Installation Loading Condition

Depending on the specific installation method selected, installation may include lifting, hanging, upending, lowering, de-ballasting, and connecting to TRA. The load cases of lifting and upending are particularly important in installation due to possibly high dynamic effects. A similar reverse sequence of operations should be considered for the retrieval of the buoyancy tank, with reduced wall thickness for structural members to account for corrosion over the BT's service life.

1.5.6 Finite Element Analysis Modeling

FEA model is developed for the FEA software. Appropriate shell, plate, and beam elements are suggested to represent the BT global structure while some local components, such as the padeyes, may be modeled by 3-D brick elements. The results can be processed and presented by postprocessor software.

1.5.7 Allowable Axial Tension

Allowable tensile stress can be expressed as:

$$\sigma_a = C_a \sigma_y$$

where

σ_a = allowable stress

C_a = design factor

= 0.6 according API RP 2A-WSD

σ_y = yield strength

1.5.8 Strength Check

1.5.8(a) Buckling. Un-stiffened shell panel for Shell and central support pipe, plate panel for Bulkhead, stiffener web and flange are checked in the following cases for an upright standing BT:

i) With the lower half of the BT compartments flooded and the top of BT under MWL of, for example, 50 m, the lowest un-flooded compartment is to be checked for installation phase.

ii) In-place condition with the top of BT under MWL of 50-200 m, each chamber being filled with pressurized nitrogen at the lower bulkhead, the lowest compartment is to be checked.

iii) The same as case 2 except for the lowest two compartments being flooded, the lowest un-flooded compartment is to be checked.

The stresses acting upon the panels from global FEA are used for buckling check.

1.5.8(b) BT Lifting. During yard fabrication and offshore installation phases, the BT will be lifted. BT strength should be checked by FEA considering actual rigging arrangement. The BT can be simplified as a uniform beam and the weight can be distributed uniformly along the beam length. The stress level within the BT should not surpass the allowable stress and the shell panel of the adjacent compartment should be checked for buckling.

1.7 Buoyancy Tank Fatigue Analysis and Procedure

1.7.1 General

The fatigue analysis is performed to confirm that the BT has an expected fatigue life longer than its design life. For a suggested safety factor 10, the designed BT has an accumulated damage of 10% or less at the end of its service life after enduring all the events as defined in the load case matrix.

The fatigue analysis should comprise the following engineering activities:

i) Motion fatigue analysis of BT due to current for in-place conditions

ii) Motion fatigue analysis of BT due to VIM for in-conditions

iii) Fatigue analysis of BT for lifting, handling and transportation

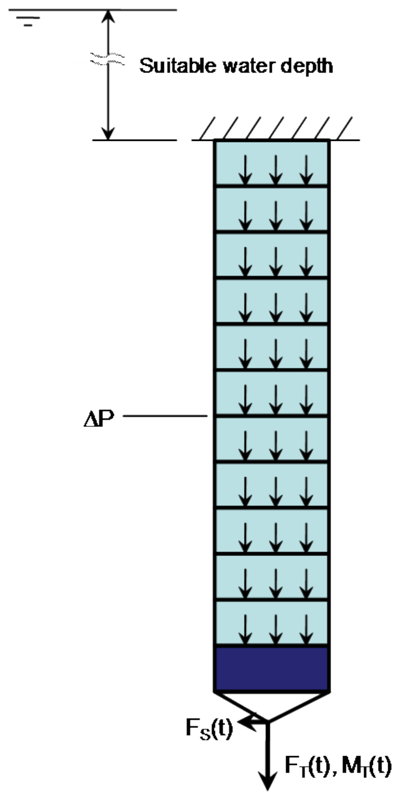
iv) Fatigue analysis of BT for installation

v) Total damage calculation and estimated fatigue life

1.7.2 In-Place Dynamic Loads

As shown in Section 5, Figure 2, the in-place analysis model for the BT fatigue analysis considers the upper-most bulkhead fixed. The bottom padeye is subjected to tension, shear, and torque, because the BT and the vertical riser pipe are connected through a tether chain/keel joint or equivalent. Other load components may be present if another kind of connection is adopted.

FIGURE 2
In-Place Model for BT Fatigue Analysis



According to the load sources, the loading can be further divided as follows.

- *Current:* Current induced hydrodynamic forces act on the BT directly and indirectly through the interaction between the BT and the rest of the hybrid riser system. The effect of current is to increase the pressure on the buoyancy tank at the stagnation point and decrease the pressure at the separation point. The load histograms can be obtained from global analysis of the hybrid riser system. Lateral displacements produced by current loading and vessel offsets result in vertical set-down of the buoyancy tank that increases external pressure loading. The magnitude of this pressure increase is dependent on the current velocity, the drag coefficient and the diameter of the buoyancy tank and riser. Additionally, non-uniform pressure distribution around the BT should also be considered for the in-place assessment.
- *VIM:* Dynamic load can be produced on the BT by VIM. Simulation results can be provided in the form of histograms of tension, shear, and torque.
- *Sloshing:* In the case where a compartment gets partially flooded (either due to failure or as a partially filled compartment for trimming purposes) oscillation of the free surface may create sloshing loads. The effects of sloshing loads in partially filled compartments may also need to be assessed.

- *Wave:* The effect of a wave passing over the top of the buoyancy tank should be assessed as it results in an increase of the pressure head and then a decrease of the pressure head acting on the buoyancy tank. The magnitude of this pressure change is dependent on the height of the wave and the installation depth of the buoyancy tank.
- *Tide:* During installation, the pressures applied to the compartments of the buoyancy tank are determined by the external pressure of the head of water. If installation occurs at low tide, then the buoyancy tank will experience a greater external pressure during high tide (collapse). Conversely, if installation occurs at high tide, then a lower external pressure will be experienced during low tide (burst).

1.7.3 Transportation Dynamic Loads

The acceleration at the CoG of the BT can be obtained for two extreme cases from the numerical simulation of the transportation vessel in 1-year Winter Storm. An extreme case of waves with consistent heading throughout the transportation process is considered conservative.

Similar to the strength analysis, the acceleration on the BT can be determined from the worst scenario location (i.e., where the BT CoG is the farthest from the vessel CoG).

1.7.4 Installation Dynamic Loads

For each phase of the installation process there is a histogram of force magnitude and a range of force directions, acting on the top/bottom padeye as concentrated force, or on the shell/bulkheads as pressure. The histogram can be established from the global analysis of the hybrid riser with the given metocean data and duration of each phase.

1.7.5 Damage Calculation and S-N Curves

The fatigue analysis for the BT should be performed in accordance to the *Fatigue Guide*. When a long-term stress range distribution is expressed by a stress histogram, consisting of a convenient number of constant amplitude stress range blocks $\Delta\sigma_i$ each with a number of stress repetitions n_i, the fatigue damage can be calculated by:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} = \frac{1}{\bar{a}} \sum_{i=1}^{k} n_i \times (\Delta\sigma_i)^m$$

where

D	=	accumulated fatigue damage
$\bar{a}$	=	intercept of the design S-N curve with the log N axis
m	=	negative inverse slope of the S-N curve
k	=	number of stress blocks
n_i	=	number of stress cycles in stress block i
N_i	=	number of cycles to failure at constant stress range $\Delta\sigma_i$
$\Delta\sigma_i$	=	stress range, in MPa

ABS offshore S-N curves defined in Section 3 of the *Fatigue Guide* should be applied. Appendix 3 of the *Fatigue Guide* should be used for the selection of alternative fatigue design criteria for an offshore structure to be sited on the U.S. Outer Continental Shelf. The *Fatigue Guide* also provides guidance on the selection of SCF values.

1.7.6 Total Damage and Estimated Life

The total damage of the BT detail being evaluated can be obtained from:

$$D_{Total} = D_{Transportation} + D_{Installation} + D_{Operation}$$

The estimated life can then be determined as:

$$L_{Calculated} = L_{Design}/D_{Total}$$

where

L_{Design} = design life

$L_{Calculated}$ = calculated fatigue life

D_{Total} = total fatigue damage during the life span of the BT with the considerations of fatigue design factors at different design conditions

$D_{Transportation}$ = fatigue damage of BT during transportation multiplied by a fatigue design factor

$D_{Installation}$ = fatigue damage of BT during installation multiplied by a fatigue design factor

$D_{Operation}$ = fatigue damage of BT during operation multiplied by a fatigue design factor

3 Riser Foundation Pile

3.1 Driven Pile

The analysis of the driven pile is to follow Section 9 of API RP 2A-WSD “Foundation Design”, API RP 2GEO, and API RP 2SK.

3.3 Suction Pile

3.3.1 General

This section describes the methodology and basis suggested for the analysis of the suction piles for hybrid riser. The suction piles should withstand loads generated by the operating and extreme storm loading conditions, accidental conditions, as well as installation, extraction and transportation loads. The pile strength, crown displacement, and fatigue life should be evaluated to meet acceptance criteria.

3.3.2 Analysis Considerations

3.3.2(a) Loads. The types of loading which the suction piles are subjected to can be summarized as follows:

- Anchor loads arising from thermal, environmental, and other loadings on the production and gas export riser. The environmental loads are derived from dynamic hybrid riser analyses. Thermal induced loads are based on detailed FEA.
- Installation, transportation, and handling loads should be developed from proposed installation procedures. Embedment loads and extraction loads should be based on the pressures derived from the geotechnical design of the suction pile.

The global sizing (geotechnical design) of the suction pile is generally governed by environmental events that induce hybrid riser system loads, and motion. Therefore, only the in-place loads under various environmental categories are presented in this subsection.

Suction pile design is affected by the maximum value, static and dynamic composition, pile design life, environmentally induced hybrid riser system loads and motion, and other loads.

The predicted time traces of the in-place loads under various environmental categories are applied essentially upward at the riser attachment point. However, the lateral load, including lateral force and bending moment, on the pile top might interact with the upward load and reduce the uplift capacity of the suction pile. Hence coupling of vertical and horizontal capacities should be considered for analysis of pile holding capacity.

3.3.2(b) Geotechnical Analysis. The geotechnical analysis of suction piles should include the following:

- Review the geotechnical/geophysical report and identify any possible geohazards, such as scour potential, presence of silt or sand layers, shallow gas, etc. that might affect the suction pile installation and in-place performance.
- Review and develop the static and cyclic soil parameters for the suction pile design and analysis.
- Develop soil setup curves using recognized methods.
- Calculate the self-weight penetration depth and determine a safety margin against penetration refusal with respect to critical suction levels for soil plug failure.
- Determine maximum pressure (suction, soil and hydrostatic) exerted on the suction anchors during operation and installation phases for the structural design of the anchors.
- Perform a holding capacity parametric study by varying the pile diameter and penetration depth to determine the optimal design with respect to pile weight, fabrication, and installation issues (e.g., embedment and extraction pressures).
- Execute the initial analysis using finite element method, limited equilibrium or plastic limit techniques or semi-empirical method with cyclic shear strength; or in the case where permanent loads are significant, for the holding capacity, utilizing static soil shear strengths with time effect factors.
- Perform penetration and removal analysis to determine penetration resistance and appropriate suction pressures required to achieve the design penetration. This includes establishing a high and low estimate of penetration resistance.
- Perform FEM analysis confirming and optimizing the preliminary design and compute the pile displacement under various design loading conditions.
- Develop soil reactions (during installation, operation and retrieval) to be used in the structural analysis.

The geometry of the suction pile anchor is to be adequate to provide lateral and axial load capacities. The maximum soil setup time (MSST) for extraction calculations may be chosen as 14 days in the GoM.

i) *Geotechnical Capacity Design Criteria.* The allowable capacity should be determined by dividing the net capacity by a factor of safety (FOS). The safety factor accounts for the uncertainties in evaluating soil properties and anticipated loads, and also the risk involved with the structure. The suction pile should achieve the minimum FOS given in Section 5, Table 2 for different loading scenarios.

In calculating axial pile resistance, the wet weight of the pile in seawater, less soil buoyancy, is to be considered.

TABLE 2
Minimum FOS for Pile Capacity

Installation		*Operation Case*		*Extreme/Temporary Case*		*Survival Case*	
Embedment	Extraction	Lateral	Axial	Lateral	Axial	Lateral	Axial
1.5	1.3	2.0	3.0	1.6	2.0	1.2	1.5

In the calculation of pile axial capacity, the pile can be outfitted with means of closure for vent openings and with a pump suction fitting, capable of sealing the pile top for the service life of the pile. The pile top seals should remain functional until reconsolidation of the soil provides adequate skin friction, in conjunction with the pile's submerged weight, to meet the required factors of safety. If the axial holding capacity of the anchor relies on the development of an inside suction pressure under pullout conditions, it should be justified based on the duration of the load and the permeability of the soil as the suction pressure may be lost when drainage occurs.

ii) *Suction Pile Embedment.* The maximum under pressure required for pump-in embedment should be less than 66.7% of the critical pressure at which soil plug failure inside the pile can occur using the upper and lower bound shear strength profiles. This should provide a FOS of 1.5 against soil plug uplift during all phases of the pump-in embedment. The lower and upper bound pump-in suction required at increasing pile penetration can be plotted against the critical pressure causing soil plug failure in order to check that the required FOS is met at all points between the self-penetration and the target penetration.

Appropriate consideration should be given to the presence of silt or sand layers on the proper installation of suction piles.

iii) *Suction Pile Extraction.* The selected suction pile geometry should permit pumping the pile out of the seabed up to MSST after initial installation. The differential pressure required for pump-out is to be less than 77% of the critical pressure at which the soil plug fails initially in bearing at the pile tip. This should provide a safety factor of 1.3 against plug failure during the initial phase of the pump-out extraction. If there is evidence of excessive movement of the internal soil plug during extraction, the pile should be reinstalled at a distance equal to a safe multiple of pile diameters from the original installation site.

iv) *Lateral Deflection Tolerance.* Pile top deflection should not exceed:

- For operating condition 12 inch
- For extreme condition 24 inch or 10% of pile diameter, whichever is smaller.

For survival conditions there is not a strict limit for the deflection, provided that gross failure will not occur. The total lateral deflection in the flowline holdback system should not exceed 5 feet.

v) *Vertical Displacement Tolerance.* The induced vertical displacement should not exceed the serviceability requirement of the hybrid riser system.

The accumulated cyclic displacement should be within certain limits to prevent significant loss of uplift resistance.

3.3.2(c) Structural Analysis

i) *Anchoring Loads.* The maximum horizontal and vertical loads based on upper bound soil strength properties should be used for the global structural analysis of the pile. A structural FEA should be developed for the global structural pile analysis to demonstrate that the pile wall structure and appurtenances have adequate strength in highly loaded areas.

The WSD method from API RP 2SK can be used in the structural analysis of the suction piles, wherein calculated stresses in all components of the structure are not allowed to exceed specified values.

Safety Categories:

- Category A: Safety criteria for conditions that exist on a day-to-day basis.
- Category B: Safety criteria for rarely occurring design conditions.

Allowable Stresses:

For structural elements designed in accordance with API RP 2A-WSD, the safety factors for normal design conditions are associated with Safety Criteria A. For extreme design conditions associated with Safety Criteria B, the allowable stresses may be increased by one-third.

For stiffened plate and cylindrical shell structures, the ABS *Buckling Guide* is preferred to be followed. Alternatively, API Bulletin 2U and 2V can be used for shell structures and flat plate structures, respectively, with FOS specified in API RP 2SK.

TABLE 3
Suction Pile Safety Criteria

Load Condition	*Safety Criteria*
Survival	B
Anchor embedment	A
Anchor extraction (MSST)	A
Anchor extraction (end of service life)	B
Handling/lifting/lowering/recovery	A
Transportation	B

For structural elements analyzed using finite element techniques, the nominal von Mises (equivalent) stress is not to exceed the maximum allowable stress as calculated below:

$$\sigma_A = \eta_i \, \sigma_y$$

where

σ_A = allowable von Mises stress

η_i = design factor for specified load condition

σ_y = specified minimum yield stress of pile material

Design factors for listed load conditions are given in Section 5, Table 4.

TABLE 4
Design Factors η_i

Load Condition	*Safety Criteria*
Survival	0.90
Pile embedment (design soil profile)	0.60
Pile embedment (upper bound soil profile)	0.67
Pile extraction (design soil profile)	0.60
Pile extraction (upper bound soil profile)	0.90
Pile extraction (end of service life)	0.90
Handling/lifting/lowering/recovery	0.67
Transportation	0.90

ii) *Embedment and Extraction Loads.* The load considerations for pile wall and pile cap structural analyses should be as follows:

- The estimated suction pressure required to embed the pile to its design penetration, based on the design soil strength profile or the upper bound soil strength profile, in conjunction with the appropriate design factor from Section 5, Table 4, whichever controls.
- The maximum suction pressure used should not be taken higher than the suction at which plug uplift occurs.
- The estimated maximum internal pressure required to extract the pile from the soil after the MSST, based on the design soil strength profile or the upper bound soil strength profile in conjunction with the appropriate design factor from Section 5, Table 4, whichever controls.
- The maximum extraction pressure used should not be taken higher than the pressure causing overload of soil bearing capacity at the pile tip.

iii) *Installation, Recovery and Handling Loads.* The suction pile structure and its installation appurtenances should be designed to withstand the maximum loads during suction pile handling, transportation and lifting, upending and recovery. Installation and recovery loads should be calculated based on procedures and typical vessel motions. Nevertheless, all lifting appurtenances and their supporting structures should meet the requirements of API RP 2A-WSD.

In particular, a load factor of 2.0 is suggested for static loads from open sea lifts during which padeyes and other internal members frame into the joints. Basic allowable von Mises equivalent stresses for the steel members of the structure are as follows:

$$\sigma_A = 0.67\sigma_y$$

where

σ_A = allowable von Mises stress

σ_y: = minimum yield stress of padeye or supporting member steel

iv) *Fatigue Loads for Structural Analysis.* The riser load history and range at the bottom connection in the extreme storm condition should be used for fatigue analysis. These cyclic dynamic loads reach the connection during extreme events. Stress concentrations and fatigue in the vicinity of load application point should be used in the analyses of the pile structure or connection receptacle. The predicted minimum fatigue life should be at least 3 times the design service life of the suction pile. Preferably, a minimum safety factor of 10 is suggested for fatigue damage calculation.

5 Other Components

5.1 General

This Subsection discusses analysis considerations of: the tether connection, Top Riser Assembly (TRA), Upper Tapered Stress Joint (UTSJ), Lower Tapered Stress Joint (LTSJ), and BRA. The methodologies for the following tasks are outlined:

- Strength analyses should confirm that the strength criteria for TRA, UTSJ, LTSJ, and BRA are satisfied for all conditions specified in the load case matrix.
- Fatigue analysis to assess the fatigue performance under variable fatigue contribution
- Transportation strength and fatigue analysis
- Installation strength and fatigue analysis

The following software can be used for strength and fatigue analysis of hybrid riser components structure:

- Linear and non-linear specialized structure analysis program
- General-purpose finite element analysis program

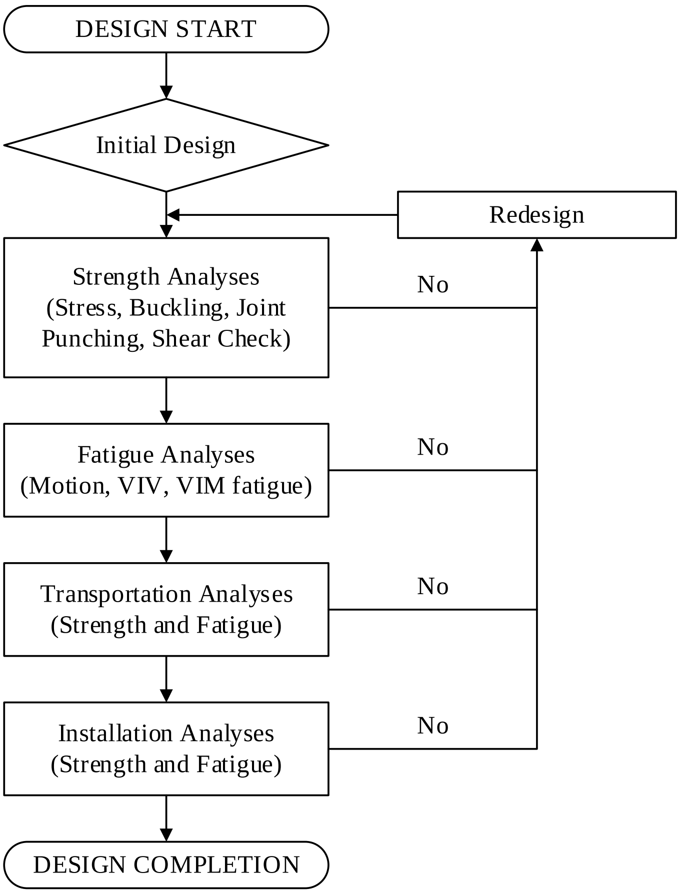
5.3 Structural Components Analysis

5.3.1 Analysis Flow Chart

Suggested design and analysis tasks for general structural components of hybrid riser are shown in Section 5, Figure 3. The design and analysis should consist of four major steps, as applicable.

1. *Strength Analysis:* Perform in-place strength analysis for the applicable environmental conditions.
2. *Fatigue Analysis:* Perform in-place fatigue analysis with consideration of FPI and BT motion and BT VIM.
3. *Transportation Analysis:* Carry out the strength and fatigue analyses based on transportation method and environmental condition.
4. *Installation Analysis:* Carry out the strength and fatigue analyses based on installation and environmental conditions.

FIGURE 3
Design and Analysis Procedure for General Hybrid Riser Structure Components



5.3.2 Strength Analysis Considerations and Procedure

5.3.2(a) Design Criteria. Pressurized conduit piping (Type A structure, e.g., induction bend pipe on TRA) should be designed according to API STD 2RD for the hydrotest, temporary, operating, extreme, and survival.

Other structure [Type B structure (e.g., tubular of TRA)] should be designed according to API RP 2A-WSD under operating and storm conditions. ASME Boiler and Pressure Vessel Code (BPVC, Section VIII, Div. 3) can to be used regarding detailed FE analysis (hot spot stress check).

5.3.2(b) Load Cases. For the strength analysis of type A structure, the load case definition philosophy and the load case matrix to be used should be described in the hybrid riser Design Basis. Hydrotest, temporary, operating, extreme and survival loads should be considered.

For the strength analysis of type B structure, only a few governing load cases may need to be considered. These load cases are selected based on the maximum von Mises stresses and unity checks from the hybrid riser global analysis.

5.3.2(c) Strength Analysis Procedure. Two analysis steps are recommended for the strength analysis of type A structure.

1. Time-domain analysis with global hybrid riser system using riser analysis software is carried out and different load categories are considered. The analysis provides the strength check on normal section considering the acceptance criteria of API STD 2RD.
2. Detailed FE analysis is performed as needed. This analysis is used to determine the hot spot stress of a geometric discontinuity.

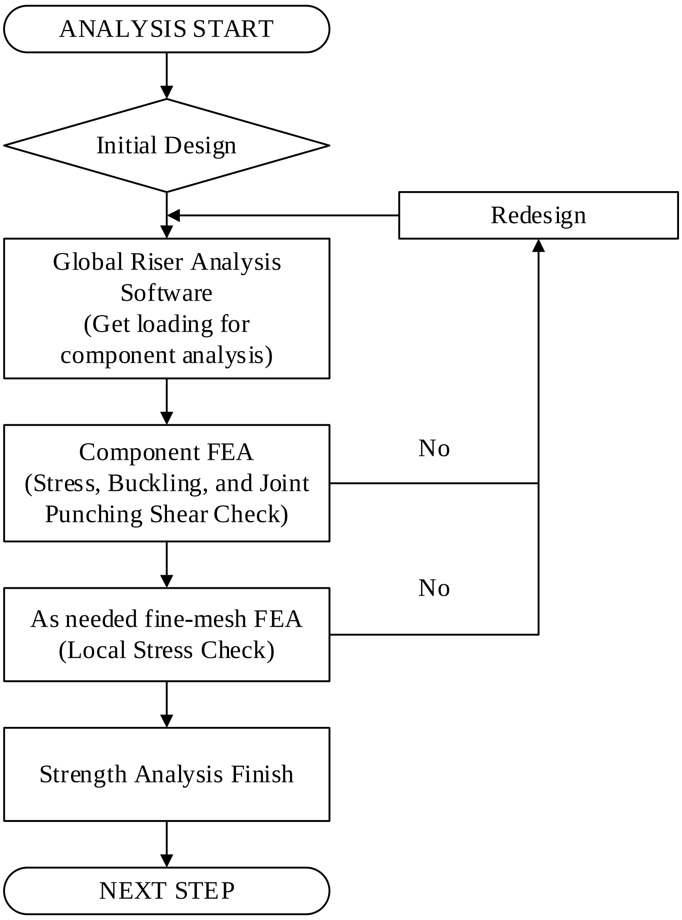
For detailed FE analysis, the loads are obtained from time-domain analysis with maximum value. The hot spot stress check is performed based on ASME BPVC.

Section 5, Figure 4 shows the suggested procedure for the strength analysis of type B structure. This analysis includes three main steps.

1. Perform global hybrid riser analysis using riser analysis software to identify the governing load cases based on stress level.
2. Perform detailed FEA using FEM analysis software with the obtained loadings and suitable boundary conditions to do code checks.
3. As needed, perform fine mesh 3D FEA, then using ASME BPVC to check the stress at hot spot location.

For detailed FEA, 3-D solid and shell elements are recommended and the element mesh is to be refined enough to capture the hot spot stresses.

FIGURE 4
Strength Analysis Procedure for Type B Structure



5.3.3 Fatigue Analysis Considerations and Procedure

The fatigue analysis should refer to the *Fatigue Guide*.

The criterion for long term fatigue of the riser structure is as follows:

$$10 \times D_W + 20 \times D_V + 20 \times D_M \leq 1/L$$

where

D_W	=	annual damage due to FPSO and BT wave motions
D_V	=	annual damage due to VIV
D_M	=	annual damage due to BT VIM
L	=	design life

SCF can be determined from detailed FEA. Alternatively, SCF can also be parametrically determined per the *Fatigue Guide*.

There are two kinds of fatigue analysis procedures. For pressurized conduit piping (Type A structure), time-domain fatigue analysis procedure is suggested. The analysis can include three steps.

1. Build a detailed FE model using FEM analysis software to determine SCF. The element type is suggested to be 20 node solid element or 8 node shell element, and element size is suggested to be less than wall thickness.

2. Build a global hybrid riser system FE model with beam elements, or equivalent, in Riser analysis software.

3. Carry out time-domain FPSO motion fatigue and BT VIM fatigue analysis in global FE model with suitable S-N curve and SCF.

Stress transfer coefficients (STCs) are stresses per unit response variables that are used in conjunction with a response variable histogram to develop the stress histogram at a given location. The stress histogram is then used in the fatigue analysis to determine fatigue damage. The stress histogram at a location is developed from the STCs and the response variable histogram in the following formula:

$$\sigma_i(t) = STC_i \times R_i$$

where

$\sigma_i(t)$	=	stress histogram at the given location
STC_i	=	i^{th} stress transfer coefficient
R_i	=	i^{th} response variable histogram

The pertinent response variables can be effective tension, torsional moments, and shear forces; and these should be obtained from the previously carried out dynamic analysis. The STCs are defined in terms of hot spot stresses.

SECTION 6 Fabrication and Installation

Fabrication and installation can have significant effects on the hybrid riser system design. Fabrication limits are to be taken into account into the design of hybrid riser, (e.g., diameter of the BT, length of TSJ, etc.). Similarly, the riser deployment process may affect the design, such as the deployment of the BT and deployment of the TRA passing through a moonpool or latching on a hang-off porch on the side of the installation vessel.

A detailed quality assurance plan should be developed as part of the design process to verify the appropriate material control and inspection criteria are used during fabrication and installation.

1 Fabrication

1.1 General

Fabrication requirements for a general riser system should be applicable to a hybrid riser system. This section outlines the minimum requirements and special considerations for the fabrication of the hybrid riser system. Such fabrication criteria are intended to cover QA/QC to verify the hybrid riser system is fabricated in compliance with the ABS requirements.

Fabrication criteria for the hybrid riser system cover forging, machining, welding, coating, testing, QA/QC, and other activities related to fabricating the components of the hybrid riser system.

All structural fabrication welding and weld qualification, qualification of welders and welding operators, inspection, and NDE of the TRA, gooseneck assembly, BRA, and RBJ should be in accordance with the Structural Welding and Fabrication Specification.

All welding and weld qualification, inspection, and NDE of pressurized structures should be in accordance with a specification of hybrid riser Pressure Pipe Welding and NDE. In addition, all welds that are accessible should be ground flush on the OD and ID.

No temporary opening should be allowed on the bulkheads and, for safety reasons, it is recommended to have two (2) openings per compartment on the side of the buoyancy tank shell.

The method to control corrosion in the compartment should be defined, including: normal corrosion inside the tank, corrosion due to localized pitting, and microbial corrosion management.

After hydrostatic test completion, the tank should be filled with nitrogen at atmospheric pressure to avoid internal corrosion from residual water.

1.3 Quality Requirements

Prior to starting the fabrication, a quality management plan should be developed addressing the following areas:

- A quality plan should be developed for each component of the hybrid riser system individually.
- The quality plan should be in accordance with ABS and other recognized offshore standards.
- The quality plan should outline the procedure for handling non-conformances including root cause and corrective action.
- The quality plan should define inspection and testing plan (ITP) including task break-down, specification requirements and third party inspection points.
- A manufacture record book should be compiled early in the project, and should address the key aspects of design, manufacture, inspection, and testing for the supply of the BT.

1.5 Qualification Requirements

1.5.1 Weld Fatigue Qualification Test

Where girth welds are subjected to cyclic loading, full scale fatigue testing should be performed to demonstrate that the designed fatigue curve can be achieved by the weld procedure proposed. Such test can be waived on the condition that the same welding procedure has been used for the identical pipe dimensions and material grade, and previous fatigue testing results are available.

1.5.2 Component Qualification Test

Components of the hybrid riser system such as tether chain, connector, VIV suppression devices (strake or fairing), dog house, coatings, monitoring system, ROV hot-stab for buoyancy tank, gooseneck assembly connection, bend stiffener, etc. should be demonstrated as fit-for-purpose through testing.

Piping with bend(s) requires special attention so that quality is maintained in terms of wall thickness, ovality and material strength. The piping material in the bends can be very fabrication process dependent. Therefore a specification and rigorous test program should be developed to confirm conformance to specification.

1.5.3 Welding and NDE Qualification Test

NDE system for welding inspection should be qualified to confirm that the acceptable flaw size based on ECA study and probability of detection can be met. This qualification test should use production material for riser pipe and designed weld configuration (beveling profile). The estimated flaw size, based on ECA study, should be adjusted to accommodate the net tolerance determined from such qualification test.

1.5.4 Fatigue Testing Requirements

For the vertical rigid riser string, full scale fatigue testing should demonstrate the developed welding and NDE procedure meet the design requirements. Such full scale fatigue testing can be waived if identical pipe and identical welding procedure have been successfully tested previously.

To quantify H_2S effect of fatigue curve degradation, lab strip testing can be performed in air and in circulated corrosive fluids. The relative degradation can be applied to the full scale fatigue testing in air results in order to get the final fatigue curve with consideration of sour and sweet service.

1.7 Documentation

The following records for each component of the hybrid riser system should be maintained.

- Material certified mechanical test reports
- Pipe mill logs
- Welding records
- NDE records
- Coating and field joint coating records
- Welder qualification records and inspector qualification records
- Traceability records
- Hydrostatic testing reports
- Qualification testing reports
- Non-conformance reports
- Photographic and Video Recording

The above documentation should be maintained as part of the DFI documentation.

3 Installation

3.1 General

There are various methods currently used for the installation of hybrid riser system depending upon concept selected (e.g., riser tower or SLHR with methods based either on laying activities, or towing constructed riser out from an onshore fabrication yard to the offshore field).

As the hybrid riser system involves structural components in addition to rigid and flexible pipes, different installation requirements are needed for different components.

3.3 Installation Methods

A different installation method may be selected for the parts of the hybrid riser system.

3.3.1 For SLHR

Rigid pipe:	J-lay or reeling-lay (S-lay may not be preferred)
Flexible jumper:	Reeling-lay, gooseneck assembly included
BT:	HLV or rigid pipe lay vessel
TRA/BRA and other structures:	Part of J-lay or reeling-lay work scope

3.3.2 For Riser Tower

Towing with multiple (three to five) vessels (1 or 2 as leading tugs, 1 trailing tug, 1 fuel/survey vessel and/or 1 support vessel).

3.5 Installation Analysis

Detailed static and dynamic analyses should be performed for the following purposes:

- Confirmation of planned installation procedures
- Determination of design requirements for rigging and installation aids
- Check riser string strength during deployment
- Check VIV fatigue damage and confirmation of any mitigations, if needed, during deployment
- Check and determination of the BT ballasting/de-ballasting requirement during deployment
- Confirmation of the standing-by weather window
- Determination of fatigue damage during towing, if applicable
- Define watch-circles/exclusion zones for safe installation of the RBJ while near the BT depth and near landing to the BRA subsea connector (to attain connector make-up)
- Confirm required RBJ design based on installation sequence of flexible jumper and resulting hybrid riser lean angle

Installation analysis should be performed for possible load conditions in combination with pertinent environmental conditions.

5 Post-Installation Survey

After the successful installation of the hybrid riser system, post-installation survey should be conducted to verify at least the following:

- BT location (depth from MWL and offset distance to the flexible jumper hang off location at the FPI)
- BT tension (from its monitoring system reading)
- Orientation and inclination (TRA, Flexible jumper and BRA)
- Riser bottom connector elevation

- Riser foundation pile inclination
- Offset distance between BRA connector hub and FLET connector hub

SECTION 7 Monitoring, Inspection, Maintenance and Repair

A riser integrity management program should be developed and implemented as required in the *Riser Guide*. Relevant national requirements on riser integrity management should be observed.

Attention is to be given to validating the load cases used in the design process to enable the integrity of the element to be verified during operation as part of an overall subsea integrity management scheme.

As the demand for efficiency increases, maintenance plays an important role in improving asset operations. Condition monitoring should be carried out to monitor riser system conditions and detect a potential failure in advance so that action can be taken to prevent that failure. Condition-based maintenance (CBM) is a maintenance plan that is based on the use of condition monitoring to trigger the relevant maintenance task and corresponding part replacement or other corrective action. This process involves establishing a baseline and operating parameters, then frequently monitoring the equipment/component and comparing any changes in operating conditions to the baseline. Maintenance and/or repair are then carried out before the equipment/component fails.

1 Monitoring

Monitoring system should be used to determine the operational state of the riser system and make appropriate adjustments as necessary. Monitored parameters should include, as a minimum, the following:

- Riser Top Tension
- Global position of BT
- Water ingress in the BT

If necessary, additional parameters such as BT motions (angles and accelerations) and structure strain may be required. A monitoring specification should be developed with the consideration of the potential for monitoring the flexible jumper and the turret buoy (if any) in the disconnected mode. Inspection and maintenance plan of the hybrid riser system can then be developed/implemented based on the monitoring data.

1.1 Instrumentation

Typical instruments can be used for condition monitoring of risers during operation are listed in Section 7, Table 1.

TABLE 1
Typical Instruments for Monitoring In-service Risers

Motion	*Tension and Bending Moment*	*Pressure*	*Temperature*
Accelerometers	Strain gauges	Transducers	thermos-sensors
Angular rate sensors	Load cells	Strain gauges	Hydro-acoustic transponders
Inclinometers	LVDTs		
LVDTs	DVRTs		
DGPS	Proving rings		

Instrument accuracy and range, frequency limit, aliasing filter, operating temperature range, drift in calibration, response time, and data transmission time should be specified in the instrument specification. FAT, calibration tests, qualification tests, SIT, and final commissioning test should be carried out to verify/validate the monitoring system.

1.3 Data Collection

A data management system for monitoring data collection should be established and maintained for the whole service life of the hybrid riser systems. The data management system will typically consist of documents, data files and databases. The data should be logged online if real-time monitoring is needed while off-line monitoring is typically used for long term monitoring purpose. Power supply and communications between sensor and data collection device should be considered for data collection.

ISO 14224 and ISO 15926 (all parts) are applicable standards for data collection and integration for oil and gas production facilities.

1.5 Automation

The complexities of a condition monitoring system including diagnostics can be transitioned into a simple standardized process for the data collection and reporting processes. This solution facilitates the automated data collection and the analysis required to meet the demands of both efficient operations and system monitoring. Without automated data capture, data would be manually collected or extracted from the database and analyzed to extract the data collected meeting the pre-defined parameters.

The limiting variable to automated data collection is the extent of installed sensors for monitoring. The goals for the diagnostics analysis and use of data must be initially identified followed by identification of sensor data required to achieve these goals. The identified data may include manually-collected data besides the automated data. The data is associated with its collection time (e.g., time stamped) and stored in the data history for trending and future analyses as required.

As more sophisticated automation systems become common in marine and offshore assets, growing concerns regarding data integrity have been raised. The concerns cover various topics in data integrity, such as basic concepts of data integrity in marine and offshore assets, how the data integrity is best managed, and what are the measurement tools for data integrity. Traditional definitions and concepts may not adequately support specialized data integrity applications in marine and offshore assets. For detailed guidance on data integrity, see the ABS *Guidance Notes on Data Integrity for Marine and Offshore Operations – CyberSafety Volume 3*.

1.7 Remote Monitoring

Monitoring data can be collected and transmitted to the FPI or onshore office for further analysis. Alerts can be issued to the onboard personnel advising proactive maintenance tasks to be performed to avoid premature equipment/component failure.

For example, riser top tension data is monitored by the load cells. This data can be extracted and sent to a separately-installed data collector and analyzer. Other sources of data can include global position of BT, automatically or manually collected condition monitoring data, and environmental data. The data can be analyzed for suitability, preliminary diagnostics performed, and prepared for satellite transmission to a service company or the operator's shoreside office for further analysis and diagnostics. Then, the analyzed results are transmitted back to the onboard personnel for information and action as required.

The data from one hybrid riser system can be compared to data from other hybrid riser systems with similar equipment/component to confirm maintenance intervals and to determine overall riser system performance and performance trends.

3 Inspection and Maintenance

A monitoring system should be installed on the hybrid riser systems. Condition monitoring technology should be utilized to assist the inspection and maintenance.

A program for inspection and maintenance should be developed with the objective of outlining inspection and maintenance procedures and tools, considering the Installation and Operation phases of the riser system's life. The typical scope of work can include:

- Determination of inspection and maintenance key points
- Review of inspection and maintenance methods
- Review of inspection and maintenance tools

Various NDE method can be used for riser system inspection, such as visual inspection, ultrasonic testing, electromagnetic field testing, electric field testing, magnetic field testing, and radiography, as appropriate.

5 Repair

5.1 Flexible Jumper Replacement

The replacement of flexible jumpers should be possible without the need to retrieve the rigid riser string.

5.3 Tether Replacement

Remote diverless replacement of the BT to riser tether (if any) should be possible without the need to retrieve the riser.

5.5 RBJ Replacement

Remote diverless replacement of the RBJ should be possible without the need to retrieve the riser.

7 Related ABS Documents

The following related ABS documents should be considered for the data management and condition monitoring of the hybrid riser systems, as applicable.

ABS *Guidance Notes on Data Integrity for Marine and Offshore Operations – CyberSafety Volume 3*

ABS *Guide for Hull Condition Monitoring Systems*

ABS *Guidance Notes on Equipment Condition Monitoring Techniques*

ABS *Guide for Surveys Based on Machinery Reliability and Maintenance Techniques*

ABS *Rules for Survey after Construction,* Appendix 14, "Surveys Based on Preventative Maintenance Techniques"

SECTION 8 Decommissioning

Hybrid riser decommissioning methodology is to be developed before deployment of the hybrid riser system. Suitable subsea equipment for decommissioning is to be listed in the documents including pumping skid capable of flushing the production fluids from the hybrid riser system to the surface floater. Dyed seawater is preferred for flushing operation. Before function testing of the equipment, It is required that certified documents are to be presented stating that the manufacturer or a recognized independent laboratory calibrated the respective subsea skid mounted measuring instruments and recorders within the last 6 months. Flushing with uncertified equipment should not be done. A liquid flow meter on the subsea pumping skid capable of measuring flushing volumes should be provided.

The followings are to be addressed as part of the decommissioning requirements:

- Decommissioning procedure
- Risk assessment/review of the proposed decommissioning procedure
- Equipment list
- Transportation and storage requirements
- Record book

APPENDIX 1 References

1. ABS *Guide for Buckling and Ultimate Strength Assessment for Offshore Structures*, 2004.
2. ABS *Guide for Building and Classing Subsea Pipeline Systems*, 2006.
3. ABS *Guide for Building and Classing Subsea Riser Systems*, 2015.
4. ABS *Guide for Fatigue Assessment of Offshore Structures*, 2003.
5. AISC, Steel Construction Manual, 14th Edition, 2011.
6. Alliot, V. and Carré, O., Riser Tower Installation, Offshore Technology Conference, OTC-14211-MS, Houston, USA, 2002.
7. ANSI/ASME B31.4, Pipeline Transportation Systems for Liquids and Slurries, 2012.
8. ANSI/ASME B31.8, Gas Transmission and Distribution Piping Systems, 2014.
9. API RP 1111, Recommended Practice for the Design, Construction, Operation, and Maintenance of Offshore Hydrocarbon Pipelines (Limit State Design), Fourth Edition, 2009.
10. API RP 16Q, Recommended Practice for Design, Selection, Operation and Maintenance of Marine Drilling Riser Systems, First Edition, 1993, Reaffirmed 2010.
11. API RP 2A-WSD, Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress Design, Twenty-Second Edition, 2014.
12. API RP 2GEO, Geotechnical and Foundation Design Considerations, First Edition, 2011.
13. API RP 2SK, Design and Analysis of Station keeping Systems for Floating Structures, Third Edition, 2005.
14. API Spec 16R, Specification for Marine Drilling Riser Couplings, First Edition, 1997, Reaffirmed, 2010.
15. API Spec 17D, Design and Operation of Subsea Production Systems-Subsea Wellhead and Tree Equipment, Second Edition, 2011.
16. API SPEC 2B, Specification for the Fabrication of Structural Steel Pipe, Sixth Edition, 2002, Reaffirmed, 2012.
17. API Spec 2H, Specification for Carbon Manganese Steel Plate for Offshore Platform Tubular Joints, Ninth Edition, 2006, Reaffirmed, 2012.
18. API Spec 2W, Specification for Steel Plates for Offshore Structures, Produced by Thermo-Mechanical Control Processing (TMCP), Fifth Edition, 2006, Reaffirmed, 2012.
19. API Spec 2Y, Specification for Steel Plates, Quenched-and-Tempered, for Offshore Structures, Fifth Edition, 2006.
20. API SPEC 5CT, Specification for Casing and Tubing, Ninth Edition, 2011.
21. API SPEC 5L, Specification for Line Pipe, Forty-Fifth Edition, 2012.
22. API Spec 6A, Specification for Wellhead and Christmas Tree Equipment, Twentieth Edition, 2010.
23. API STD 2RD, Dynamic Risers for Floating Production Systems, Second Edition, 2013.
24. API TR 6AF, Technical Report on Capabilities of API Flanges Under Combinations of Load, Third Edition, 2008.
25. ASME Boiler and Pressure Vessel Code (BPVC), Section VIII, Div. 3, Alternative Rules for Construction of High Pressure Vessels, 2015.

26. ASTM A36/A36M, Standard Specification for Carbon Structural Steel, 2012.

27. ASTM A370, Standard Test Methods and Definitions for Mechanical Testing of Steel Products, 2013.

28. ASTM E8/E8M, Standard Test Methods for Tension Testing of Metallic Materials, 2013 (13a).

29. AWS D1.1/D1.1M, Structural Welding Code – Steel, 22nd Edition, 2010.

30. BS 7910, Guide to methods for assessing the acceptability of flaws in metallic structures, Third edition, 2013.

31. BS EN 12496, Galvanic anodes for cathodic protection in seawater and saline mud, 2013.

32. BS PD 5500, Specification for unfired fusion welded pressure vessels, 2014.

33. Cerkovnik M., Chang S. and Griffin C., Fatigue Analysis of Tether Chain in Hybrid Risers, 31st International Conference on Ocean, Offshore and Arctic Engineering, OMAE2012-83954, Rio de Janeiro, Brazil, 2012.

34. Cruz, D, et al, The Greater Plutonio Riser Tower, Offshore Technology Conference, OTC-19929-MS, Houston, USA, 2009.

35. Deka D., Cerkovnik M., Panicker N. and Achanta V., Subsea jumpers vibration assessment, 32nd International Conference on Ocean, Offshore and Arctic Engineering, OMAE2013-11011, Nantes, France, 2013.

36. Djia, F, et al: Design of the Greater Plutonio Riser Tower, 28th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2009-79015, Hawaii, USA.

37. Hatton S. and Brownridge J., "Hybrid Risers, A Cost Effective Riser Solution?", DEEPTEC 95, Aberdeen, UK, 1995.

38. Hatton S. and Howells H., Catenary and Hybrid Risers for Deepwater Locations Worldwide, Advances in Riser Technologies, Aberdeen, UK, 1996.

39. Hatton S., and Lim F., Third Generation Deepwater Hybrid Risers, WorldWide Deepwater Technologies, London, 1999.

40. Hatton S., Lim F. and Luffrum S., Hybrid Riser Foundation Design and Optimisation, OTC 2005, OTC-17199-MS, Houston, USA.

41. Hatton S., Low Cost Deep Water Hybrid Riser System, OTC 1997, OTC-8523-MS, Houston, USA, 1997.

42. Hatton S., McGrail J., and Walters D., Recent Developments in Free Standing Riser Technology, 3rd Workshop on Subsea Pipelines, Rio de Janeiro, 2002.

43. Huang, K, Du, D, Song, R., Zhou, X., VIM of Dual Buoyancy Can FSHR System, The Twenty-third International Offshore and Polar Engineering Conference, ISOPE-I-13-376, Anchorage, USA, 2013.

44. ISO 14224, Petroleum, petrochemical and natural gas industries - Collection and exchange of reliability and maintenance data for equipment, 2016.

45. ISO-15589-2, Petroleum, petrochemical and natural gas industries – Cathodic protection of pipeline transportation systems – Part 2: Offshore pipelines, 2012.

46. ISO 15926, Industrial automation systems and integration - Integration of life-cycle data for process plants including oil and gas production facilities – All Parts.

47. ISO 19900, Petroleum and natural gas industries – General requirements for offshore structures, 2013.

48. ISO 19901-6, Petroleum and natural gas industries – Specific requirements for offshore structures – Part 6: Marine operations, First edition, 2009.

49. Lim F., Walters D., SLOR Production System - Making It Easy for the Platform, Semi-Sub/Floaters Asia Conference, Singapore, 2007.

50. Maclure D. and Walters D., Freestanding Risers in the Gulf of Mexico – A Unique Solution for Challenging Field Development Configurations, Offshore Pipeline Technology Conference, Amsterdam, 2006.

51. NACE SP0169, Control of External Corrosion on Underground or Submerged Metallic Piping Systems, 2013.

52. NORSOK L-005, Compact flanged connections, Edition 3, 2013.

53. Plouzennec, S., Sonawane M. and Eyles T., New Approaches to the Design of Rigid Jumpers for Freestanding Hybrid Risers, Rio Pipeline Conference & Exposition 2011, Rio de Janeiro, Brazil, 2011.

54. SAE AS4059, Aerospace Fluid Power – Contamination Classification for Hydraulic Fluids, Revision F, 2013.

55. Song, R. and Streit, P, Design of the World's Deepest Hybrid Riser System for the Cascade & Chinook Development, Offshore Technology Conference, OTC-21338-MS, Houston, USA, 2011.

56. Song, R. and Zhou, X., VIV Analysis of Deepwater Free Standing Hybrid Riser, 33rd International Conference on Ocean, Offshore and Arctic Engineering, OMAE2014-23691, San Francisco, USA, 2014.

57. Song, R., Stanton, P. and Zhou, X., Engineering Design of Deepwater Free Standing Hybrid Riser, 29th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2010-20600, Shanghai, China, 2010.

58. Thiébaud F., Alliot V., Hatton S., Innovative Hybrid Riser Concept for FPSOs, Advances in Riser Technologies, Singapore, 1998.

59. Walters D. and Hatton S., Installation Considerations for Ultra Deep Water Risers, Marine Construction, Houston, 2004.

APPENDIX 2 Design and Analysis Example

1 General

This Appendix gives an example of the use of the criteria given in the *Riser Guide* for a hybrid riser system.

It should be noted that the project specific design and analysis data and procedures do not need to be the same as described here as long as the actual information and design requirements are clearly defined.

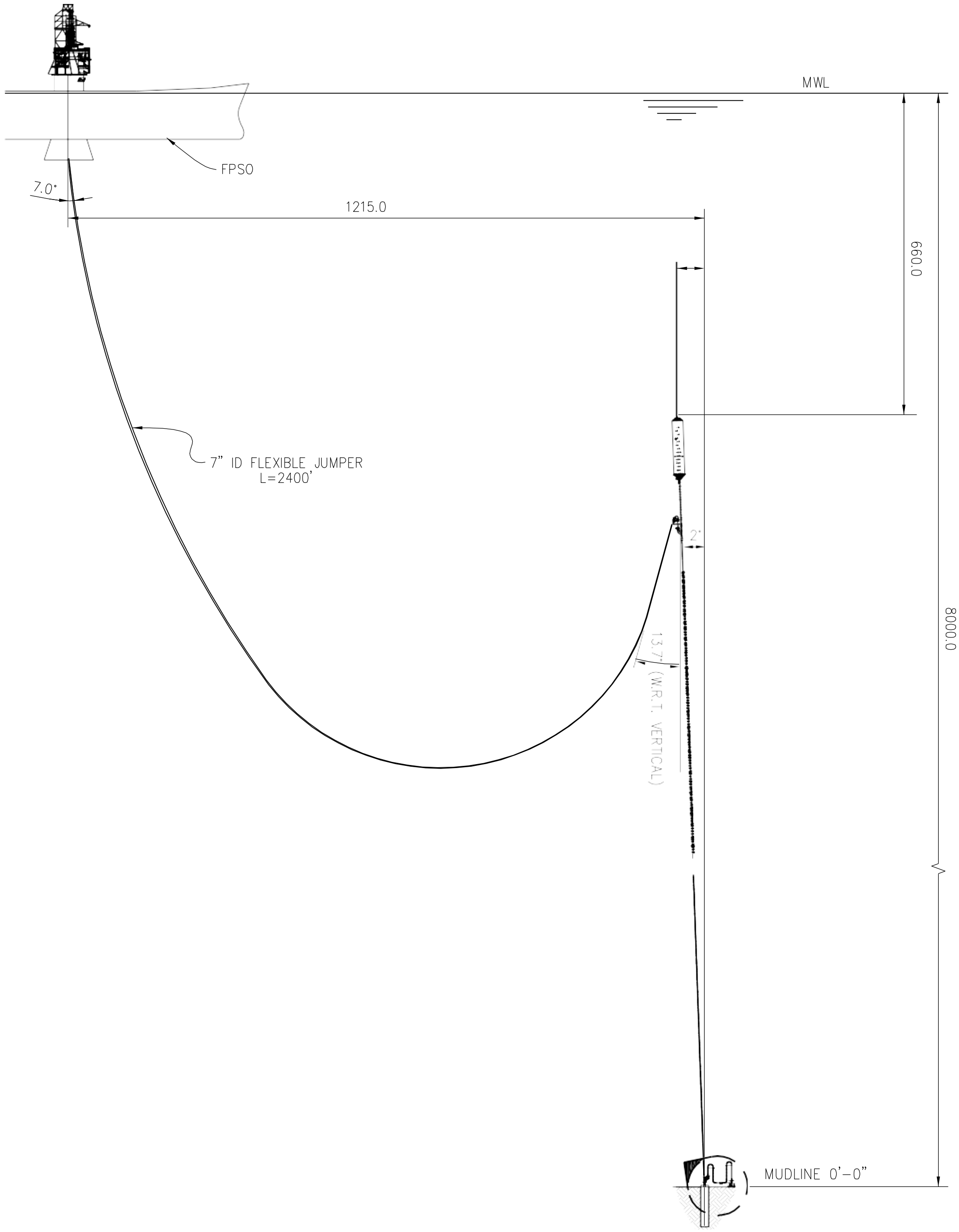
Also note that the design data presented here are provided for illustrative purposes only.

3 General Design Data and Tolerance

General design data for the example hybrid riser system include the following:

- *Water Depth (WD):* FPI/FPSO moored location and potential variation in WDs. For the example the WD is assumed to be approximately 8,000 ft in the Gulf of Mexico.
- *Design Life:* May include EPS and standby period, if any. It is assumed that the service life is 25 years.
- *Hybrid Riser Field Layout:* Showing FPI/FPSO field arrangement including floater, mooring lines, and risers. UTM coordinates of FPI/FPSO as well as riser base locations.
- *Hybrid Riser General Arrangement:* This provides a starting point including riser offset to FPI/FPSO; depth to top of BT; length of flexible jumper; depth of connection of the flexible jumper to vertical riser pipe. This information is preliminary in the initial design stage and will be subject to design verification. The general arrangement of the hybrid riser system used in the example is shown in Appendix 2, Figure 1.

FIGURE 1
Example General Arrangement of a Hybrid Riser System



The nominal configuration of the hybrid riser system provides acceptable clearances between the adjacent lines. The corresponding configuration data of the example hybrid riser system is described in Appendix 2, Table 1.

TABLE 1
Hybrid Riser General Arrangement Data

Parameter	*Unit*	*Value*
Foundation/FPI Offset	ft	1215
Depth to top of Buoyancy tank (neutral)	ft	660
Length of Flexible Jumper (Stiffener length included)	ft	2400
Depth of Connection of the Flexible Jumper to SLHR (approximately)	ft	880
Distance between RBJ and Riser/BRA	ft	7

3.1 Floater Data

The vessel particulars and motion response are required for strength, fatigue, interference, and installation analysis. The vessel related information should include the following information:

- Vessel particulars – Configuration with particulars such as width, breadth, deck elevation
- Vessel motion – RAOs and/or time traces
- Riser to vessel interfaces
- Station-keeping criteria – Vessel offsets as a percentage of water depth

The maximum FPI/FPSO offsets provided for the analysis for collinear wind and current loading should be available. The offset may be correspond different floater and mooring conditions (e.g., intact, broken or damaged).

Where the primary surface environment is wind driven, linear interpolation of FPI/FPSO offset should be based on wind speed. Where the primary surface environment is loop current, linear interpolation should be based on surface current speed. If the offsets are assumed to be omni-directional, the interpolation should be calculated using the omni-directional wind speed (or current speed, as applicable). Analysis should be performed for both the minimum and maximum FPI/FPSO offsets, if it is not clear which extreme will govern the design.

3.3 Riser System Data

Hybrid riser components and physical data, such as the riser line pipe, and flexible jumper are given below. Other components such as tapered stress joints and connectors are defined during the design process.

3.3.1 Riser Line Pipe

The properties of the standard riser line pipe for the production hybrid riser system in this example are given in Appendix 2, Table 2.

TABLE 2
Riser Line Pipe Physical Data

Parameter	*Unit*	*Value*
OD	inch	9.6
ID	inch	7
Internal Corrosion Allowance	inch	0.118
Material Grade (API 5L)		X-70
Material Yield Stress	ksi	70
Ultimate Tensile Strength	ksi	82
Young Modulus	ksi	3.0×10^4
Poisson Ratio		0.3
Steel Density	pcf (lb/ft^3)	490

The details of the cathodic protection system should be defined during the design. However, for the purpose of the example, the weight of the riser line pipe is increased by 1.5% to account for appurtenances including anodes, anode attachment devices and other items such as flanges, etc.

3.3.2 Thermal Insulation Coating

The insulation coating properties for the riser joints and top and bottom assembly components should be provided giving equivalent density and thickness.

For this example, it is assumed that the thermal insulations of the production SLHR hybrid riser system has a thickness of 2.5 inches and density of 44 pcf.

3.3.3 Fluid Properties

The internal fluid densities and design pressures are listed in Appendix 2, Table 3.

TABLE 3
Internal Fluid Properties and Design Pressures

Component	*Unit*	*Value*
Max. Allowable Operating Pressure	psi	10,000
Hydrotest Pressure	psi	12,500
Shut Down Pressure	psi	400
Location of Pressure Definition (below MWL)	ft	Surface
Design Temperature, Maximum	°F	230.0
Design Temperature, Minimum	°F	35.0
Internal Fluid		Produced Oil
Nominal Fluid Density	pcf	55.0

3.5 Riser Components Data

3.5.1 Flexible Jumper Data

The flexible jumper (FJ) data used for the detailed analysis of the hybrid riser system is given in Appendix 2, Table 4.

TABLE 4
Flexible Jumper Characteristics

Description	*Unit*	*Value*
Inside Diameter	inch	7
Outside Diameter	inch	13.4
Design Pressure	ksi	10
Equivalent ID	inch	7.28
Weight in Air, Empty	lb/ft	197.3
Weight in Air, Full of Seawater	lb/ft	215.8
Weight in Seawater, Empty	lb/ft	134.2
Weight in Seawater, Full of Seawater	lb/ft	152.7
Bending Stiffness	lb-ft^2	2.79×10^5
Torsional Stiffness	lb-ft^2/rad	4.04×10^4
MBR Operating	ft	10.9
Relative Elongation at Design Pressure		0.13%

3.5.2 Bend Stiffeners

The bend stiffener data at the flexible jumper ends are given in Appendix 2, Table 5.

TABLE 5
Stiffener Characteristics for Flexible Jumper

Description	*Unit*	*Value*	
		FPI Side	*SLHR Side*
Root Diameter	inch	42.8	29.4
Tip Diameter	inch	15.7	15.7
Inner Diameter	inch	13.7	13.7
Length	inch	74.8	59.1

3.5.3 Roto-Latch™ Rotational Stiffness

As a conservative assumption, a rotational stiffness of 25 kN·m/deg, on the whole range of deformation, could be used as a starting point. The rotational stiffness of the flex joint behaves differently under dynamic and quasi-static loading. The dynamic stiffness is highly nonlinear and the nominal stiffness should be used for global analysis, which increases as the amplitude of rotation decreases.

3.5.4 RBJ Data

The rigid base jumper consists of X70 material grade steel pipe and is configured in an 'M' shape so the jumper can absorb the expansion of the pipeline.

TABLE 6
RBJ Data

Parameter	*Unit*	*Value*
OD	inch	10
ID	inch	7
Internal Corrosion Allowance	inch	0.118
Bend Radius	inch	50
Material Grade (API 5L)		X-70
Material Yield Stress	ksi	70
Ultimate Tensile Strength	ksi	82
Young Modulus	ksi	3.0×10^4
Poisson Ratio		0.3
Steel Density	pcf (lb/ft^3)	490
Total Length (Base to Base)	ft	80
Bend Section Length	ft	10
Left Base Section Height	ft	24
Right Base Section Height	ft	42

3.7 Environmental Data

3.7.1 Seawater Data

Seawater data includes density, temperature profile along the water column.

3.7.2 Marine Growth

This information should be available. Here typical GoM values are used (i.e., marine growth of 1.5 inches from the mean sea level to –150 ft is considered). The density of marine growth in air and water is assumed to be 95.76 lb/ft^3 and 74.91 lb/ft^3, respectively.

3.7.3 Wave Data

Wave data include extreme wave data corresponding to 1 year, 10 year, 100 year and 1,000 year return events.

In this example, the long term wave sea states are defined by the omni-directional scatter diagram. The JONSWAP wave spectrum is used in conjunction with the scatter diagram. The peakedness factor for the long term sea states is assumed to be 1.0. FPI/FPSO offset and current loads are generally not necessary to be applied for the first and second order motion fatigue analysis.

To define feasible installation window, wave data for installation can be determined through dynamic analysis assessment considering different combinations of wave height and current profile taken from the load cases.

3.7.4 Current Data

Current data include both extreme and normal current profiles. Depending upon the field location, different current could be experienced such as loop current, background current, bottom current, submerged current, and soliton current.

Current profiles are generally provided through the water column and are then combined with wave data for hybrid riser global strength analysis as well as the VIV fatigue analysis.

3.7.5 Tidal Data

The minimum and maximum tidal data are considered for buoyancy tank design.

3.7.6 Soil Data

The geotechnical data for hybrid riser foundation suction pile design should be available. The upper and lower bound submerged unit weights and undrained shear strengths (s_u) should be available.

3.9 Hydrodynamic Coefficients

3.9.1 Riser Pipe

Values used for the drag coefficients of the riser system are selected depending upon Reynolds number and the presence of VIV. Where unsuppressed VIV is predicted to occur, drag coefficients should be modified accordingly.

Hydrodynamic coefficients provided in the following tables could be used for global hybrid riser analysis.

TABLE 7
Hydrodynamic Coefficients of Riser Pipe

	Drag Coefficient	*Added Mass Coefficient*
Bare pipe (depending on roughness)	Varies with *Re* and KC numbers	1.0
Bare pipe (VIV is anticipated)	1.4	1.0

For a stationary smooth circular cylinder, the drag coefficient can be selected depending upon the mean Reynolds number *Re* as defined in Figure 35 in API RP 2RD (First Edition).

3.9.2 Buoyancy Tank

The selection of drag coefficients for BT (without strakes) should consider the effects of BT surface roughness, aspect ratio, and cross-flow VIV. The initial values for the BT hydrodynamic coefficients are summarized in the following table.

TABLE 8
Hydrodynamic Coefficients of Buoyancy Tank

Direction (with respect to BT axis)	*Added Mass Coefficient*	*Drag Coefficient*
Normal	1.0	1.4
Axial	0.2	0.12

3.9.3 Flexible Jumper

The drag and added mass coefficients of the flexible jumper should be provided by the flexible pipe manufacturer. Data provided in Appendix 2, Table 9 are used for preliminary studies. Axial drag coefficient is assumed zero in this example.

TABLE 9
Drag Coefficients of Flexible Jumper

Reynolds Number	*Drag Coefficient*
1.00×10^3	1.0
1.00×10^4	1.2
2.00×10^5	1.2
3.00×10^5	0.6
1.00×10^6	0.6
4.00×10^6	0.8
1.00×10^8	0.8

Added mass coefficient $C_a = 1$, and the inertia coefficient $C_m = C_a + 1$.

3.11 Mooring System Data

The mooring system data for the FPI/FPSO should include layout, mooring line properties and their configurations. This information should be obtained for both interference analysis and global riser analysis.

3.13 Tolerances

The weight and dimensional tolerances of the riser pipes and components and the installation tolerances should be considered in the design and analysis of the SLHR.

5 Load Case Matrix

Different loading conditions should be considered based on the ABS *Riser Guide* or API STD 2RD covering the following:

- Operating
- Hydrotest
- Extreme conditions
- Survival conditions

Within each category, a number of separate load cases should be defined consisting of various combinations of environmental conditions, pressures, vessel offsets, mooring conditions, buoyancy tank conditions, and flexible jumper conditions.

There are two scenarios where the flexible jumper may accidentally disconnect at the floater end; namely during installation (or stand-by mode) and in-place. Both cases should be assessed as survival cases.

The following is the partial example of a load case matrix developed for a hybrid riser global strength analysis. The usage factor for combined loads is given in subsection 2-3/5 of the ABS *Riser Guide* and Subsection 5.4.3 of API STD 2RD.

TABLE 10
Example SLHR Load Case Matrix for Global Strength Analysis (GoM)

Load Cases	*Load Condition*	*Wave (Year Return)*	*Current (Year Return)*	*Buoyancy Tank Condition*	*FPSO Offset Direction*	*Limit State*	*Usage Factor for Combined Loads*
1	Operating	10-year Winter Storm	Associated	Intact	Near	SLS	0.8
2					Far		
3					Transverse		
4	Operating	Associated	10-year Loop Current	Intact	Near	SLS	0.8
5					Far		
6					Transverse		
7	Extreme	Associated	100-year Loop Current	Intact	Near	ULS	0.8
8					Far		
9					Transverse		
10	Survival	Associated	100-year Loop Current	One Compartment Flooded	Near	ALS	1.0
11					Far		
12					Transverse		
13	Survival	Associated	1,000-year Loop Current	Intact	Near	ALS	1.0
14					Far		
15					Transverse		
16	Hydrotest	1-year Winter Storm	Associated	Intact	Near	SLS	0.8
17					Far		
18					Transverse		

7 Burst and Collapse Check

7.1 General

Preliminary strength code checks are used to determine the wall thickness of the hybrid riser pipe. Burst and collapse pressures were checked against the minimum burst pressure and minimum collapse pressure, as defined in Chapter 2, Section 3 of the *Riser Guide*. Pipe wall thickness with corrosion/wear allowance is used in the burst and collapse pressure equations for the vertical riser. The detailed riser pipe data are listed in Appendix 2, Table 2.

7.3 Burst Check

The pipe wall thickness used for the minimum burst pressure capacity calculation is:

$$t = t_{fab} - t_{ca}$$

$$= (9.6 \text{ in.} - 7 \text{ in.})/2 - 0.118 \text{ in.}$$

$$= 1.3 \text{ in.} - 0.118 \text{ in.}$$

$$= 1.182 \text{ in.}$$

The minimum burst pressure of the vertical riser pipe is:

$$p_b = 0.45(SMYS + SMUS) \times \ln\left(\frac{D}{D-2t}\right)$$

$$= 0.45(70\text{ ksi} + 82\text{ ksi}) \times \ln\left(\frac{9.6\text{ in.}}{9.6\text{ in.} - 2 \times 1.182\text{ in.}}\right)$$

$$= 19.34\text{ ksi}$$

The internal overpressure limits for vertical riser pipe are listed in Appendix 2, Table 11.

TABLE 11
Internal Overpressure Limits for Vertical Riser

Condition	*Design Factor* η_b	*Allowable Internal Pressure (ksi)* $(p_i - p_e) \le \eta_b\, p_b$
Hydrostatic Test	0.90	17.4
Production Casing with Tubing Leak	0.81	15.7
Incidental Pressure	0.67	13.0
Design Pressure	0.60	11.6

7.5 Collapse Resistance Check

The riser pipe capacities of collapse resistance to external pressure should be checked in accordance with the requirements of the *Riser Guide*. Both of the methods listed in the *Riser Guide* can be used for collapse resistance check.

7.5.1 Method 1 (no initial ovality)

The wall thickness used in the minimum collapse pressure capacity is:

$$t = t_{fab} - t_{ca}$$

$$= (9.6\text{ in.} - 7\text{ in.})/2 - 0.118\text{ in.}$$

$$= 1.182\text{ in.}$$

The elastic collapse pressure, p_{el}, is calculated as:

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

$$= \frac{2 \times 3.0e4\,\text{ksi}}{1-0.3^2} \times \left(\frac{1.182\text{ in.}}{9.6\text{ in.}}\right)^3$$

$$= 123.1\text{ ksi}$$

The yield collapse pressure, p_y, is calculated as:

$$p_y = SMYS \cdot \frac{2 \cdot t}{D}$$

$$= 70\text{ ksi} \times \frac{2 \times 1.182\text{ in.}}{9.6\text{ in.}}$$

$$= 17.2\text{ ksi}$$

The collapse pressure is then calculated as the function of the elastic collapse pressure, p_{el}, and the yield collapse pressure, p_y:

$$p_c = \frac{p_{el}\, p_y}{\sqrt{p_{el}^2 + p_y^2}}$$

$$= \frac{123.1\ \text{ksi} \times 17.2\ \text{ksi}}{\sqrt{(123.1\ \text{ksi})^2 + (17.2\ \text{ksi})^2}}$$

$$= 17.0\ \text{ksi}$$

The external overpressure limits for vertical riser pipe are listed in Appendix 2, Table 12.

TABLE 12
External Overpressure Limits for Vertical Riser (Method 1)

Condition	*Design Factor* η_c	*Allowable External Pressure (ksi)* $(p_e - p_i) \le \eta_c\, p_c$
Cold expanded pipe (e.g., DSAW)	0.6	10.2
Seamless or ERW pipe	0.7	11.9
Accidental (ALS)	1.0	17.0

7.5.2 Method 2 (considering initial ovality and fabrication factor)

Alternative method considering fabrication factor and initial ovality can be used for the collapse pressure check as well. In this example, the fabrication factor α_{fab} = 1.0 and the initial ovality δ = 0.02.

The plastic collapse pressure p_p is calculated as:

$$p_p = SMYS \cdot \frac{2 \cdot t}{D} \cdot \alpha_{fab}$$

$$= 70\ \text{ksi} \times \frac{2 \times 1.182\ \text{in.}}{9.6\ \text{in.}} \times 1.0$$

$$= 17.2\ \text{ksi}$$

The collapse pressure, p_c, is the solution of the following equation:

$$(p_c - p_{el}) \times (p_c^2 - p_p^2) = p_c \times p_{el} \times p_p \times \delta \times D/t$$

$$(p_c - 123.1\ \text{ksi}) \times [p_c^2 - (17.2\ \text{ksi})^2] = p_c \times 123.1\ \text{ksi} \times 17.2\ \text{ksi} \times 0.02 \times 9.6\ \text{in.}/1.182\ \text{in.}$$

The solution of this equation gives the collapse pressure p_c = 15.7 ksi, which is lower than the value (17.0 ksi) obtained by method 1 by considering the initial ovality and fabrication factor.

TABLE 13
External Overpressure Limits for Vertical Riser (Method 2)

Condition	*Design Factor* η_c	*Allowable External Pressure (ksi)* $(p_e - p_i) \le \eta_c\, p_c$
Cold expanded pipe (e.g., DSAW)	0.6	9.4
Seamless or ERW pipe	0.7	11.0
Accidental (ALS)	1.0	15.7

7.7 Collapse Propagation Check

The buckle propagation pressure p_p is calculated as:

$$p_p = 24 \cdot SMYS \cdot \left(\frac{t}{D}\right)^{2.4}$$

$$= 24 \times 70 \text{ ksi} \times \left(\frac{1.182 \text{ in.}}{9.6 \text{ in.}}\right)^{2.4}$$

$$= 11.0 \text{ ksi}$$

Buckle arrestors are to be used when:

$$p_e - p_i \geq \eta_p \cdot p_p$$

$$= 0.8 \times 11.0 \text{ ksi}$$

$$= 8.8 \text{ ksi}$$

7.9 Summary of Vertical Riser Pipe Capacity

The pipe wall thickness used for the tension capacity, yield moment and plastic moment calculation is the nominal wall thickness:

$$t = 1.3 \text{ in.}$$

The tension capacity of the vertical riser is:

$$T_y = SMYS \cdot A = SMYS \cdot \pi \cdot (D - t) \cdot t = 70 \text{ ksi} \times 3.14 \times (9.6 \text{ in.} - 1.3 \text{ in.}) \times 1.3 \text{ in.} = 2371.6 \text{ kips}$$

The yield moment of the vertical riser is:

$$M_y = \frac{\pi}{4} SMYS \cdot (D - t)^2 \cdot t = \frac{3.14}{4} \cdot 70 \text{ ksi} \times (9.6 \text{ in.} - 1.3 \text{ in.})^2 \times 1.3 \text{ in.} = 4921.2 \text{ kips-in} = 410.1 \text{ kips-ft}$$

The plastic moment of the vertical riser is:

$$M_p = \frac{4}{\pi} M_y = \frac{4}{3.14} \times 410.1 \text{ kips-ft} = 522.4 \text{ kips-ft}$$

The summary of the vertical riser pipe capacity is presented in Appendix 2, Table 14:

TABLE 14
Summary of Vertical Riser Pipe Capacity

Pipe Capacity	*Symbol*	*Units*	*Value*
Burst Pressure	p_b	ksi	19.34
Collapse Pressure	p_c	ksi	15.7
Yield tension	T_y	kips	2371.6
Yield moment	M_y	kips-ft.	410.1
Plastic moment	M_p	kips-ft.	522.4

9 Combined Load Check

Strength analysis of the hybrid riser system in different load conditions is captured using "snapshots" of the worst motions and offset of the FPI. Nominal pipe wall thickness is used in the analysis for both the vertical riser and flexible jumper. Detailed FEA studies were carried out to obtain the effective tensions and bending moments along the vertical riser pipe. From the FE analysis, the load case and the location in the riser pipe with the highest utilization are identified.

In this example, the hybrid riser system in 100-year loop current condition (ULS case) is the load case with the highest utilization. Survivability of the riser system in a 1000-year Loop current (ALS case) is also presented.

It was found the most critical positions are at the top of the riser pipe, just below the bottom of the UTSJ. The results from the FEA studies at this position are presented in Appendix 2, Table 15. Combined loads at this location are evaluated using the methods specified in subsection 5.4.3 in API STD 2RD.

TABLE 15
Riser Loads at Bottom of UTSJ

Riser Loads (Bottom of UTSJ)	*Symbol*	*Units*	*ULS Case*	*ALS Case*
Internal Pressure	p_i	ksi	10.57	10.53
External Pressure	p_e	ksi	0.66	0.61
Net internal pressure	p	ksi	9.91	9.92
Effective tension	T	kips	914.97	979.24
Bending moment	M	kips-ft	1.18	1.51

9.1 API STD 2RD Combined Loads Criteria (Method 1)

The stress-based combined loading criteria check is met if the combined loads satisfy the following internal overpressure inequality:

$$\frac{\left|\frac{M}{M_y}\right| + \left|\frac{T}{T_y}\right|}{\sqrt{F_D^2 - \left(\frac{p_i - p_e}{p_b}\right)^2}} \le 1$$

The followings are the example calculations of combined loads criteria (Method 1) check for both the ULS and ALS cases at the most critical position.

9.1.1 Riser Combined Loads at Bottom of UTSJ for the ULS case:

$F_D = 0.8$

$$\frac{\left|\frac{M}{M_y}\right| + \left|\frac{T}{T_y}\right|}{\sqrt{F_D^2 - \left(\frac{p_i - p_e}{p_b}\right)^2}} = \frac{\left|\frac{1.18}{410.1}\right| + \left|\frac{914.97}{2371.6}\right|}{\sqrt{0.8^2 - \left(\frac{9.91}{19.34}\right)^2}} = 0.633\ (\le 1)$$

9.1.2 Riser Combined Loads at Bottom of UTSJ for the ALS case:

$F_D = 1.0$

$$\frac{\left|\frac{M}{M_y}\right| + \left|\frac{\mathrm{T}}{T_y}\right|}{\sqrt{F_D^2 - \left(\frac{p_i - p_e}{p_b}\right)^2}} = \frac{\left|\frac{1.51}{410.1}\right| + \left|\frac{979.24}{2371.6}\right|}{\sqrt{1^2 - \left(\frac{9.92}{19.34}\right)^2}} = 0.485 \ (\le 1)$$

Thus, Method 1 combined loads check for riser critical position at bottom of UTSJ is satisfied for SLS (not presented here), ULS and ALS cases. As Method 1 combined loads check passes, there is no need to confirm the bending strains. The usage factor results for the combined load criteria are satisfactory.