ECCM 2010
IV European Conference on Computational Mechanics
Palais des Congrès, Paris, France, May 16-21, 2010

IV European Conference on Computational Mechanics

B. Andrew[1], T. Eyles[2]

1 Senior Engineer, 2H Offshore Engineering Ltd,(Ben.Andrew@2hoffshore.com)
2 Director, 2H Offshore Engineering Ltd (Tim.Eyles@2hoffshore.com)

Global Analysis of Single Leg Hybrid Risers

Abstract

During the past five years the Single Leg Hybrid Riser (SLHR) has been selected for a number of worldwide deepwater developments. SLHRs comprise of a number of components including a vertical steel pipe spanning the majority of the water column, a buoyancy tank to provide top tension, and a flexible jumper to connect the steel pipe section to the floating production vessel. The interfaces between these components are often managed through fabricated structures.

Global analysis of SLHRs requires a detailed understanding of their complex response to ensure that an acceptable design is obtained which takes advantage of all the benefits of the hybrid riser system – specifically a reduced requirement for high-quality welding and inspection due to low fatigue damage rates and reduced vessel payload. A number of analysis studies are required including extreme stress analysis, fatigue assessment (due to vessel motions and vortex-induced-vibration) and clearance analysis. In addition, loads must be obtained for input into the design of the fabricated structures and local FEA models.

This paper presents an overview of the analysis typically conducted for deep water SLHRs to and a summary of the approach used for exchanging information between local and global analysis models and software.

Background

The Single Leg Hybrid Riser (SLHR) concept has been selected for a number of deepwater developments offshore West Africa, Brazil and in the Gulf of Mexico. The concept allows riser installation ahead of the floating production unit (FPU) arrival giving significant development schedule flexibility. Furthermore the concept offers substantial motion decoupling between the FPU and the riser, reducing fatigue damage. FPU hang-off loads are also substantially reduced when compared with SCRs or flexible pipes making it an attractive solution for deepwater applications, when turret moored vessels are required or where a large number of riser are envisaged. The concept is suitable for production, service, injection, gas lift and export duties.

The SLHR concept comprises of a number of components and can vary slightly from development to development. In all cases a vertical steel pipe is connected to a foundation system near the seabed and tension is maintained by a buoyancy tank. The connection between the foundation and vertical steel pipe is made through a lower assembly which typically includes a flexible elastomeric joint to avoid inducing bending loads on the foundation. The buoyancy tank is located some distance beneath sea level to reduce the influence of waves and surface currents. An upper assembly is located at the top of the vertical steel pipe section and provides the interface to the buoyancy tank, often again with a flexible elastomeric joint or with a short section of chain. A flexible jumper is then connected between this upper assembly and the FPU. The vertical steel pipe section can be insulated to meet flow assurance requirements or configured in a pipe-in-pipe arrangement to deliver riser base gas lift.

Key Components

The key characteristics of, and the design considerations relating to, each SLHR component are described below and shown graphically in Figure 1.

Vertical Steel Pipe – This spans the majority of the water column and consists of welded pipe sections, typically in 60 to 70ksi yield strength material. Internal corrosion resistant alloys or plastic lining may be used where significant internal corrosion is expected. The pipe wall thickness is driven primarily by tension and pressure loading. Bending moments and shear forces are minimal and localised at the interfaces to the lower and upper assemblies, see Figure 4. As tension is largely constant and (both static and dynamic) bending moments are low, fatigue damage is typically low. In some offshore locations, vortex induced vibration can be a cause of more significant fatigue damage but can be mitigated through the use of suppression stakes. If insulation or strakes are required, this does result in greater drag loading and can substantially affect the response of the riser.

Buoyancy Tank – This is a large fabricated structure and provides the top tension for the riser. It is designed to be largely pressure balanced with the internal pressure being slightly above the external hydrostatic pressure. The structure is filled with nitrogen to prevent internal corrosion. It is divided vertically into a number of compartments so that a leak does not result in significant loss of tension. The top of the buoyancy tank is typically 50-150m below sea level. A system of external valves and pipe work allows the tank to be flooded and lowered to the required depth and subsequently evacuated with nitrogen.

Flexible Jumper – This forms the connection between the vertical steel pipe and the FPU. The length is a function of the water depth, but for a development in around 2000m water depth, it would typically be around 500-600m. Substantially less flexible pipe is therefore required compared to a catenary flexible riser solution and with a much reduced design depth. Flexible pipe sizes are substantially limited at increased depth, so the SLHR system can allow larger bore sizes in deep water. Bend stiffeners are specified at each end to manage increased bending moments in these regions.

Foundation – This forms the anchor to the sea floor. Typically a driven or suction pile would be specified depending on the local soil conditions. In most scenarios sufficient foundation mass is specified to resist the uplift from the riser without relying on soil friction or suction capacity.

Riser Base Spool – This forms the connection between the vertical steel pipe and the flowline and comprises of a series of pipe bends and straights forming a ‘M’ or ‘Z’ shaped assembly together with a pair of subsea connectors. The main purpose of the riser base spool is to decouple riser motions and flowline expansion thereby managing stresses at the riser base.

Flexible Joints – At the base of the riser a flexible joint (consisting of steel and elastomer components) is typically used to allow rotations due current loading and vessel offset. This component avoids the need for a large tapered stress joint forging. A similar joint can be used to attach the buoyancy tank to the upper assembly.

Upper and Lower Assemblies – The interfaces between the components above are managed through fabricated structural assemblies. They are typically constructed from a trussed tubular frame together with short forgings to provide the interface with the vertical steel pipe. The upper assembly may include features for hydrate remediation and flexible jumper installation. The lower assembly may incorporate gas lift (either via a pipe-in-pipe system or from dedicated gas-lift risers and flowlines).

Configuration

The preliminary riser positions are typically dictated by the global field layout (well-sites and flowline routing). Riser diameters are selected based on flow-assurance requirements. Precise locations, riser tensions and buoyancy tank depths are then selected to ensure that no clashing occurs between adjacent field components (risers, mooring lines and umbilicals). Higher tensions may be required to control rotation of the flexible joint at the riser base and control clashing.

Riser pipe wall thicknesses are then determined based on the selected tensions and pressures. Buoyancy tank and foundation sizes are determined based on the selected tension. The length of the flexible jumper is selected in order to ensure that reasonable bend stiffener sizes are required – in general longer jumpers result in a reduction in the required size of the bend stiffeners. In addition, jumper lengths may be adjusted to ensure standard hang-off angles at the URA to increase ease of fabrication.

Design Codes

The primary industry design codes for design of SLHRs are API-RP-2RD [1] and DNV-OS-F201 [2].

These are supplemented by a number of additional codes where necessary:

- For defining S-N fatigue curves used in confirming that the design life is met – DNV-RP-C203 [3] or BS-7608 [4].
- For design of the fabricated structures – API-RP-2A (WSD) [5]. This code details calculations and safety factors for checking stresses. In addition equations are provided for ensuring that no buckling or collapse occurs.

Due to the number of design codes involved, it is important to correctly manage compatibility between the codes. This is particularly important when passing design loads from the global analysis (conducted in line with API-RP-2RD) to local structure models (analysed in line with API-RP-2A for example).

Global Analysis Overview

Risers are subject to loading from a number of sources which can be classed into the following groups:

- Functional Loading – internal pressure, hydrostatic pressure, temperature, weight / tension;
- Environmental Loading (Direct) – waves and currents;
- Environmental Loading (Vessel) – vessel motion due to waves, currents and wind.

The three principal SLHR global analysis activities are:

- Extreme Analysis – conducted to ensure that material stresses and component capacities do not exceed allowable levels in extreme events (including safety factors appropriate for the likelihood of each loading event);

- Fatigue Analysis – conducted to confirm that the weld quality or material properties are sufficient to ensure that fatigue damage induced by long-term cycling loading does not cause failure;

- Clearance Analysis – conducted to ensure that adjacent risers and other subsea architecture do to not come into contact (or if they do, to assess impact energies and the risk of damage).

Global analysis is conducted using an industry-specific finite element (FE) analysis tool, such as Flexcom [6], Deeplines [7], OrcaFlex [8] or RiFlex [9] and will consider a model of the entire SLHR system. These packages typically provide a limited set of element types (beam elements, non-linear springs, articulations, etc). The beam elements are specified in such a way as to make the modelling of subsea pipes intuitive – inputs are stiffness, mass, buoyancy, drag, internal diameter, etc. This approach allows for efficient analysis of deepwater systems and captures all loading and response aspects. Models are also easily scalable for increased water depths and riser sizes without unacceptable increases in runtimes.

For riser systems with simple geometry (e.g. Top Tension Risers (TTRs), Steel Catenary Riser (SCRs) and Flexible Risers) this approach is sufficient to capture the response of the entire system. However, for SLHRs, a more accurate model is required for assessment of the fabricated structures (for example, the upper and lower assemblies and buoyancy tank). These structures are typically a combination of tubulars, plated structures and bolted connections. For analysis of these local structures a general purpose FE package is preferred, such as ANSYS [10], SACS [11] or ABAQUS [12].

Global Extreme Analysis

The loading considered in the global extreme analysis consists of:

- Direct current and wave loading (using Morison's equation for drag);
- Periodic vessel motions due to waves (using a linearised RAO approach);
- Vessel drift due to long-term wave, current or wind (using a static offset);
- Internal and external pressure;
- Static tension and bending (due to component weights and tension).

Global extreme analysis is conducted using a complete riser model. The vertical steel pipe and flexible jumper sections are modelled using beam elements with appropriate mass, buoyancy and stiffness. The buoyancy tank is simplistically modelled using beam elements with averaged mass and buoyancy and with appropriate stiffness. Fabricated structures are also approximated with beam elements, with particular focus on mass, dimensions and centre of gravity and buoyancy. Where plated structures are present, high-stiffness beam elements are employed to ensure that conservative bending moments are predicted.

Extreme loads are sub-divided into two distinct groups – quasi-static loads and dynamic loads, see Figure 2. Quasi-static loads include quantities that result in constant or slowly-changing loads on the riser system. A range of quasi-static load cases are assessed, considering:

- Fluid mass
- Internal pressure
- Vessel offset (effected by wind, current and mooring line status)
- Current
- Buoyancy tank status

A limited number of load cases are then selected based on a range of critical response parameters for each riser component. For example:

- Vertical Steel Pipe
    - Von Mises stress
- Flexible Joints
    - Rotation
    - Tension
- Upper Assembly / Flexible Jumper Interface
    - Bending moment
    - Tensions
- Upper Assembly / Vertical Steel Pipe
    - Bending moment
    - Von Mises Stress

Dynamic loads (due to waves) are then applied. Both direct loading on the riser system due to wave particle motions are considered (using Morison's equation) and indirect loading due to vessel motions. Riser response is driven by vessel motions, particularly by large vertical accelerations of the hang-off points on the FPU due to vessel pitch, roll and heave motions. In order to reduce the number of load cases, preliminary calculations are undertaken to select wave periods and headings that maximise vertical accelerations. This selection is achieved based on statistical analysis of the wave spectra and vessel motion response amplitude operators (RAOs), see Figure 3.

Dynamic analysis is then conducted considering the selected quasi-static load cases combined with the selected wave loading cases. The response parameters listed above are then re-assessed to confirm acceptability of the system as a whole. In addition bending moments, shear forces and tension at the interfaces on the fabricated structures are extracted, Figure 6.

For SLHRs, the response of the rigid structures (the riser pipe and fabricated structures) are found to be primarily quasi-static in nature. This is due to the efficiency of the flexible jumper in decoupling vessel motions for the vertical steel pipe and upper and lower assemblies. In order to simplify analysis of the fabricated structures, quasi-static loads can be provided to the upper and lower assemblies design teams, together with Dynamic Amplification Factors (DAFs). The DAFs are typically small (1.1 to 1.3) for the upper section of the riser (upper assembly and buoyancy tank) and are very low (<1.05) at the base of the riser (lower assembly and foundation).

Global Fatigue Analysis

The loading considered in the global fatigue analysis consists of:

- Periodic loading due to waves (vessel motions and direct loading);
- Excitation of natural modes of the riser due to vortex-shedding (VIV).

Fatigue loads due to vessel motions are determined by application of long-term wave loading to the global model described above. For the plain pipe sections, stress ranges are determined and fatigue lives calculated based on SN curves selected according to weld quality. For fabricated structures, bending moment, shear and tension histograms are developed. Tension loads are fairly constant in the riser system so associations between shear and bending moments are developed at each point of interface to a fabricated structure.

Current flow past a smooth cylinder (e.g. the riser pipe) causes regular frequency vortices to be shed. When the shedding frequency matches a natural frequency of the system over a sufficient length of the riser, significant riser motion can result. Mode shapes and frequencies, together with curvatures along the length of the riser are determined using the global riser finite element model. The magnitude of this response and the resulting fatigue damage is then determined using dedicated VIV analysis software – e.g. SHEAR7 [13], VIVA [14] or VIVANA [15].

For fabricated structures, bending moment histograms are developed based on the modal curvatures and frequencies at the interface locations.

Clearance Analysis

The combination of low-stiffness articulation elements at the base of the riser systems, the presence of insulation and the likely occurrence of VIV (which can increase effective drag areas), substantial lateral displacements of the riser are likely to occur under current loading. Displacements of 50m to 80m can be expected under 100-year current loading in a 2000m water depth. The presence of multiple risers in the field with different tensions and drag areas means that different displacements may occur between adjacent risers. In addition, deepwater developments typically include a number of other field components – e.g. mooring lines and umbilicals.

Analysis is therefore conducted considering the following structure pairs:

- Adjacent risers;
- Adjacent risers and umbilicals;
- Adjacent risers and mooring lines.

The analysis considers extreme current and offset loading, and accounts for variations in riser tension (due to changes in internal fluids or buoyancy tank compartment failures).

Under extreme current loads (which drive clearance between structures), VIV is likely to occur. The effect of VIV motion on drag coefficients is therefore accounted for based on the RMS displacements predicted by the VIV software mentioned above. In addition, wake effects are assessed by calculating the reduction in current velocity downstream from a riser (using the methodology defined in [16]) and applying these reduced velocities to the downstream riser. These wake effects can be highly directional (see Figure 5), but can result in significant reductions in clearance, particularly when combined with the effects of VIV.

In order to minimise wake effects between adjacent risers, buoyancy tank depths are staggered between adjacent risers – e.g. alternating 100m and 150m below sea level. Riser tensions are adjusted to minimise differences in displacement of adjacent risers. However care must be taken not to increase riser pipe wall-thickness requirements too excessively as this results in increased buoyancy tank and foundation sizes. Finally, riser positions in the field are selected to ensure clearance under extreme current loads and vessel offsets.

Local Analysis

For the tubular components of fabricated structures such as the upper and lower assemblies, local analysis under extreme loads is conducted using a beam element model, constructed in a package such as SACS and loads (bending moments, tensions, shear forces) applied. The following code checks, as described in API-RP-2A, are then conducted to confirm acceptability of the design:

- Stress check (tension / compression, bending, shear);
- Euler Buckling;
- Hydrostatic Collapse.

For those components where code checks are considered insufficient (for example where substantial assumptions are required) local FE models are generated in generic FEA software (e.g. ANSYS or ABAQUS) using shell or volumetric elements. Typically these components are plated structures and complex forgings. Loads (bending moments, tensions, shear forces) extracted from the global analysis model are then applied. Stresses are then assessed in-line with API-RP-2A and API-RP-2RD.

Local analysis under fatigue loading is conducted by applying a nominal load and determining stress transfer functions at critical weld locations – i.e. stress ranges are defined as a function of applied loads. These can then be applied, together with appropriate S-N details to the load histograms from the global analysis to determine fatigue lives for the fabricated structures.

When applying loads to local FEA models (either beam element models in SACS or detailed FEA models in ANSYS / ABAQUS), extreme care must be taken to understand the axis systems. For non-axisymmetric systems (such as hybrid risers), substantially asymmetrical loading is often present and hence the direction of loading is important. In addition, the direction of shear forces relative to bending moments becomes increasingly critical as local FEA models increase in size.

Conclusions

Global analysis of SLHRs requires a detailed understanding of their response to ensure that an acceptable design is obtained. A number of design codes, analysis techniques and software packages are required in order to demonstrate acceptability and integrity of the design.

Fatigue and extreme loads must be extracted from global analysis software and passed to local FEA models, and care is required to ensure that the loads are correctly applied.

Finally, although a conservative design is always a requirement, it is important to limit conservatism to an acceptable level in order to achieve the benefits of a hybrid riser system – namely a reduced requirement for high-quality welding and inspection due to low fatigue damage rates, and reduced vessel payload.

References

[1] American Petroleum Institute (API), API-RP-2RD – “Recommended Practice for Design of Risers for Floating Production Systems (FPSs) and Tension Leg Platforms (TLPs)”.

[2] Det Norske Veritas (DNV), DNV-OS-F201 – “Dynamic Risers”.

[3] Det Norske Veritas (DNV), DNV-RP-C203 – “Fatigue Design of Offshore Steel

Structures”.

[4] British Standards (BS), BS-7608 – “Fatigue Design and Assessment of Steel Structures”.

[5] American Petroleum Institute (API), API-RP-2A (WSD) – “Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms (Working Stress Design)”.

[6] Marine Computational Services (MCS) – “FLEXCOM Three-Dimensional Nonlinear Time Domain Offshore Analysis Software”.

[7] Principia – “DEEPLINES Global Analysis of Risers, Moorings and Flowlines”.

[8] Orcina – “ORCAFLEX Dynamic Analysis of Offshore Marine Systems”

[9] MarinTek – “RIFLEX FEM Program for Static and Dynamic Analysis of Slender Marine Structures”.

[10] ANSYS Inc. – “ANSYS FEA package”.

[11] SACS – “Structural Analysis Computer System”.

[12] SIMULIA – “ABAQUS FEA package”.

[13] J.K. Vandiver and L. Li (MIT) – “User Guide for SHEAR7 Version 4.4”.

[14] M.S. Triantafyllou (MIT) – “VIVA Extended User’s Manual”.

[15] C.M. Larsen et al. (MarinTek) – “VIVANA – Theory manual”.

[16] E. Huse (MarinTek) – “Interaction in Deep Sea Riser Arrays”.

Figures

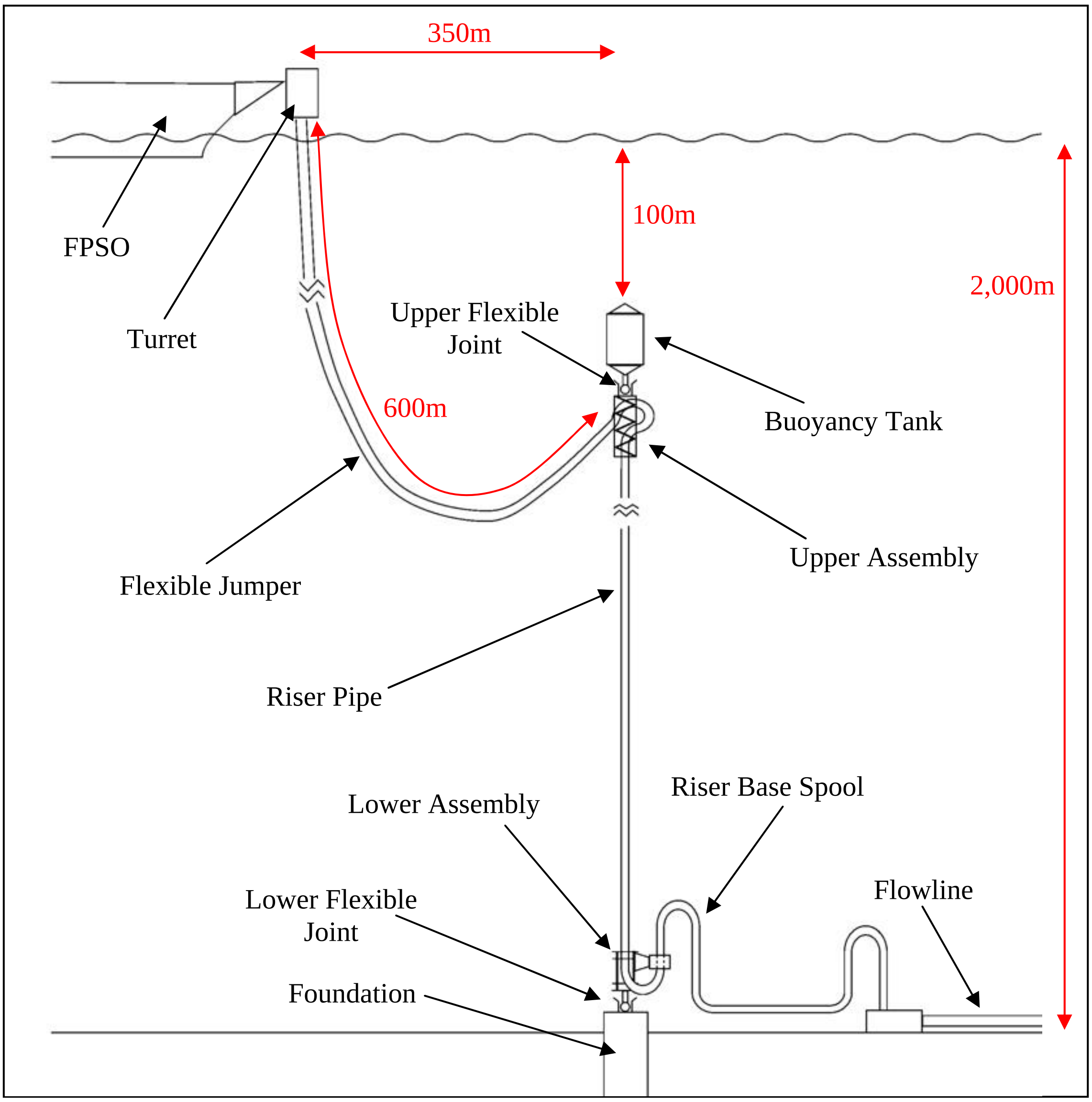

Figure 1 – SLHR Overview

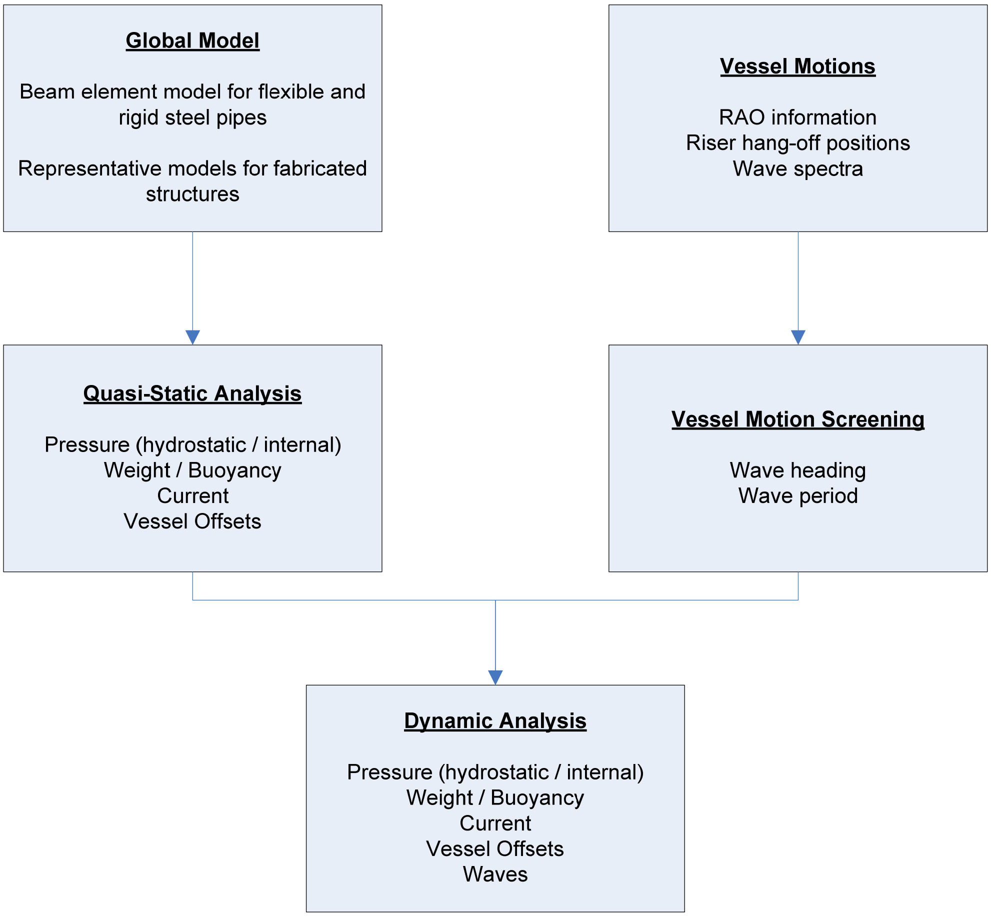

Figure 2 – Extreme Analysis Procedure

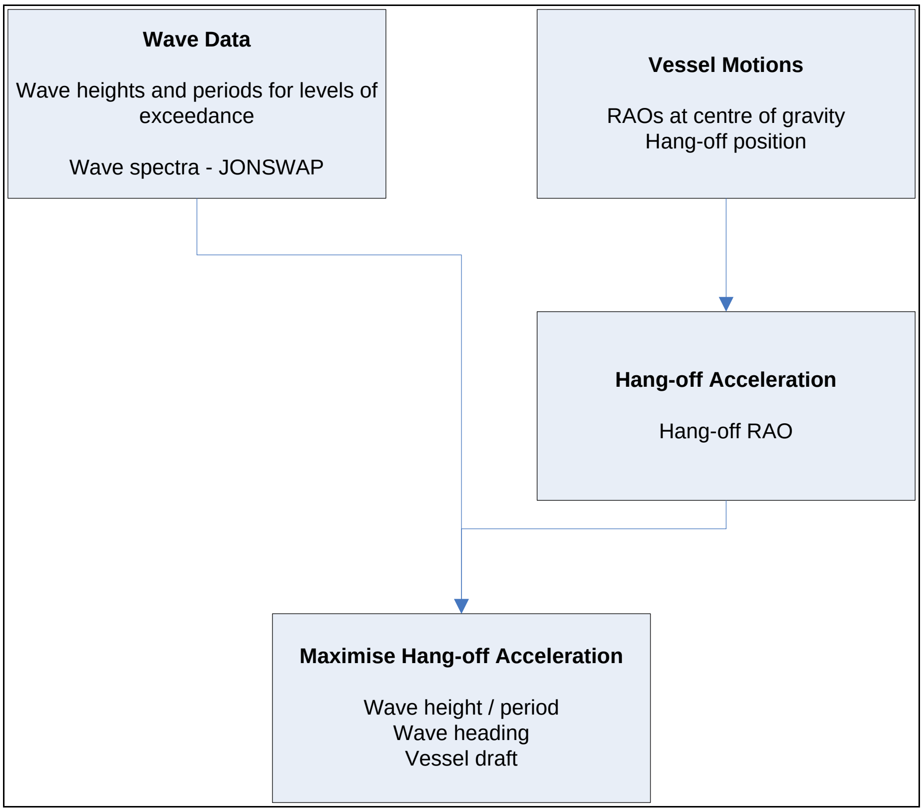

Figure 3 – Vessel Response Assessment

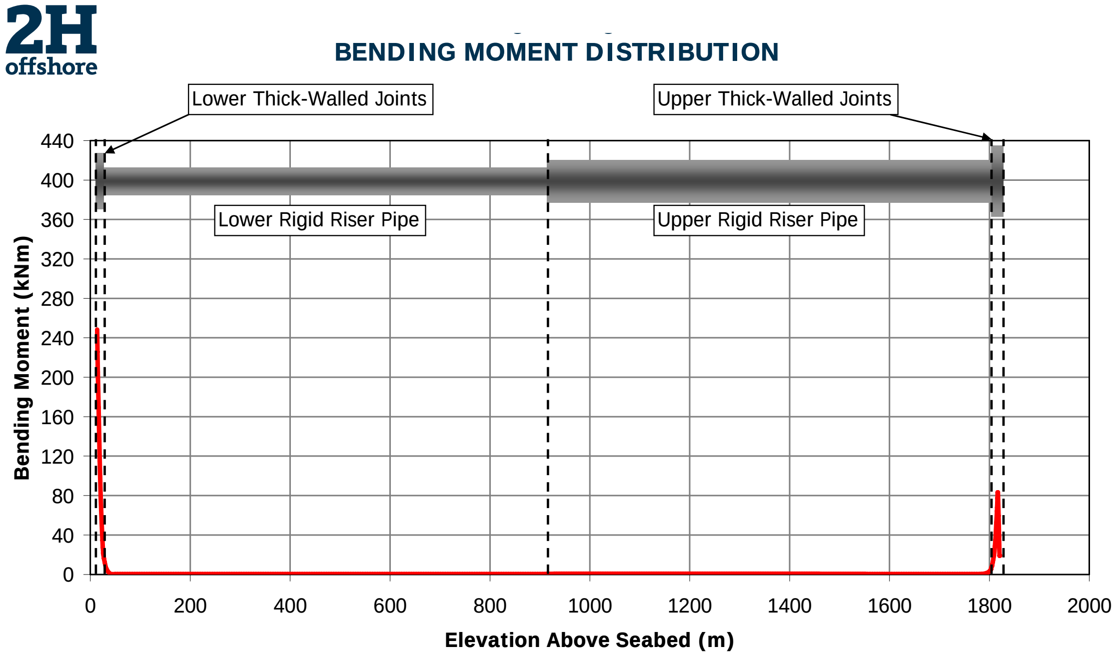

Figure 4 – Riser Bending Moment

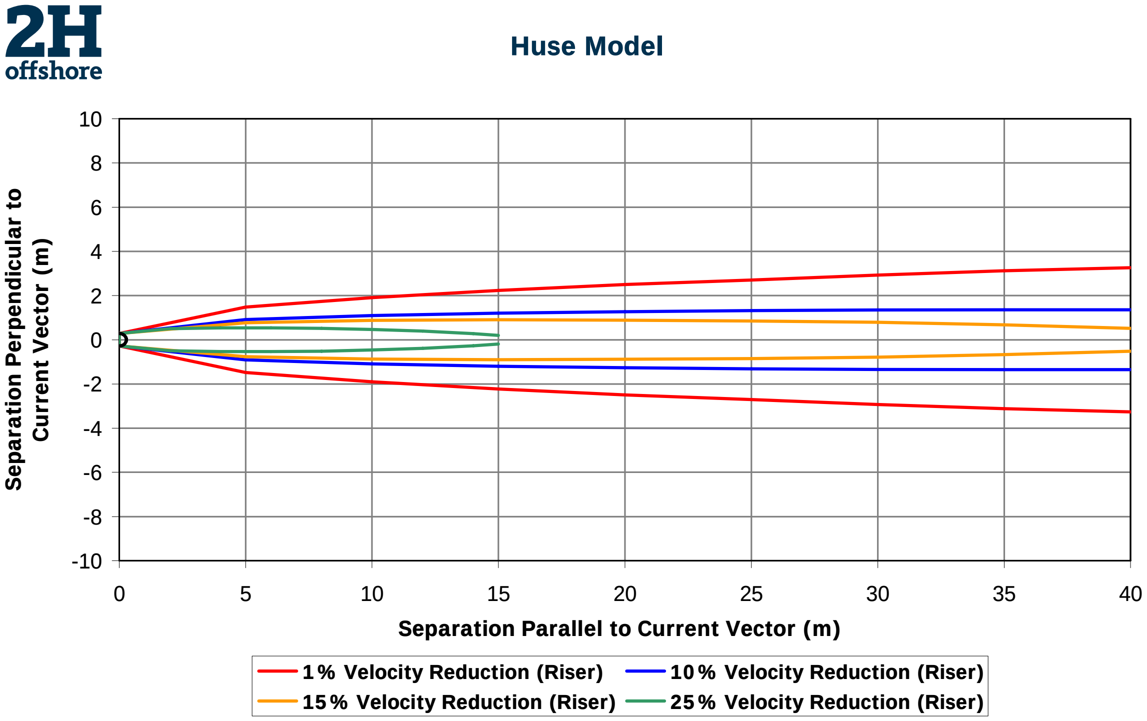

Figure 5 – Riser Wake Effects

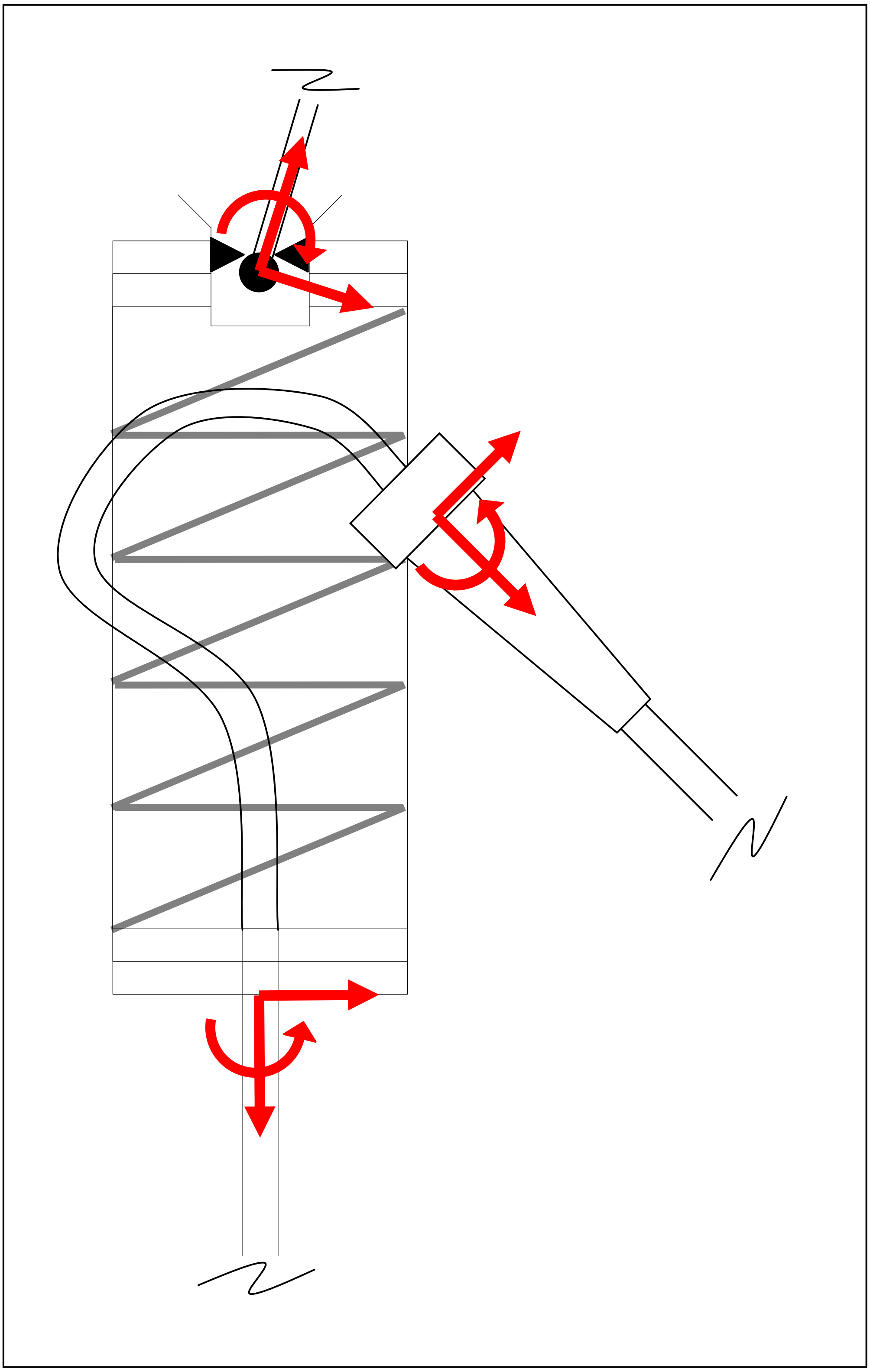

Figure 6 – Load Interface Points on Upper Assembly