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Steel Catenary Risers for Deepwater Environments

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Abstract

Steel catenary risers are a potential solution for future deep and ultra deepwater production applications. However, the complexity of design and installation is greater than for flexible riser systems. The challenge is even more significant when steel catenaries are considered for harsh environments such as West of Shetland, where extreme and long-term environmental conditions are amongst the most severe in the world, causing the risers to be highly dynamic and fatigue sensitive.

The *STRIDE* JIP (*ST*eel *RI*sers for *D*eepwater *E*nvironments) was initiated with the purpose of increasing confidence levels in the design methods and defining practical installation procedures suitable for harsh environments. In these locations weather windows are short, installation vessel motions high and fabrication quality is paramount.

The paper presents the scope of the *STRIDE* JIP and key findings of Phase I. Remaining areas of uncertainty and the proposed approach for resolution of these during Phase II are discussed. These include improved VIV prediction, touch down point response confirmation, definition of weld quality requirements and effects of plastic deformation.

Introduction

2H Offshore Engineering initiated the *STRIDE* JIP in January 1997. The main objective of the JIP is to develop steel catenary technology to a level whereby it may be applied with confidence.

The impetus for developing steel catenary technology is the continuing push into deep and ultra deep water, and the growing belief that riser systems based on steel pipe, rather than flexible, offer the best technical and commercial solution. However, current industry knowledge and capability is largely based on flexible dynamic risers and static steel pipelines. Consequently, successful application of steel catenary riser systems requires designers and installation contractors to develop new capabilities.

An important feature of the *STRIDE* JIP is the participation and involvement of Operators, installation contractors and vessel contractors. This is seen as critical to the resolution of important interfaces and development of practical fabrication and installation solutions.

The JIP has a total duration of 4 years with three distinct phases covering design, testing and a large/full scale installation. 14 Operators and 6 Contractors supported phase I of the JIP, which was completed in January 1998.

Phase I Scope

The scope of Phase I covers riser system design and installation methods. The riser design scope, conducted by 2H, includes pipe sizing, riser analysis (extreme storm, fatigue and parametric studies), material and welding requirements and hardware selection. The installation scope, conducted by the installation Contractors as payment ‘in kind’, covers a general review of steel catenary riser installation strategies, documentation of previous experience, current capability and an installation study covering detailed procedures, installation sequence drawings, schedule and cost information.

A wide range of riser configurations are considered, Table 1, covering risers of 10-30 inches diameter suspended from TLP, Spar and FPSO production platforms. Water depths in the range of 400m to 2000m are evaluated with the majority of work concerned with harsh environments typical of the West of Shetland and Voring Plateau. Benign environments such as the Gulf of Mexicio and West Africa are also considered but form a smaller proportion of the analytical effort. Three riser configurations, shown in Figure 1, form the basis of the study:

- Simple Catenary Riser (SCR)
- Wave Catenary Riser (WCR)

- Bottom Weighted Riser (BWR)

The SCR is suited to TLP and Spar applications, whilst the wave catenary has increased compliancy to accommodate the higher motions and offsets of the FPSO. The bottom weighted riser is only considered for large diameters (>20inches) and relatively shallow water depths (400-800m) where the additional compliancy provided by the use of multiple flex joints provides a solution for large diameter export from an FPSO.

Design Basis

The selected environments are particularly severe combining wave heights up to 32m and strong current profiles throughout the water depth. Surface and seabed currents of 1.8m/s and 0.7m/s respectively are typical extremes. These conditions make riser design challenging, particularly when considered in conjunction with an FPSO, which has a severe motion response. High current and wind loads also result in large vessel excursions. The TLP is assumed to have a maximum offset of 8/10% for intact mooring and failed mooring conditions whilst 20/25% is assumed for the FPSO.

Process assurance requires thermal insulation to be applied to production lines (44mm thick). This has the effect of reducing the riser weight in water and increasing the drag diameter. This problem is compounded by the need for high levels of VIV suppression, which if achieved with helical strakes, further increases riser drag loads. As a result, pipe walls are thicker than required for burst and collapse resistance to provide stability.

All sizing and analysis is conducted assuming API Grade X65 carbon steel. This is readily available and combines good strength and weldability.

Design Codes

The most applicable design guidance, for steel catenary risers, is fragmented between a number of Codes and Recommended Practices. Rationalisation of these is currently the subject of other forums, in America (API), and Europe (ISO). The approach adopted within *STRIDE* is to combine elements of DnV '96 [9] and API RP 2RD [8]. Pipe sizing for burst and collapse is in line with DnV whilst extreme storm response is largely in accordance with API.

It has been found that global dynamic response rather than burst or collapse resistance largely dominates catenary riser wall thickness requirements in harsh environments. This simplifies the usual discussions regarding the most appropriate burst equations and collapse only becomes an issue in ultra deep water and/or for large diameter risers.

Riser maximum equivalent stresses during extreme storm conditions are limited to 80% yield. 100% yield is acceptable during abnornal conditions such as a mooring line or tether failure. This approach has been adopted on other (vertically tensioned) riser systems and is in line with API RP 2RD and the ASME Boiler Code [10]. However, the question arises as to whether a higher allowable can be considered for steel catenary applications.

Higher stress allowables are of particular interest at the Touch Down Point region (TDP) where stresses are largely displacement controlled. Langner et al [7] propose a stress of 1.0 and 1.5 times yield for extreme and abnormal conditions. Whilst this offers some scope to the designer to address extreme storm response, caution must be exercised. Designing with higher utilisation may lead to an unacceptable fatigue life and the validity of assuming TDP response is displacement controlled is not always correct. This is particularly true where low tension levels are observed. Additionally, the effects of plastic deformation on weld fatigue performance must be confirmed before higher utilisation levels can be adopted with confidence.

Analysis Methods

Extreme Storm

Extreme storm analysis is conducted for 148 riser configurations. The primary objective of this work is to define basic geometry and assess acceptability of response. The majority of analysis is conducted using FLEXCOM3D [11] a time domain analysis package. Some analyses are also conducted using RIFLEX [12] for comparative purposes.

A large number of analysis runs need to be considered when optimising a steel catenary riser. The approach is highly iterative in order to ensure that the response is optimised for all combinations of load and vessel offset.

The severity of environmental conditions and vessel motions results in highly dynamic risers. Tension fluctuations are large and in extreme load cases low tension or even compression can occur near the TDP. Analysis of these arrangements is sensitive to selection of analysis parameters and model/mesh refinement. The scatter of results produced by different software is also greatest for these conditions with stress differences ranging from 10-40% for some of the configurations considered.

Fatigue

Riser fatigue arises from the following:

- First order loading (wave frequency)
- Second order vessel motions
- Vortex induced vibrations

First order fatigue analysis of steel catenary risers is best evaluated in the time domain since the non-linearities of the system can be large, particularly around the critical touch down point. This approach is numerically demanding but is considered necessary to achieve an adequate level of confidence in the results.

The interaction of first order and second order vessel motions is important. If not addressed correctly, the distribution of fatigue damage along the touch down length may be either over or under estimated.

VIV is probably the single most important design issue for steel catenary risers, particularly for high current locations. High frequency vibration of the riser pipe due to vortex shedding leads to high frequency cyclic stresses, which can result in high rates of fatigue damage (Figure 2). The vibration or the addition of VIV suppression strakes increases the hydrodynamic drag loading on the riser. This impacts all aspects of the riser response as well as riser hardware, materials, fabrication and installation methods. This effect is particularly important for production risers where service lives in excess of 25 years are often required.

Analysis of vortex induced vibrations in riser systems is carried out using the program SHEAR7 [1], developed at MIT under a joint industry research study. The program enables prediction of riser VIV response under uniform and sheared current flows and has been validated for vertically tensioned risers by model tests.

Analysis Results

Extreme Storm

The severity of the environmental conditions, combined with the requirement for thermal insulation and VIV suppression strakes along the majority of the suspended riser length results in all riser configurations being highly stressed. Acceptable configurations can only be achieved by increasing the wall thickness up to 40% (SCR) and 80% (WCR) compared to the minimum required for pressure considerations. This provides additional tension and stability to resist drag loads, allowing acceptable response in the near load case condition, ie. where vessel excursion and current direction is towards the TDP. Additionally, relatively high top angles are required which help to maintain riser tension, but as a result the dynamic angle range and extreme tension is increased.

Acceptable simple catenary arrangements could not be achieved for the 400m water depth. However, all other configurations are shown to be feasible. In some configurations a short length (20-30m) of higher grade material (up to 80ksi) is required adjacent to the vesesl and at the TDP.

Tables 2 and 3 summarise typical results for SCR and WCR.

An alternative to increasing the wall thickness along the whole riser length is the attachment of ballast weights at predefined points along the risers. Whilst this approach has not been progressed during *STRIDE,* improvements in the global response could be achieved but the size of the ballast weights could make installation difficult. Additionally, the ballast weights would cause local increases in loading, requiring thickened wall sections, and in some cases tapered sections. In SCR’s, ballast weights can be beneficial for control of the TDP response, suppressing the onset of compression and buckling. This could be cost effective if the alternative is to use a WCR.

!st and 2nd Order Fatigue

Fatigue analysis is conducted for a range of riser configurations selected to allow comparisons to be made between vessels, water depths and riser sizes.

Results for three different vessels are given in Table 4. Analysis is conducted assuming an F2 S-N curve [12] with an SCF of 1.3.

Looking at the 800m case, the fatigue response of the 14 inch Spar SCR is the least severe of the three vessels investigated. Virtually all of the riser length is well above the unfactored fatigue life requirement of 250 years. Approximately 10 metres of the riser has a fatigue life below the design requirement and this is found at the TDP.

The 14 inch TLP SCR has greater first order damage than the Spar, although the response is similar. The riser has little damage along the majority of its length and a peak near the touch down point. The length of riser falling below the design requirement increases to approximately 40m.

Unlike the other risers the 800m WCR experiences high fatigue damage at the top due to the dynamic tension variations resulting from vessel heave. The damage at the touch down point is also greater than the other riser arrangements, with minimum unfactored fatigue lives of 12 and 19 years at the TDP and vessel respectively. The areas of high damage are restricted to fairly small sections of the riser (20-30m).

The 14 inch FPSO WCR is also analysed in water depths of 1200m and 2000m in a Northern Norway environment. Increased water depth reduces the fatigue life at the vessel and improves it at the touch down point. This is due to the higher cyclic tensions near the vessel, as the longer riser length provides more damping of first order response.

A summary of the fatigue damage, due to first and second order effects, of the 14 inch TLP SCR and a 14 inch WCR in 800m water depth are given in Tables 5 and 6. The results show that second order fatigue damage is a significant factor in the overall fatigue life of the SCR, but the area of highest damage is still limited to a relatively short section of riser (40m).

First order effects dominate the fatigue life of the WCR, with virtually no change in the overall riser fatigue life with the addition of the damage from second order effects. This is because the WCR experieneces much smaller TDP motions than the SCR. However, it should be pointed out that these results are sensitive to the magnitude of second order motions assumed. Accurate second order motions are often difficult to obtain during preliminary studies, and in these cases conservative data is believed to have been assumed.

VIV Fatigue

Results show that damage contribution resulting from VIV response is high, for both SCR and WCR. Consequently, VIV suppression devices appear necessary over long sections (50-100%) of the suspended length. Many suppression systems have been proposed [2] although experience is limited.

Two suppression systems that provide high levels of suppression and have been used in previous operations are helical strakes and fairings [2]. Both strakes and fairings can reduce VIV fatigue damage by over 80%, but both systems introduce handling difficulties. Strakes have the added disadvantage of increasing riser drag, whereas fairings can reduce drag loading. However, fairings need to rotate with current direction and design complexity may limit use of these devices, particularly if they are required over a large portion of the riser length and if they are required to perform for a long field life. Helical strakes are therefore assumed for the purpose of the study.

The requirement for suppression over large portions of the riser length is costly, both in terms of the capital cost and installation. Additionally, the higher drag caused by helical strakes is detrimental to extreme storm response, and is partially the reason for the need for heavier and higher-grade pipes.

While first and second order effects are the main contributors to the fatigue damage at the TDP of TLP SCR’s, vortex induced vibrations produce virtually all of the damage at the top of the risers even though the risers are fitted with strakes along the whole of the suspended length.

First order effects dominate the fatigue life of the WCR at the TDP and vessel with virtually negligable contribution from second order effects and vortex induced vibrations at these points. The maximum damage caused by vortex induced vibrations alone is found at the arch. The minimum unfactored fatigue life in the arch of 57 years assumes the maximum damage due to VIV occurs at the same point as the maximum damage due to first order effects.

VIV analysis is conducted using SHEAR7, and whilst there is a high level of confidence in results for vertically tensioned risers, there are a number of program limitations which introduce uncertainty for catenary shapes. It is therefore possible that the predictions made by SHEAR7 are overly conservative. In view of the importance of VIV on the overall design, there is considerable benefit in quantifying areas of conservatism and benchmarking/validating the program for catenary shapes. This is a key aspect of the *STRIDE* Phase II scope.

The conclusion of the fatigue analysis studies is that all the configurations assessed are highly fatigue sensitive. However, realistic lives are achievable. High quality weld details are required, with better quality than F2 [12] for the majority of the riser, and better than E at the TDP. The fatigue analysis methodology is complex and time consuming. Whilst increased sophistication will help to eliminate unnecessary conservatism it should be pointed out that the results are only as good as the base input data. This highlights the need for quality information regarding vessel motions, particularly second order, and long term current and wave conditions, including directionality.

Parametric Studies

A wide ranging parametric study has been conducted to assess the effects and importance of:

- Thermal Insulation
- VIV Suppression
- Internal Corrosion Allowance
- Rigid Seabed
- Vessel Offset and Mooring Stiffness
- Slugging and Internal Fluid Density
- Flex Joint Stiffness
- Titanium Catenary Risers
- Steep Wave
- Riser Clashing and Interference
- Turret Position
- Alternate Vessel Interfaces
- Benign Environment (Gulf of Mexico and West Africa)

Presentation of the results of these studies is beyond the scope of this paper. However, the results provide essential data to assist in future optimisation of catenary riser systems.

Installation Studies

Studies have been conducted by five participating Engineering Contractors as a “work-in-kind” contribution to the JIP including:

- Brown and Root/Rockwater
- Coflexip Stena Offshore
- McDermott Marine Construction
- Saipem
- Stolt Comex Seaway

The scope of the studies comprise:

- General review of steel catenary riser installation strategies

- Previous applicable experience and capability report

- Installation studies, including a complete installation strategy for a WCR to an FPSO in a harsh environment with detailed procedures, installation sequence drawings, and schedule/cost information.

Studies focused on three methods of installation:

- Reel lay
- J Lay
- Towout

The use of S lay was not investigated in detail due to excessive tension requirements in deep water and with large diameters. However, recent developments and new build vessels have increased the scope of the S lay process, and further investigations may be conducted.

Reeled Installation

Reeling is an attractive candidate for catenary riser installation, offering speed of installation conducive with the small weather windows associated with harsh environments, and the prospect of linking riser installation seamlessly with field flowlines. Two significant problems were identified before the studies – the effect of plastic deformation during reeling on fatigue life, and the mechanism for attaching or accommodating VIV suppression strakes.

The riser and its joint welds see significant plastic strains (2%) during the reeling, unreeling and straightening processes associated with reeled installation methods. This is the subject of ongoing investigative work within *STRIDE* by TWI (formally The Welding Institute). At the time of writing, insufficient confidence remains in the ability of a reeled riser to meet field fatigue life requirements. Based on current knowledge, only one strategy is offered. This would be to overmatch the riser weld strength, i.e. to ensure that the pipe will yield in preference to the weld, preventing welding flaws being stretched into crack initiators. This approach will be investigated during further Phase II work.

The consensus of opinion from the reeling contractors is that bonding rubber strakes directly to the riser, at the back of a reel vessel is not practical or viable, because of bond quality limitations, space restrictions and increase in the cycle time.

Attaching VIV strakes mechanically by use of tensioned wires and clamps is a possibility, however the reliability of these systems for long term applications is uncertain and the time take to assemble such systems may be impractical.

A possible solution is to develop a deformable strake design, that can be reeled, unreeled and passed through the straighteners, but which will return to a satisfactory shape once installed. Such a design is under development. An alternative suggestion is the use of temporary rubber buffers either side of each strake profile, held in place by retaining bands along the riser. The bands and buffers are removed before the riser enters the water. However, the cost of this system, and the ability of the reeling tensioners to cope with such an arrangement is currently unknown.

Based on the uncertainties regarding plastic deformation and VIV strake attachment, reeling cannot be recommended as an installation method without further investigation. This will be addressed in Phase II.

J Lay Installation

Steel riser J lay with offshore welding was investigated by a number of the contractors, each looking at different combinations of diameter, water depth and installation vessel. In summary, this is considered a viable technique for the smaller diameters, but top tension capacity restricts the larger diameter, deeper water scenarios.

The derrick barge option was evaluated by McDermott, drawing on Mars/Auger experience. It requires fast cycle times to keep within the relatively short weather windows, considering the poor motion response of the barge. This will mean automated welding and UT along with sophisticated handling equipment. The need for a variable ramp angle is also identified for wave catenary risers to accomodate the variation in departure angle as the buoyant section is installed. The possibility to use temporary ballast weights was considered though subsequent removal once the riser is installed causes additional complication.

A solution developed by Saipem uses a transportable J-lay spread, suitable for fixing on the port or starboard midship location on their Maxita monohull, or replacing the drilling derrick on their Scarabeo 5 DP drilling semi. This conceptual design uses a multi-station J-lay tower capable of on-line hydraulic angle adjustment from vertical to 45^{o}, and mounted on a bearing platform to allow the Maxita to weather vane. The system takes 12m joints, has 2 welding stations and an NDT station in the firing line. The riser is deployed using friction pad modules, one fixed, one moving.

Stolt Comex Seaway considered the modification of the Seaway Falcon for J lay, since the current arrangement requires plastic deformation of the riser as it travels from the firing line over the tower. The modifications would include a new strongback for raising quad joints to the J lay position, and the caterpillar tensioners must be replaced by a hydraulic walking clamp system, to prevent damage to the VIV strake profile.

Stolt Comex also considered the use of a semi-submersible for J-lay, based on the Amethyst, and propose a stinger arrangement located in the moonpool to control departure angles. The semi is only considered suitable for simple

catenaries, since it will not accommodate the change in departure angle as a buoyant arch section of the riser is installed.
From the work conducted it is concluded that only McDermott have a current system for J lay of steel risers, and this will require upgrading to cope with the high tensions anticipated and the ability to vary the ramp angle for WCR. The motion response of the vessel will mean that weather windows may be limited.

Tow Methods
Rockwater/Brown and Root investigated the use of controlled depth tow methods (CDTM). Based on current technology, and use of existing vessels, this looks the most viable technique for a harsh environment riser installation. The penalty is cost, in particular the costs associated with the deepwater temporary buoyancy, i.e. purchase/rental cost and costs associated with offshore buoyancy removal. The amount of temporary buoyancy required is driven by the heavy riser walls, which is largely driven by possibly conservative VIV assumptions. Investigations proposed within *STRIDE* Phase II may enable this to be reduced considerably.

Near-surface tow is also a possibility, using much cheaper low pressure temporary buoyancy. However, problems of fatigue and extreme load damage during transportation, and difficulty in controlling the upending process on arrival need further investigation.

Controlled depth tow is considered the only current construction method for larger diameter deepwater riser installation where J lay top tensions are prohibitive. CDTM also seems the most developed method for the WCR, pending detail design of variable ramp or ballast systems for J lay techniques.

Welding and Fabrication

Within *STRIDE* Phase I, work was conducted in conjunction with TWI to investigate riser material issues including:

- Guidance on welding, fatigue, fracture and NDT aspects of welded joints in catenary risers
- Fatigue of reeled risers
- Development of a test programme to evaluate the implications of plastic strain on steel risers

The following summarises the main conclusions of this work to date:

- There is only limited fatigue data for single-side girth welds of direct relevance to risers, but this indicates that Class E S-N design curve may well be appropriate, instead of the normally used Class F2. This relies on achieving a good quality weld root and good pipe-end alignment being maintained.
- AWS Class C1 design line should not be used for single side girth welds as this may be unconservative.
- NDT girth weld inspection from the OD has a 1 in 2 chance of missing a weld root flaw as big as 2mm deep by 12mm long.
- Weld root defects will significantly reduce fatigue life. Automated tungsten inert gas weld roots (TIG or GTAW) are in general prefered to manual metal arc (MMA or SMAW). Riser weld fatigue failures would be expected to emanate from the weld root (ID) not the cap (OD) regardless of root flaws.
- Data analysed did not indicate a connection between welding position and fatigue life
- Existing knowledge relating to fatigue and fracture performance of reeled pipe is very limited. Some experimental and predictive data on weld flaw extension during reeling is available, but needs validation for catenary riser applications, which are higher strength and subject to greater weld/parent strength mismatch.
- Significant plastic strain and weld/pipe strength mismatch are not currently accounted for in the industry design and assessment procedures. Data to confirm applicability in these conditions is needed.
- Residual stresses remaining in a reeled riser pipe are likely to be complex, and may effect fatigue and fracture performance.
- Strain ageing during reeling is not predicted to be a problem for the parent pipe, but may be for the weld and HAZ.

Vessel Interface Studies

Single Buoy Moorings investigated aspects relating to the interface between a steel riser array and a range of production vessels. They looked in detail at an FPSO in an 800m West of Shetland environment, accommodating 16 buoyant wave steel catenary risers of 10” to 14” diameter, and a single 30” export riser.

Their key findings are summarised as follows:

- The turret can be based on a top mounted internal turret design similar to that designed for the POGO Tantawan, Petrobras P-33 and P-35 FPSO’s
- Hand-over from the installation vessel to the FPSO can be “lay-toward” or “lay-away”

- Due to the relatively high riser departure angles, pigging operations may be limited to smaller sea-states.
- The upper bearing can be a roller bearing, though deeper water may demand a “bogey” system
- A radial friction bearing assembly is required at the bottom of the turret to reduce the loads on the upper bearing.
- The diameter of the bottom of the turret is relatively large, at 19m. This is driven by the fairly high riser mean departure angles (typically 26^o to vertical)
- FEA analysis indicates that the turret can comfortably accommodate the riser and mooring loads at the 800m water depth. Of the STRIDE water depths, 800m was chosen because a satisfactory 400m harsh environment steel riser design has not yet been achieved. The move from 800m to 1200m reduces radial loads and increases vertical loads, but since the turret is more susceptible to the radial loads, the 800m is the harder design case
- Diver access is required for flex-joint IMR.

In summary, SBM have found that there is no major conceptual change to the turret design for a steel wave riser array compared to that for a flexible riser system

Phase II Scope

Results from *STRIDE* Phase I demonstrate the feasibility of steel catenary risers for harsh environments. However, many areas of uncertainty remain. To resolve these issues, testing and further analysis are to be conducted during Phase II. A breakdown of the study areas is given in Table 7. The main areas of interest are VIV and TDP testing which will be commenced early in 1998. Further analysis work and material testing will be commenced later in the year, subject to levels of support.

Vortex Induced Vibration (VIV)

The effects of riser vibration, caused by vortex shedding around the riser pipe, is considered the single most important issue for further development within *STRIDE*.

Due to lack of available empirical information, the Phase 1 analysis assumed that suppression strakes were required over the whole riser length. This may be over-conservative. The increase in riser drag from the VIV strakes means greater deflections and stresses, thicker riser walls, and higher installation loads and costs.

Even with 100% coverage and with 80% efficient strakes, predicted VIV damage is significant. However there are many areas of uncertainty relating to VIV software and methods of analysis:

- VIV software simplifies catenary riser structures to vertically tensioned columns - this has little or no verification
- VIV response of inclined, skewed and curved pipes has very little documentation - it is possible that pipes configured not normal to the flow may be less susceptible to VIV
- Facilities for modelling VIV suppression devices are limited, not well understood or verified
- The effect of inclination on strake and other suppression device effectiveness is not documented
- End effects in deep water, TDP interaction and seabed proximity are not fully understood, particularly for applications in mildly sheared profiles
- The effects of first order vessel surge and heave on VIV response of bare and suppressed catenary risers is not known. Current references are TLP’s and drilling risers, not FPSO’s.

The proposed scope addresses these issues, with the objective of providing increased confidence in VIV response prediction. A stepwise approach is recommended, whereby significant benefit is gained at small scale, low cost, with results feeding into more sophisticated larger scale testing.

***Tow tank VIV testing* -** Testing is proposed in a 270m long linear tow test tank. Towing is to be performed on a horizontally mounted pipe, 6m long, 8 inches diameter with velocities up to 3 m/s, though higher speeds are possible if required (up to 12.5m/s). This will produce valuable data on riser response at representative Reynolds numbers, in particular the effects of inclination, and different VIV suppression systems.

***Large scale VIV testing* -** Results from tow tank testing will feed into a large-scale test at a medium depth, sheltered water location (fjord or lake). It is proposed to tow a 10 inch diameter 200m long riser between two tow vessels (Figure 4).

A clump weight attached at the bottom of the riser provides the necessary degree of end restraint for modal VIV to occur. By varying the tow configuration, the inclination of the riser in the water can be adjusted and catenary shapes can be induced. VIV response is to be monitored using accelerometers and inclinometers located along the riser length. This arrangement allows a range of riser shapes, inclinations, VIV suppression systems/distributions to be evaluated and compared with analytical predictions produced using SHEAR7.

TDP Response Prediction

Local instability and buckling response is complex and it is uncertain whether existing tools correctly predict the onset of buckling and whether they can accurately predict the response when the buckle has been initiated.

In Phase II, further comparisons between FLEXCOM and RIFLEX are proposed, for models close to and within the buckling regime. Also, the effects on analysis results of structural damping, hydrodynamic drag coefficients, element refinement, pipe imperfections and seabed stiffness will be investigated. This work will be followed by model testing, at small-scale, to validate and benchmark analysis predictions. Depending on results, this may provide the focus for large/full scale testing during future work.

Pipe Collapse

Within the industry, there are considerable differences between recommended methods for sizing riser pipe for resistance to collapse and propagation buckling in deepwater particularly for low D/t ratios. Existing formulations are based on empirical data, which attempt to account for variations in material properties and pipe imperfections. Application of these codes to deepwater applications provides scatter of results. Additionally, the effects of tension and bending (dynamic and static) are uncertain, depending on the nature of the loading condition. It is proposed that this is investigated using 2 and 3 dimensional FEA techniques. This work will investigate the effect on collapse pressures of the following factors:

- Pipe geometric tolerances (ovality, eccentricity, wall thickness variation)
- Pipe material property variations through section
- Welding defects and mismatch
- Pipe wall damage due to corrosion, handling and impact

Results form this work will allow increased confidence in pipe wall thickness selection. In ultra deep water this may have a significant effect on vessel payloads and risers costs.

Materials Documentation

A material documentation program is proposed to investigate the effect of plastic deformation on the fatigue performance of welded joints. A testing program of coupon and full scale welded joints is proposed by TWI, which forms an extension of Phase I activities. The objectives and benefits of this work are:

- Confirm feasibility of reeling as an acceptable installation method

- Confirm acceptable strain for installation to maximise weather windows

- Determine acceptability of higher utilisation levels during storm conditions

- Confirm feasibility of preforming critical riser sections

A number of areas of uncertainty are identified. The following areas of further investigation are intended:

- Full scale fatigue tests on strained and unstrained welded pipes

- Fatigue tests on strip specimens taken from strained welded pipes

- Residual stress measurements on strained welded pipe

- Fatigue crack growth measurements on strained and unstrained welded pipe in air and product environments

- Measurements of weld flaw extension during reeling

- Material property changes as a result of straining

- Validation of flaw assessment procedures for high plastic strained welds and weld strength mismatch

- Definition of flaw acceptance criteria

Installation

A number of areas are identified from Phase I as requiring further development:

- Reelable VIV strakes
- Detachment of temporary buoyancy after tow-out
- Detachment of ballast chains after buoyant arch deployment
- Tow-out installation of bundled risers
- Near surface tow

Analysis

Continuing development and refinement of analytical procedures is necessary to optimise catenary riser systems and to ensure confidence and reliability of results. Areas identified for Phase II include:

- Analysis and feasibility assessment of bundled risers

- Development and verification of a recommended VIV analysis approach for steel catenary risers and update of Phase I analysis work/conclusions following Phase II test results.

- Parametric analyses covering 1st order fatigue sensitivities to determine the effect of variations in seabed stiffness, mooring stiffness and alternative wave spectrum.

- Riser installation analysis
- Investigation into the effect of “springing”, caused by flexure of the production vessel hull, on riser response and fatigue life

- Analytical assessment of the effect of seabed trenching and pull-out in the riser TDP area

- Analysis of ultra deep water configurations for depths up to 3000m

- Preparation of a design recommended practice applicable to deep-water steel catenary risers

Phase 3 Preparation

The most promising prospect for *STRIDE* Phase 3 is currently the proposed Voring Plateau barge to be installed by Statoil to test synthetic moorings in the winter of 1998/99. After completion of the mooring tsets, the barge will be available for suspension of a catenary riser in the summer of 1999. This will allow installation and monitoring of a riser over the winter of 1999/2000.

Design of the test riser will be commenced in Phase II and will include fabrication and installation and procedures.

Conclusions

Awareness of steel catenary riser technology has advanced considerably over the course of Phase I of the *STRIDE* project. However, there remain significant challenges to be overcome if steel catenary risers are to be used in harsh environments and with FPSO vessels.

The work conducted during *STRIDE* Phase I confirms the feasibility of such risers and identifies the activities that must be conducted during Phase II to address and resolve the remaining uncertainties.

The main area of uncertainty is VIV, which is highly complex. A better understanding of the suceptibility of steel catenary risers to VIV and improved methods of VIV prediction are fundamental to the successful future application of this promising technology.

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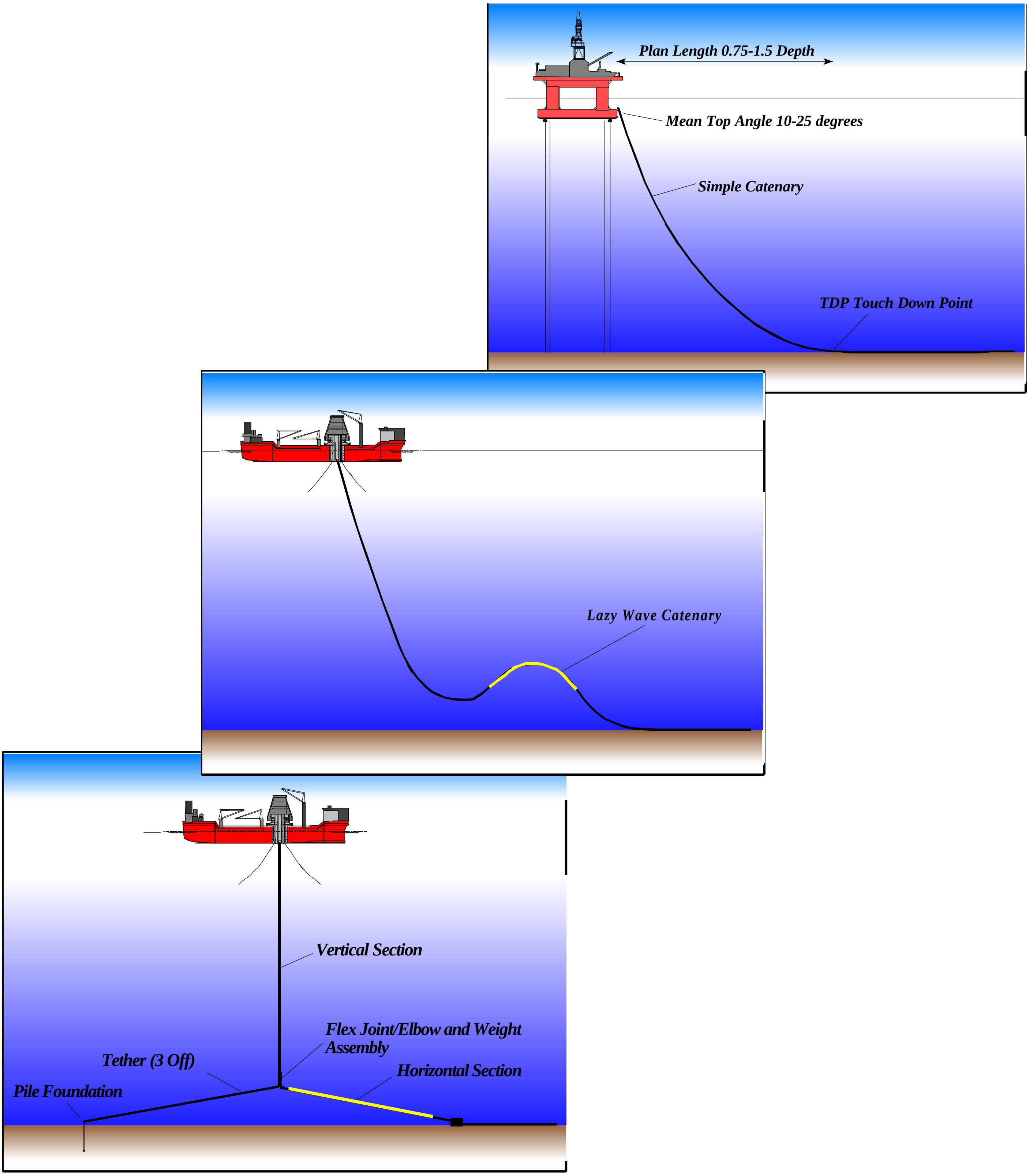

Figure 1 – Simple Catenary, Wave Catenary and Bottom Weighted Risers

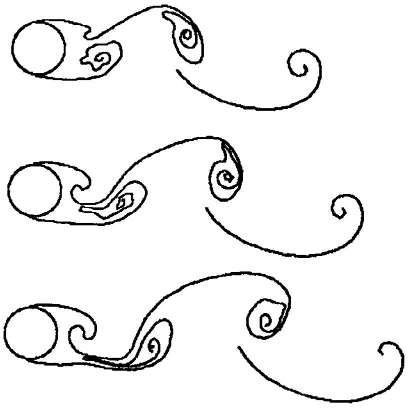

Figure 2 – Typical Vortex Street producing Cyclic Vibration

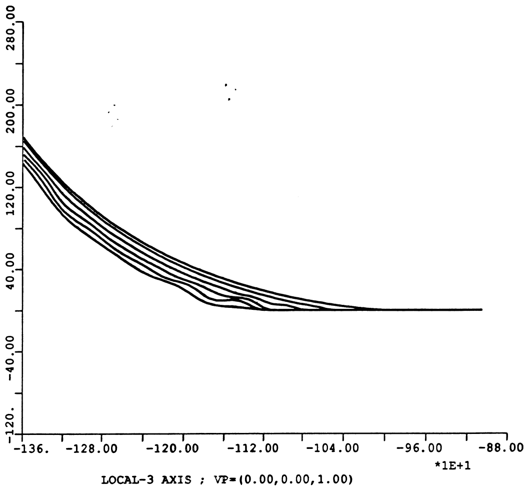

Figure 3 – Touch Down Point Buckling Under Extreme Load Conditions

Vessel Type	**Environment**	**Water Depth (m)**	**Riser Diameter (in)**	**Riser Configuration**
FPSO	West of Shetland	400, 800, 1200	10,14,20,30	SCR,WCR,BWR
SPAR	West of Shetland	400, 800, 1200	10,14,20,30	SCR,WCR
TLP	West of Shetland	400, 800, 1200	10,14,20,30	SCR
Ship FPS	North Norway	1200,1600,2000	10,14,20,30	SCR,WCR
FPSO	Gulf of Mexico	1200,1600,2000	10,14,20,30	SCR,WCR
FPSO	West Africa	1200,1600,2000	10,14,20,30	SCR,WCR

Table 1 – Summary *STRIDE* Riser Configurations

Riser Size	**Loading Condition**	**100 year wave, 10 year current**			**10 year wave, 100 year current**		
		Max. Equiv. Stress (/yield)	Max. Vessel Tension (kN)	Flexjoint Angle Range (deg)	Max. Equiv. Stress (/yield)	Max. Vessel Tension (kN)	Flexjoint Angle Range (deg)
10”	Near	0.930	1168	8.8	0.836	1103	7.4
	Far	0.648	2243		0.617	2090	
14”	Near	0.834	1876	9.4	0.758	1779	7.9
	Far	0.665	3704		0.633	3439	
20”	Near	1.033	2659	10.4	0.941	2501	8.9
	Far	0.755	5683		0.717	5172	
30”	Near	0.955	6012	14.0	0.880	5695	13.0
	Far	0.912	12800		0.753	11710	

Table 2 – Summary TLP SCR Results (1200m)

Water Depth (m)	**Pipe Size (Inches)**	**Wall Thickness (mm)**	**Buoyancy Length, diameter (m,m)**	**Distance to Start of Buoyancy (m)**	**Total Suspended Length * (m)**	**Touch Down Point Distance * (m)**	**Top Angle Mean, angle (degrees, degrees)**
400	10	25.4	390, 0.7650	736	1342	1156	38, ±20
	14	27.0	390, 0.9093	736	1342	1156	36, ±20
800	10	25.4	460, 0.7881	1196	1922	1476	26, ±19
	14	27.0	455, 0.9364	1186	1912	1451	25, ±18
	20	28.6	425, 1.1504	1156	1852	1451	30, ±18
	30	35.0	515, 1.5723	1246	2087	1706	27, ±18
1200	10	25.4	570, 0.8076	1560	2350	1575	18, ±17
	14	27.0	570, 0.9364	1560	2350	1575	18, ±17
	20	28.6	530, 1.1982	1540	2290	1575	21, ±16
	30	35.0	715, 1.6367	1700	2692	2037	21, ±17

Table 3 - Buoyant Wave Riser Configuration Summary – West of Shetland

Riser Type	**Environ-ment**	**Vessel**	**Water Depth (m)**	**Unfactored Minimum Fatigue Lives (years)**			
				Vessel	Arch	TDP	Other
14inch Simple Catenary	W.O.S	Spar	800	2641	-	146	-
14inch Simple Catenary	W.O.S	TLP	800	1535	-	57	-
14inch Buoyant Wave	W.O.S	FPSO	800	19	95	12	107 (25m from vessel)
14 inch Buoyant Wave	W.O.S	FPSO	1200	15	79	14	152 (450m from Vessel)
20 inch Buoyant Wave	W.O.S	FPSO	1200	26	24	4	153 (450m from Vessel)
14 inch Buoyant Wave	Norway	FPSO	2000	6	200	92	-
30 inch Bottom Weighted Riser	W.O.S	FPSO	800	100	-	-	123 (top of 22.2mm wall section) 36500 (titanium arm)

Table 4 – Summary Riser First Order Fatigue Lives

Fatigue Load	**Fatigue Damage at:**	
	Vessel	TDP
First Order Effects	0.0007	0.0173
Second Order Effects	0.0000	0.0117
Vortex Induced Vibrations (100% suppresion)	0.0029	0.0054
Total Damage	0.0036	0.0344
Unfactored Fatigue Life (years)	277	29

Table 5 Fatigue Damage Summary - 14 inch Simple Catenary Riser, 800m Water, West of Shetland

Fatigue Load	**Fatigue Damage at:**		
	Vessel	Arch	TDP
First Order Effects	0.0521	0.0105	0.0813
Second Order Effects	0.0001	0.0000	0.0050
Vortex Induced Vibrations (100% suppresion)	0.0016	0.0068	0.0065
Total Damage	0.0538	0.0173	0.0928
Unfactored Fatigue Life (years)	18	57	10

Table 6 Fatigue Damage Summary - 14 inch Buoyant Wave Riser, 800m Water, West of Shetland

Area	**Concern**	**Proposal/Solution**	**Benefits**
VIV	Limitations of existing software, unknown effect of pipe inclination, no validation	Tank and large scale testing	Validate analysis methods Reduce wt & strake coverage Simplify installation Reduce cost
TDP Response	Ability to predict low tension instability and TDP interaction	Software comparison Parametric sensitivity Tank testing	Benchmark analysis tools Remove conservatism Reduce costs
Pipe Collapse	Variation in collapse criteria and wall thickness requirements for small D/t ratios	Finite element analysis of practical pipe geometry's, including welds	Confirm wt requirements Reduce vessel payloads Reduce material costs Reduce installation costs
Materials	Effect of plastic deformation on weld fatigue unknown	Fatigue testing of coupons And full scale welds	Confirm ability to reel Justify storm allowables
Installation Aspects	Several areas identified or not covered by Phase 1 installation study work	Further study work and testing	Firm up strategies. Identify vessel/equipment mods and new-builds. Improve installation confidence. Reduce costs
Analysis	Riser response complex and not fully understood particularly VIV and 1st order fatigue, bundled risers	1st order fatigue studies Installation analysis Ultra deep water Bundled risers	Improve confidence Remove conservatism Confirm design criteria Develop design RP

Table 7 – Summary STRIDE Phase II Scope of Work

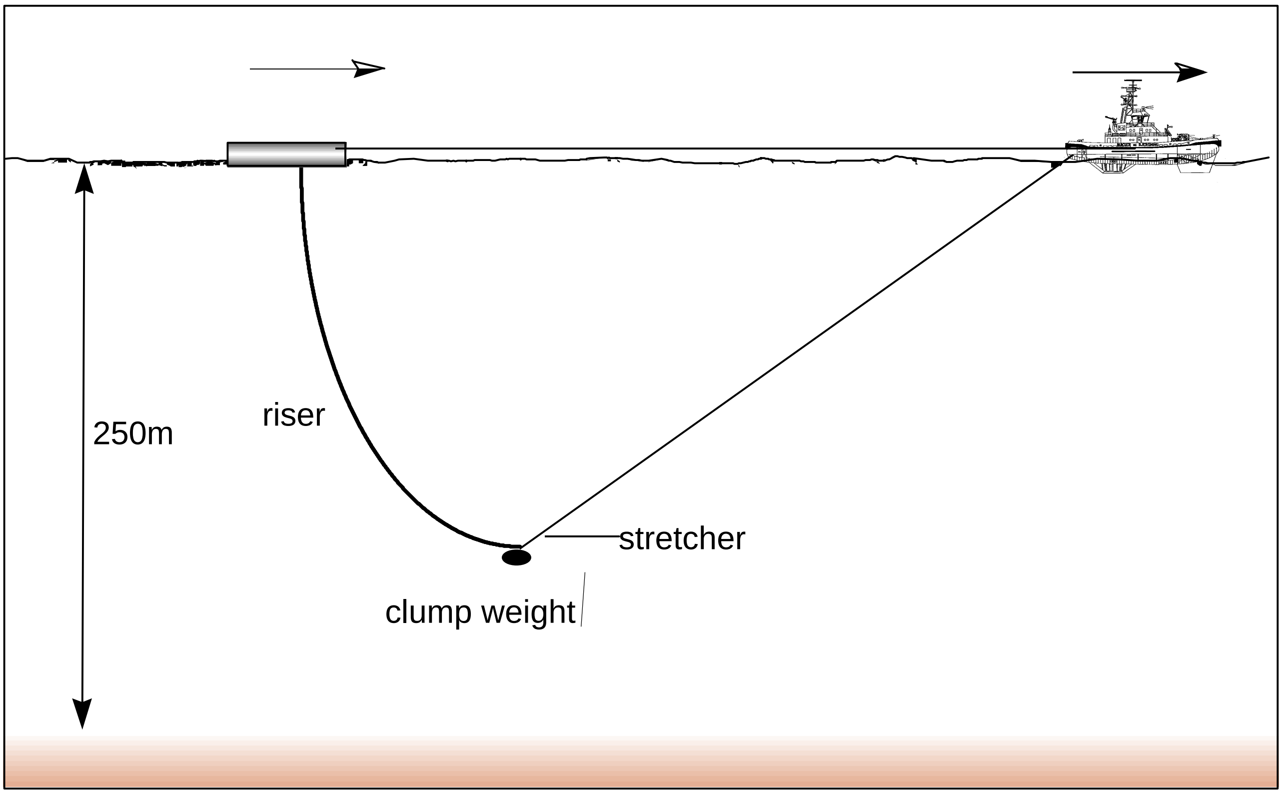

Figure 4 – Tow Arrangement