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**WEIGHT OPTIMIZED SCR – ENABLING TECHNOLOGY FOR TURRET MOORED
FPSO DEVELOPMENTS**

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ABSTRACT

Steel catenary risers (SCRs) used in conjunction with a turret moored FPSO in deepwater environments present significant design challenges. The large vertical motions at the FPSO turret induce severe riser response. This results in difficulty meeting strength and fatigue design criteria at the Touch Down Point (TDP) and at the riser hang off location. It is typically considered challenging to achieve feasibility for a conventional SCR application on a turret moored FPSO.

Previous industry work for an SCR application used with other floating hosts has demonstrated that SCR strength and fatigue response can be improved using heavy and light coatings strategically placed along the riser [1]. An optimization study is performed, based on previous industry work, which demonstrates that a weight optimized configuration can enable the application of an SCR on a turret moored FPSO. The effect of adding different coatings along the length of the SCR is discussed. The position, length, and density of the coating type are varied to determine an optimum configuration for both strength and fatigue response. This paper will also discuss observations which may help explain why weighted sections can improve SCR response at the critical area.

INTRODUCTION

Steel catenary risers (SCRs) have been used successfully with floaters such as TLPs, SPARs and Semis. Recently SCR applications have been extended to FPSOs. However, the SCRs have been attached at mid-ship of the FPSOs with milder motion. SCRs in conjunction with a turret moored FPSO in deepwater environments present significant design challenges. The large vertical motions at the FPSO turret induce severe riser response including compression and potential buckling at the TDP area and result in difficulty meeting minimum fatigue life requirements. Special efforts are needed to develop an optimized, feasible SCR configuration to be used in conjunction with a turret moored FPSO for West African environment.

The feasibility of a conventional SCR on turret moored FPSO is assessed initially and is confirmed to be difficult to achieve the desired strength and fatigue requirements. Based on previous industry work [1], an optimization study expands on the idea of using varying weight, in the form of different density coatings, along the length of the riser in order to improve SCR strength and fatigue performance. The study demonstrates that the SCR with weighted sections, which improve SCR response at critical area, is a potential alternative solution for the application of SCRs on turret moored FPSO.

Further study to understand why the mechanism of the increased weight at the TDP area improves riser performance is carried out, which is key to addressing the issues involved with the feasibility of this type of application. The study also determines the key parameter for SCR peak response, which included static shape, dynamic motions and velocities. This

understanding would help provide further insight for future optimization design work.

DESIGN DATA AND CRITERIA

A production SCR mounted to a turret moored FPSO in a water depth of 1500m off West Africa is evaluated. The key properties are as follow:

- 10.75in O.D., 1.0in (25.4mm) wall thickness;
- X65 steel;
- Insulated with 3.5in thick, 768kg/m³ syntactic foam.

Typical West African environmental data is used in the analysis. The concept of the proposed SCR configuration with weighted sections is shown in Figure 1.

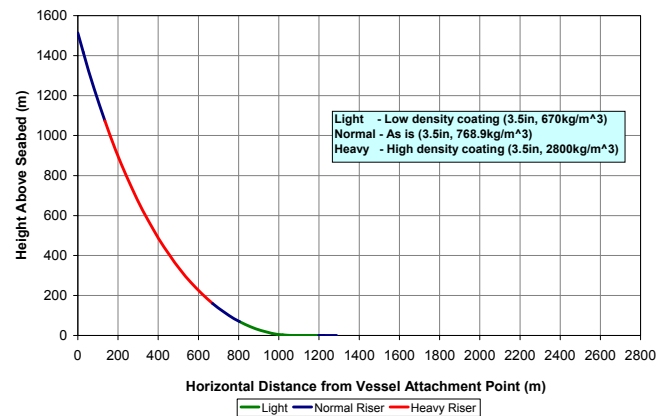


Figure 1 – SCR Configuration with Different Density Coatings

The strength analysis is performed based on a 12-hour 100 year extreme swell condition. Extreme strength response is considered to be acceptable if, along the entire riser, the maximum von Mises stress does not exceed 80% of the yield stress. It is also desirable to maintain positive effective tension in SCR at all load cases. Three FPSO draft conditions are considered including ballast, intermediate and fully loaded.

The target field life is 15 years so that the design fatigue life needs to be 150 years or more with a safety factor of ≥ 10 . Fatigue analysis is conducted for 41 condensed swell bins at 3 dominant swell directions. Fatigue damage is calculated using rainflow counting approach to reduce conservatism. Vessel orientation is 15° from the direction of the swell or local sea (165° vessel heading).

FEASIBILITY OF A CONVENTIONAL SCR

An initial attempt was needed to see if a conventional SCR, without weight optimization, could be made feasible for the turret moored FPSO application.

Preliminary strength analysis results showed compression and unacceptable stresses with a wall thickness of 25.4mm as given in Table 1. It was found that the hang off angle has to be increased to 15 deg and the wall thickness to 31.8mm to

marginally satisfy the strength. But the effective tension condition is still not satisfied for the ballast draft condition.

The maximum stress utilization with a 31.8mm wall thickness at the TDP is given in Table 1 and shown in Figure 2 for three different draft conditions. For the ballast draft condition the maximum compression at the TDP is 146kN resulting in a maximum stress utilization of 102%.

Riser Description	Draft Condition	Stress Utilization at TDP (%)	Min Effective Tension (kN)
25.4 mm WT, 10 deg Top Angle	Ballast	116	-99.5
31.8 mm WT, 15 deg Top Angle	Fully Loaded	85	1.7
	Intermediate	94	-18.6
	Ballast	102	-146

Table 1 – Strength Results for Conventional SCR at TDP

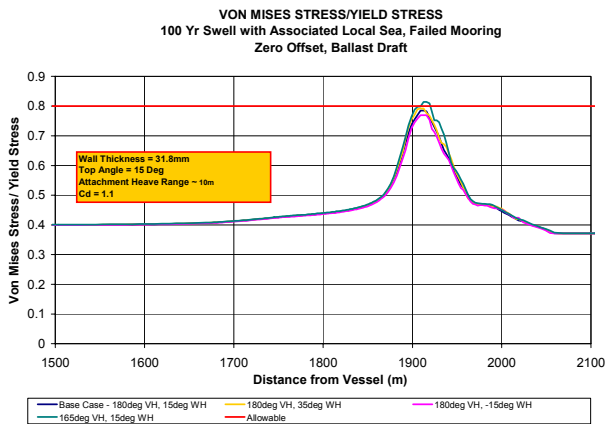


Figure 2 – Von Mises Stress at TDP

The minimum effective tension is shown in Figure 3 for the different drafts considered. The cause of the high stress for the ballast draft condition is due to large compressive tension in the TDP region of the SCR, as a result of the large heave motion at the hangoff location in the order of about 10m.

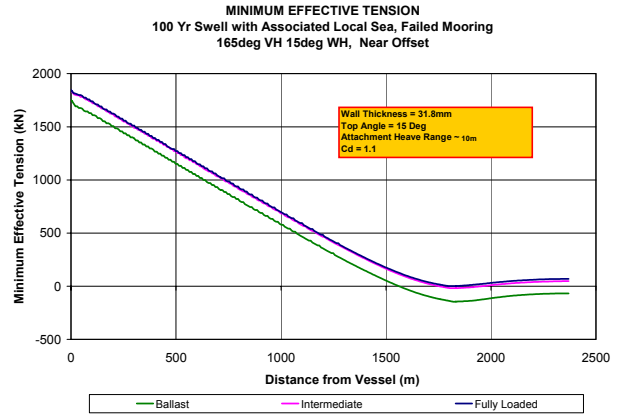


Figure 3 – Minimum Tension at TDP

First order fatigue analysis is carried out using time domain random sea analysis. The minimum fatigue life along the length of the riser is shown in Figure 4 for three different SN curves and given in Table 2.

S-N Curve	Min Fatigue Life at TDP (Yrs)
B	227
C	62
D	15

Table 2 – Fatigue Life at TDP for Conventional SCR

The fatigue life at the TDP area due to all swell bins is below the target fatigue life of 150 years when considering the use of the best weld “C” fatigue curve. The fatigue performance may be improved due to variations in vessel drafts during operating. This spreading effect may increase fatigue life by a factor of about 2.5 at the TDP area. However, the fatigue performance is still considered to be very marginal even if the best weld fatigue curve is used.

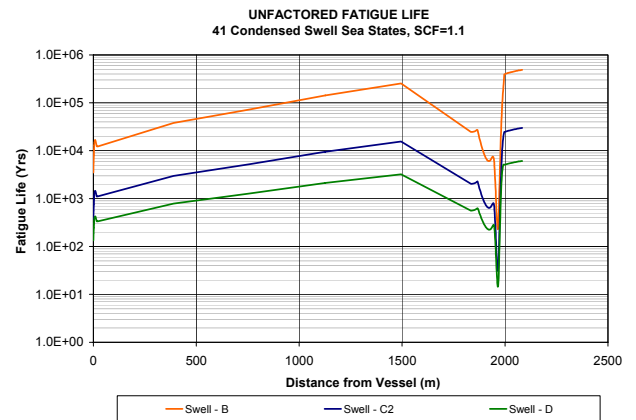


Figure 4 – Fatigue Life of SCR for Different Curves

In summary, feasibility of a conventional SCR with turret moored FPSO is questionable. Hence, as a means of improving

the SCR response, an optimized SCR configuration is needed to obtain a feasible solution.

OPTIMIZATION OF SCR CONFIGURATIONS

Previous studies for SCR applications on other floating hosts indicate that a heavy section in the sag-bend region and light section along the touch-down region improves response [1]. To improve the response of the SCR on a turret moored FPSO in both strength and fatigue performance, an optimization study on SCR configurations with weighted sections is carried out. The general arrangement used as the base case for this study is shown in Figure 5. An initial weight optimized SCR configuration is adopted based on the use of heavy 2800kg/m³ and light 650kg/m³ density coatings along the length to vary the weight of the riser at key locations.

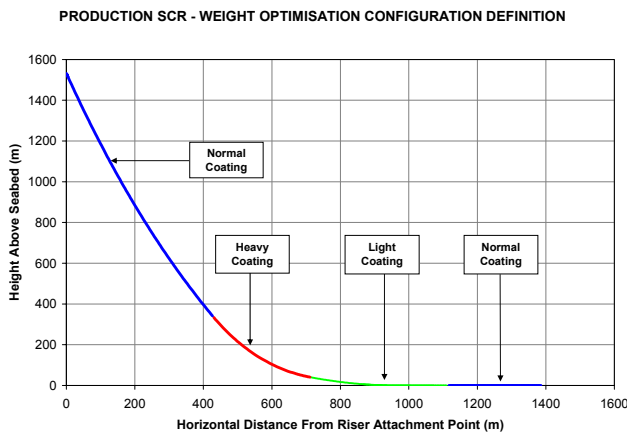


Figure 5 – Layout of Weight Optimized Sections

To obtain an acceptable configuration, a total of 9 configurations which vary the light and heavy section lengths and thicknesses are evaluated for strength and fatigue response. Of these, a configuration is found which satisfies both fatigue and strength criteria. A comparison between the weight optimized configuration and the conventional SCR is given in Table 3.

Case	Max von Mises Stress/Yield		Mini Fatigue Life DoE C/2 (yrs)	
	Hangoff	TDP	Hangoff	TDP
Conventional Riser	0.50	0.82	372	31
Weight optimized	0.57	0.48	318	264

Table 3 – Weight Optimized Configuration with Heavy and Light Sections

Analysis of the multiple weight optimized configuration indicates that a section of heavy coating closer to the touchdown zone improves the strength and fatigue performance of the SCR.

Following the development of a feasible weight optimized configuration, further optimization is conducted by:

- Removing the lightweight coating at the TDP;
- Reducing overall weight of the heavy section whilst still meeting design criteria.

While the strength performance is acceptable as the coating density is decreased to 1500kg/m³, effective tension approaches zero at the touch down zone, as shown in Figure 6. A final configuration is chosen which uses an 1850kg/m³ heavy coating along 425m of the sag-bend region and no light weight coating.

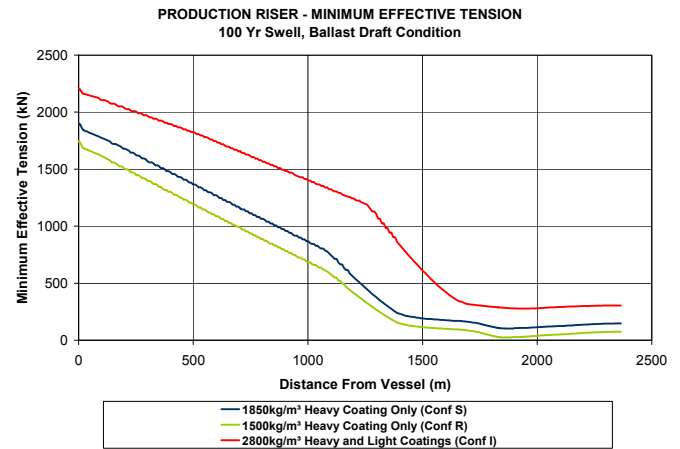


Figure 6 – Effective Tension along Riser Length

DESIGN OF SCR WEIGHTED SECTIONS

High density coating provides an acceptable solution from a structural standpoint. Other weight options are desirable to allow flexibility in cost and installation conditions. Hence, alternative means of achieving increased weight are evaluated, including:

- Increasing the J-lay collar diameter to meet weight per-joint weight requirements
- A pipe-in-pipe configuration where an external steel sleeve is added to the riser
- Increasing the wall thickness of the riser to meet weight requirements
- A clump weight solution where a weight is added during installation to each joint in the heavy section

The above solutions would all allow for proper insulation of the riser. However, due to the amount of extra weight needed per riser joint, increasing the weight by thickening the wall or adding a pipe sleeve are not feasible; the required wall thickness pipe could not be welded. Increasing the J-lay collar thickness would also not be feasible due the 60in diameter associated with a 2ft long collar. A qualitative comparison of these options is listed in table 4.

Solution	Pros	Cons
High Density Insulation	Even distribution of weight	Limited proven supplier
Increased Wall Thickness	Even distribution of weight	Required thickness not feasible
Steel Pipe Sleeve	Even distribution of weight, retains insulation properties	Sleeve too thick, pipe ovality mismatches
J-Lay Collar Modification	Collar already integrated, will not slip or fall off	High cost, locally high stresses over welds
Clump Weight	Cheap, deployable through the moonpool, can be located to avoid high SCF at welds	Further development required to prevent sliding, locally high stresses

Table 4 – Pros and Cons of Weight Optimization Options

The most promising solution appears to be a clump weight design which could be installed on an installation vessel, and away from welds, as shown in Figure 7. It allows for the riser to be fully insulated and potentially reduces procurement and installation costs. Clump weights have been successfully installed on other SCR application in the Gulf of Mexico in order to improve riser response during extreme events [2].

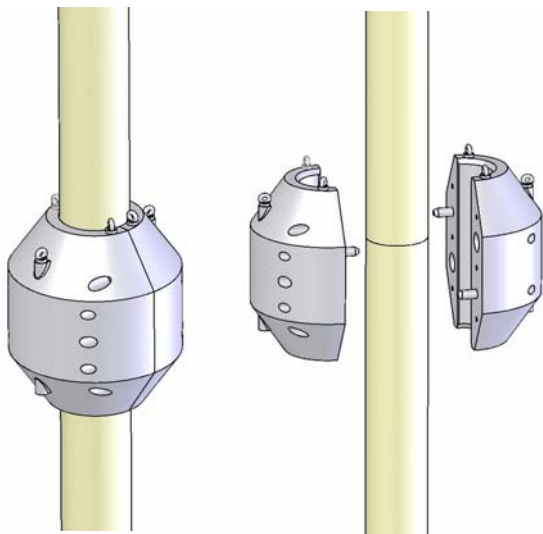


Figure 7 – 2H Design Clump Weight

As shown in Table 5, the weight and OD of the clump weight are such that it is light enough to be manipulated on

deck with existing equipment and narrow enough to fit through the J-lay tower. Only one clump weight is required per joint over the heavy section.

Length (m)	OD (m)	ID (m)	Weight (lb)	Number Required
1.000	1.261	0.457	5520	34

Table 5 – Clump Weight Parameters

Strength and fatigue analysis is performed on a clump weight solution with a weight distribution equal to the riser with only heavy coatings and equivalent density of 2250kg/m³. Strength response is found to be acceptable. However, the fatigue performance is significantly reduced. The best welds with “C” class fatigue performance are required in the TDP area to satisfy the fatigue design requirements, as shown in Table 4. This change is probably due to the additional drag imparted from the clump weights.

The locally higher drag and higher weight caused by the clump weights also decreases fatigue life along the clump weight region, as seen in Figure 8. However, because the relative dynamic motions are significantly lower and the fatigue performance is higher, the decrease in life in this region is acceptable.

Sensitivity	Unfactored Fatigue Life (yrs)	
	TDP (C Class)	Hang Off (C/2 Class)
Heavy Coating	455	819
Clump Weights	190	595

Table 4 – Effect on Fatigue Life due to Clump Weights

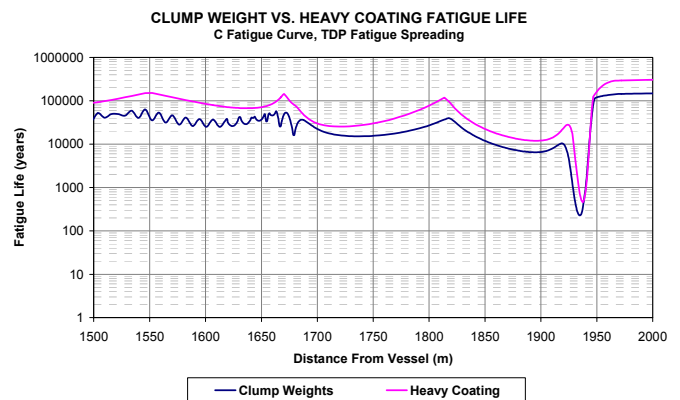


Figure 8 – Fatigue Response of Clump Weight Riser

SCR PEAK RESPONSE ASSESSMENT

The typical parameter used in design to predict peak response of an SCR is the maximum wave height. However,

other parameters also drive the SCR response. A study was performed to understand the correlation between the peak response and the following parameters:

- Maximum and minimum wave height
- Maximum upward porch velocity
- Maximum downward porch velocity
- Maximum upward porch acceleration
- Maximum downward porch acceleration
- Hang off degree of freedom 1 through 6

Environmental loading conditions consist of 12 one hour random sea analyses. Each random sea analysis uses a 100 year swell conditions and associated current and a different random seed. Extreme motions and SCR response are plotted against each other in order to identify the correlation between peak SCR response and the various vessel motion characteristics.

The relationship between maximum downward porch velocity and minimum effective tension at the TDP for the SCR is shown in Figure 9.

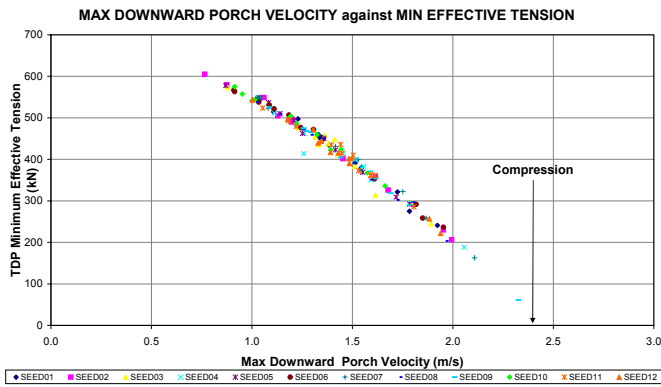


Figure 9 – Maximum Downward Porch Velocity vs. TDP Minimum Effective Tension

The results show that maximum downward porch velocity is a reliable indicator to capture the occurrence of minimum effective tension at the TDP. The results show that compression is expected to occur in the SCR for maximum downward porch velocities greater than 2.5m/s.

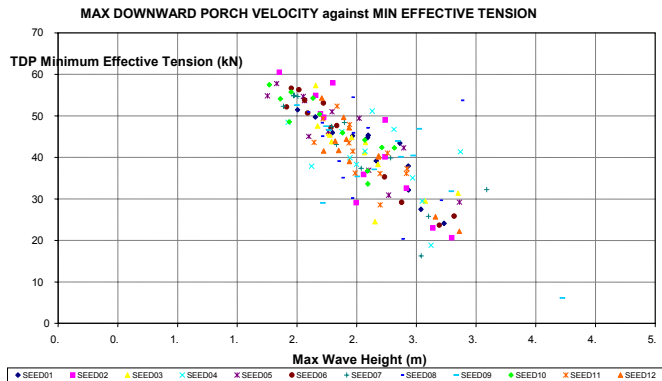


Figure 10 - Maximum Wave Height vs. TDP Minimum Effective Tension

The correlation between significant wave height and minimum TDP effective tension, which is a commonly used parameter to determine response, is shown in Figure 10. The results show that there is only moderate and considerably scattered correlation between wave height and peak response.

STUDY OF THE WEIGHTED SCR CONFIGURATION

As discussed above adding distributed weight to the SCR above the sag-bend region improves the SCR strength and fatigue response. It is desirable to understand the reason why the added weight improves the response of the SCR, which may facilitate better SCR design. The mechanism behind the improvements in response is investigated by performing a detailed assessment of the SCR strength response.

The SCR response for three SCR configurations is assessed including evaluation of: static shape, tensions and bending moments, dynamic motions, and velocities. The results are evaluated in a number of ways including time traces, envelopes and snapshots. The SCR configurations including normal, heavy coating, and clump weight are shown in Figure 11.

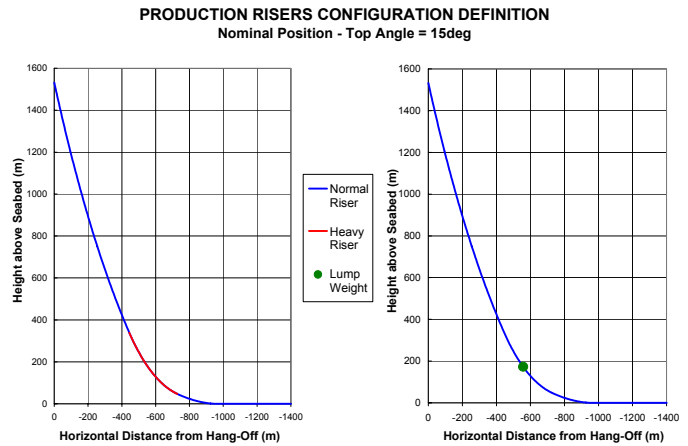


Figure 11 – SCR Configurations

Static Response

SCR static response shows that the addition of weight increases tension but reduces TDP bending moments and curvatures. The reduction in static TDP curvature for the heavy coating and clump weight configurations is shown in Figure 12. The SCR static curvature at the TDP is reduced by a factor of 0.8 with the introduction of the additional weight (See Figure 16). As expected, the single lump mass causes a locally high increase in curvature that can be reduced with the use of smaller distributed lump masses.

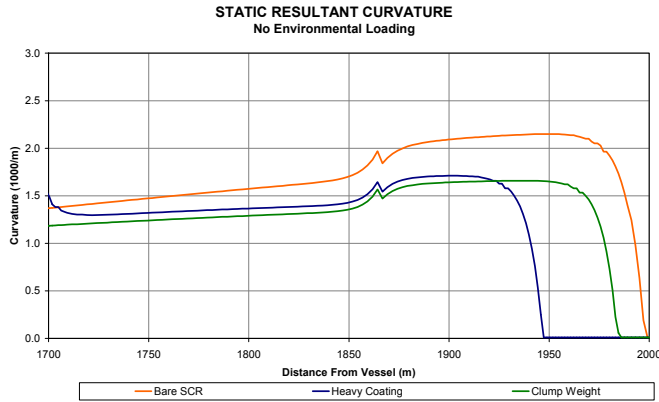


Figure 12 – Static Curvature

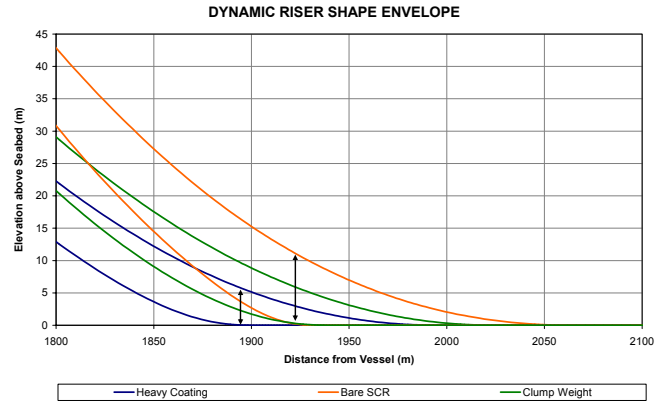


Figure 14 - Dynamic Riser Shape Envelope in TDP Region

Dynamic Motions

Riser dynamic motion envelopes and snapshots of the structure are investigated in order to determine how the motion response of the various SCR configurations differs. The vertical motion range extracted from 6 positions along the length of each SCR is shown in Figure 13.

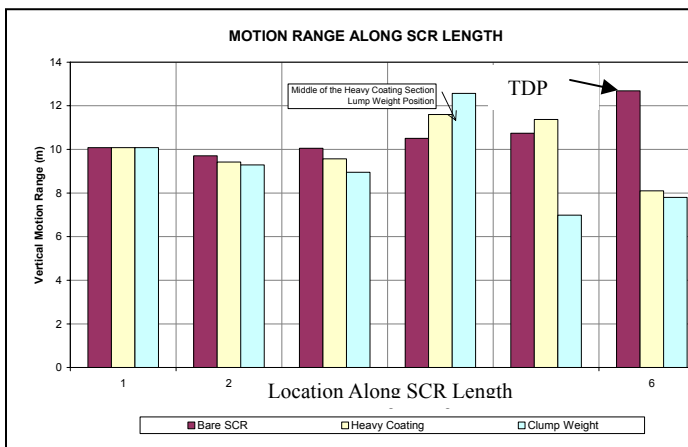


Figure 13 – Vertical Motion Range Along Riser Length

The addition of weight increases the motion response in the region of the weight by a factor of 1.2, and consequently reduces the motion response directly above the TDP by a factor of 0.6. The reduced motion response in the TDP region of the weight optimized SCR results in lower velocities and consequently the dynamic response is improved as shown in Figure 14. Therefore, reduced loads and stresses occur in the TDP region.

SCR Velocity Response

The SCR velocity response is assessed to help understand if it is a factor in the changing motion characteristics. The terminal velocity and actual velocity along the riser length is calculated. Terminal velocity of a free falling body is the speed at which the surrounding fluid drag force matches the pull of gravity, resulting in a constant fall rate. It is defined as follow:

$$v_{term} = \sqrt{\frac{2W}{C_d A \rho_{fluid}}}$$

Where:

- v_{term} - terminal velocity of the free falling body
- W - weight of the body
- C_d - drag coefficient
- A - cross sectional projected area (perpendicular to flow direction)
- ρ_{fluid} - density of the surrounding fluid

Terminal and actual velocity along the length of the SCR for both configurations are shown in Figure 15 and Figure 16. The actual vertical velocity response in the region of the added weight of the SCR configuration with the heavy coating is approximately 20% greater than the bare SCR, as shown in Figure 15. Below the distributed weight, the velocity reduces to 50% of the value for the normal configuration. For the non weight optimized SCR, without the additional weight, the velocity is transferred to the TDP region. Hence, locally high velocities, that exceed the terminal velocity, occur directly above the TDP, where compression occurs.

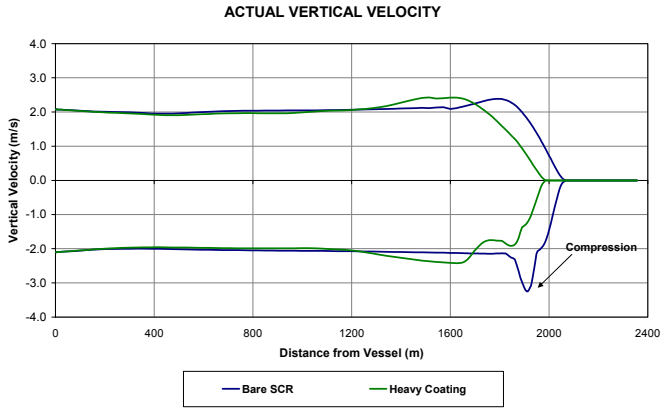


Figure 15 - Actual Peak Vertical Velocity Envelope along Riser Length

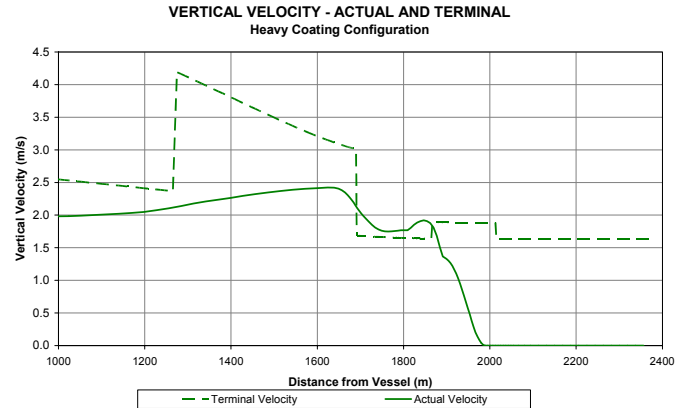


Figure 17 - Terminal and Actual Velocities Heavy Coating Configuration

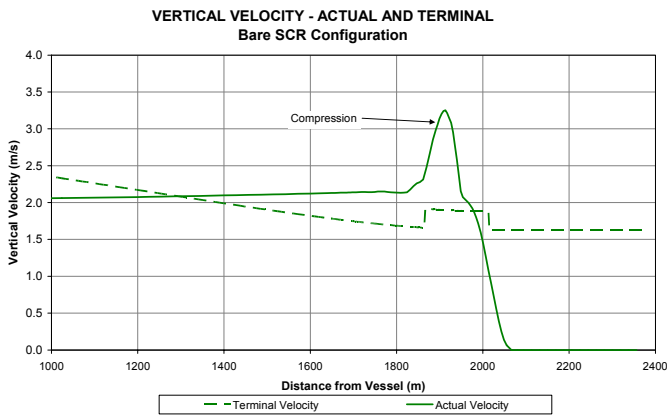


Figure 16 - Terminal and Actual Velocities of Bare SCR Configuration

The addition of weight locally increases the terminal velocity, allowing the riser to ‘fall’ faster and hence further during cyclic downward vertical motion. For the heavy coating configuration, the actual maximum downward velocity at the TDP only slightly exceeds its terminal velocity, as shown in Figure 17.

Thus, one possible explanation for TDP compression is that if the hang-off forces the TDP region to move downward faster than its terminal velocity, then the upward drag force in this region tends to deflect the riser and the catenary’s shape is locally deformed as a consequence of high compression.

Effect of Drag Coefficients on SCR Response

The effective tension at the TDP is lower for higher drag coefficients and compression occurs when the actual downward vertical velocity exceeds the terminal velocity by a certain amount. For the non-optimized SCR, compression occurs for drag coefficients of 0.8, 1.1 and 1.4, as shown Figure 18.

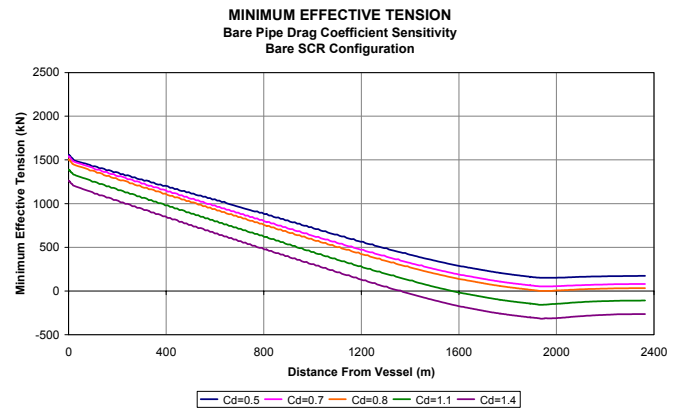


Figure 18 – Minimum Effective Tension for Different Drag Coefficients – Bare SCR Configuration

Compression does not occur for the case with a drag coefficient of 0.5 because the actual velocity is only slightly higher than the terminal velocity as shown in Figure 19. For the weight optimized configuration the minimum effective tension is achieved for a drag coefficient of 1.4 and, as shown in Figure 19, compression does not occur even though the actual velocity slightly exceeds the terminal velocity as discussed above. Further work is required to better understand the physics of these observations.

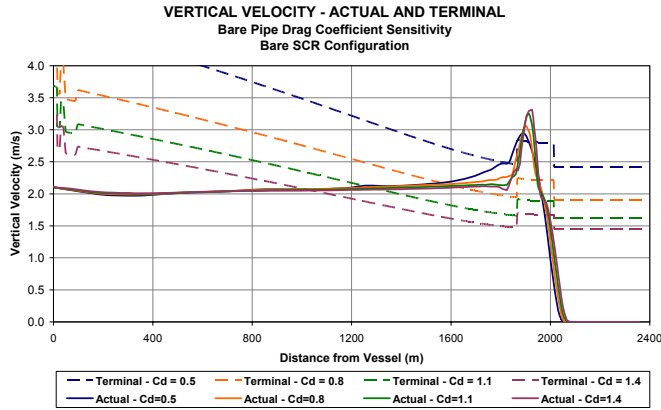


Figure 19 - Terminal and Actual Velocities of Bare SCR Configuration for Different Drag Coefficients

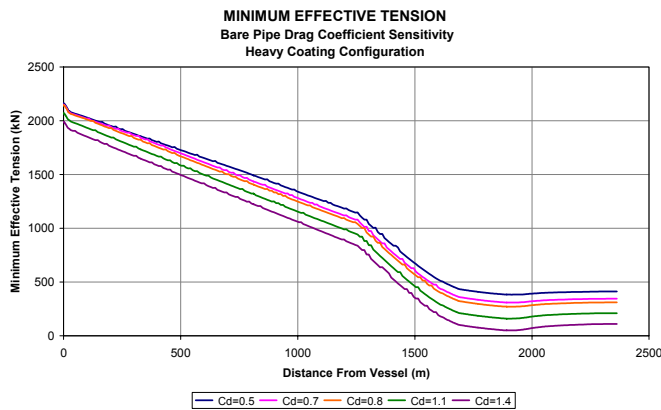


Figure 20 - Minimum Effective Tension for Different Drag Coefficients – Heavy Coating SCR Configuration

- The clump weight option, which may provide flexibility from installation and cost perspective, gives acceptable fatigue and strength response.
- The study shows that there is a strong correlation between maximum downward porch velocity and peak SCR response. The maximum downward porch velocity is a reliable indicator for the occurrence time of the minimum effective tension at the TDP.
- The addition of a clump weight or heavy coating appears to result in a reduced static curvature and dynamic motion response in the TDP area of the weight optimized SCRs.
- TDP compression appears to be related to max downward velocity that significantly exceed the terminal velocity. Weight optimized SCRs may enhance performance, in part, by changing the terminal velocity profiles of the rises.

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CONCLUSIONS

The design challenges of utilizing an SCR on a turret moored FPSO are addressed in this paper. An optimum weighted SCR configuration is presented as an alternative solution to these challenges. This configuration takes installation flexibility and cost into account. In addition, the physics behind the reasons for improvement in response have also been discussed. The following conclusions can be drawn from the study:

- With the implementation of optimized weighted sections, SCR strength and fatigue response is improved sufficiently to be within acceptable limits provided high fatigue performance welds be used.
- Static response shows that the addition of weight increases tension but reduces TDP bending moments and curvatures. Stress and fatigue performance at the TDP is improved as weight above the TDP increases.