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The Effect of FPSO's Mooring System on Dynamic Response and Fatigue Life of Riser

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ABSTRACT

The effects of mooring system selection (turret and spread) are investigated on dynamic performance and fatigue life of steel catenary riser (SCR) and lazy-wave steel catenary riser (LWSCR) as two of the most conventionally used flexible risers. The fully coupled hull, mooring, and riser models are simulated by finite element method under the same environmental conditions and floater specification. It was demonstrated that the changes in the mooring system from turret to spread have more influence on SCR than LWSCR in terms of the displacement range of the TDP, dynamic response, and maximum von-misses stress. The fatigue results of the two types of risers are considerably affected by mooring systems selection. According to the results, it can be inferred that the use of the turret mooring system increases the fatigue life of SCR while in LWSCR, the spread mooring system improves fatigue life.

1. Introduction

Risers and mooring systems are the most important parts of all offshore structures, especially in deep-sea conditions. Risers oscillatory motion cause fatigue and other dynamic failures in the structure while mooring system reduces the motions and consequently, increases the reliability of the operations. Different types of risers and mooring systems have been developed to satisfy specific requirements related to special environmental conditions and operational demands. So the interaction between riser and mooring system is an interesting research subject affecting the operation and economy.

Many studies have recently focused on platform responses affected by mooring system which directly influence the Touch Down Point (TDP). Maffra et al. [1] investigated the optimization of the mooring lines of semi-submersible platforms using a genetic algorithm to increase the station keeping ability and decrease the motions of the platform due to harsh environments considering important design factors such as cost. Howell et al. showed that the mooring systems have been designed for several deepwater fields without taking into account all the relevant interfaces, leading to expensive mid-project changes, increased component costs, and impact on schedule and installation [2]. Han and Kim [3] performed a comparative analysis for different mooring systems and found out that the number of mooring lines could affect the fatigue life of a platform. Qiao et al [4] studied the behavior of platforms under mooring system conditions with different pre-tensions. Each system had different effects on the motions of the platform and since the motions of the platform are directly transformed to the touchdown point of the riser, the importance of the proper selection of the mooring system was revealed. L. Shanying et al. [5] compared the analysis of the dynamic response of Catenary mooring system and taut mooring system of floating production storage and offloading vessel (FPSO). The results showed better position ability and mooring strength for taut mooring system with polyester material in middle part than that of catenary mooring system.

The studies have been conducted on different types of risers to identify the advantages and disadvantages of each type and to develop more efficient designs to improve the flexibility of the system, the life of the riser, and reliability of the operations. Feng Zi and Ying Min [6] studied a Steel Catenary Riser (SCR) at the touchdown point and mentioned that this point undergoes the worst bending stresses and is subjected to the greatest uncertainties such as those arising from riser-seabed contact. They revealed the significance of these uncertainties for SCR fatigue analysis. Zhao [7] represented that locating the most critical point in the flexible riser and using an accurate enough fatigue analysis method are both important for the safety of the whole riser system Vidic-Perunovic et al. [8] analyzed the feasibility of using steel catenary riser in combination with a circular FPSO concept considering the strength and longtime fatigue life of the riser. According to their study, this combination will be a cost-efficient solution for development of ultra-deepwater fields located in the Gulf of Mexico. Royer et al. [9] identified alternatives to SCRs in both geometry and material aspects in the first half of their study. Those alternatives were, then, selected to check if they could safely meet the constraints of both high motion vessels such as a semi-submersible or a ship-shape FPSO and ultra-deepwater for the second half of the study. Comparison of dynamic responses for alternatives resulted in an understanding of their concept limitations. According to their study, considering developed technologies and costs, Lazy Wave Riser Steel Catenary Riser (LWSCR) is a viable alternative to SCR for conventional semi-submersible with an estimated cost that is 30-60% higher than that of an SCR. The authors of this paper modeled an SCR connected to an FPSO in deepwater with a harsh environment and found out that the point which was subjected to the worst bending stresses was not located in touch down zone (TDZ) and was located just near the upper end of the TDZ [10]. Seungjun Kim and Moo-Hyun [11] conducted a general and detailed analysis on SCR and LWSCR in both aspects of structural and dynamic responses. Keeping floater and environmental conditions constant, they compared results of the risers and found unacceptable excessive fatigue damage, buckling, and induced structural stress amplifications for the conventional SCR. On the other hand, LWSCR shows elimination of this dynamic buckling and considerably less stress and damage because of its self-motion isolating effect. They also reduced the amount of stress by changing the location of the LWSCR touch-down point. According to this advantage of LWSCRs, they are highly recommended for very harsh environmental conditions, but LWSCR concept has some disadvantages such as design difficulties, probability of slugging problems for internal flows, and, above all, higher cost. Rodolfo B. Sancio [12] conducted quasi-static analyses using a finite element method-based program by simplifying the interaction of the SCR and the sea bed as that of a beam resting on, and surrounded by, linear and non-linear springs. The von Mises stress range was calculated for conditions in which the SCR was subjected to vertical motions and to vertical and horizontal motions while varying the amplitude of the motion, the undrained shear strength of the sea bed, the initial embedment of the riser in the seabed and the boundary conditions applied to the SCR. The results show that, for the conditions that were studied, the effect of incorporating horizontal interaction between the SCR and the sidewalls of a trench on the von Mises stress range is typically less than 5%. The analyses also indicate that the effect of the lateral interaction of the SCR with the seabed increases as the amplitude of the vertical and horizontal motions increase; the contribution of the lateral motion decreases as the soil strength increases and the soil stiffens; the contribution of the lateral motion decreases as the embedment depth increases. This study showed that horizontal seabed-SCR interaction may not have a substantial effect on the fatigue life of the SCR.

Considering all valuable previous efforts, this study has focused on finding the effect of proper mooring system selection on dynamic performance of SCR and LWSCR as two of the most conventionally used flexible risers. With proper selection of riser and mooring system, excessive and unnecessary costs of the projects including initial and maintenance costs can be significantly decreased which can be further studied from an economical point of view.

The riser is in the interface between a static structure at bottom interface and a dynamic floater structure at top interface. The dynamic behavior and motions of the floater, especially surge and heave, at the surface, are the main challenge for riser system design [10]. The compliant riser with different types of configurations and ability to resist severe floaters motions, which is used for deepwater field platforms, provides flexibility in floater motions. SCR and LWSCR as common types of flexible riser configuration are shown in Figure 1 [13, 14]. Riser configuration design shall be performed according to the production requirements and site-specific environmental conditions.

The free-hanging catenary riser is widely used in deep water. This configuration does not need heave compensation equipment. When the riser is moved up and down together with the floater, it is simply lifted off or lowered down on the seabed. The surface motion is directly transferred to the TDP implying that the failure mode could be over bend or compression at a point near the TDP. From the first-order vessel motion, the most severe motion is heave. In lazy wave configurations, buoyancy and weight are added along part of riser length to decouple the vessel motions from the touchdown point. Lazy waves require minimal subsea infrastructure in contrast with other configurations except free hanging catenary type, while lazy waves are prone to configuration alterations if pipe content density changes during the riser's lifetime [14].

All petroleum mobile offshore platforms require a

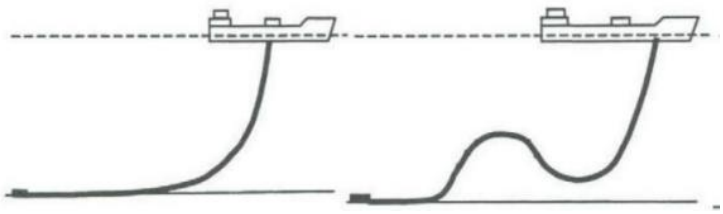

Figure 1. Free hanging and Lazy wave compliant riser configurations

method for maintaining their position with high reliability during oil and gas production operations in offshore environmental conditions which have caused a variety in designing mooring systems, each one with special characteristics allowing the production facility to avoid excessive movement that could affect the reliability of both vessel and riser systems [15]. Turret and spread are the most convenient mooring systems in mobile platforms. A spread mooring system can adequately hold the structure on location. The main advantage of a spread mooring system is that it fixes the orientation of the floating structure so that drilling, completion, and well intervention operations can be carried out on subsea wells. This system has a fairly large mooring spread. Thus, the presence of anchors and mooring lines should be considered in the installation or maintenance of pipelines, risers, or any other subsea equipment.

Single point or turret mooring is used extensively in ship-shaped floating structures such as FPSOs and FSOs. The main characteristic is that the mooring system allows the vessel to weathervane. There is a wide variety in the design of turret mooring, performing essentially the same function. The turret has bearings to allow the structure to rotate around the turret's vertical axis. In some cases, the turret is designed such that the lower chain table can be disconnected to enable the floating structure to depart from the location to avoid severe environmental events, e.g. a tropical cyclone or an approaching iceberg.

2. Riser Analysis

Global analysis of a riser can be divided into three main consecutive steps including static, dynamic, and fatigue analysis. In static analysis, the position of the system is confirmed at equilibrium condition under the effect of weight, buoyancy, hydrodynamic, and drag. Dynamic analysis is carried out for simulating the motion of the riser at a specific time interval under the effect of environmental and operational conditions, considering the static equilibrium position of the system as an initial condition. The cyclic nature of the environmental loads applied on the riser during its long operational lifetime emphasizes the necessity and importance of a global riser fatigue damage analysis. Damage caused by an irregular wave is calculated by rainflow cycle counting method according to Palmgren-Miner law which is based on the S-N curve data for the material, as shown in Eq. 1. Maximum allowable damage, under which no fatigue is considered to occur, is defined as the structure's critical damage and depends on the importance and risk susceptibility of the structure itself. Risk susceptibility of the structure is defined as its design fatigue factor. Riser fatigue analysis has two concepts known as short-term and long-time fatigue analysis. Short-term fatigue analysis indicates when the first damage will be caused by fatigue while the riser faces a continuous storm or harsh cyclic environmental load. Long-time fatigue analysis also indicates when the first fatigue damage will occur considering the estimated probability of the real load case for the design life time of the riser as shown in Eq. 2 [16].

$$D_S = \begin{cases} 0 & S \le F \\ \dfrac{1}{N_S} & S > F_L \end{cases} \tag{1}$$

$$D_L = \sum_{i=1}^{N} D_i P_i \tag{2}$$

Finite element method is used as an effective method in riser analysis. In this method, riser is discretized into segments and each segment is modeled by two nodes with 6 DOF and a line element considering axial, bending and rotational, stiffness, and damping. Also, the ability of the element to model wall tension allows considering the pipe's internal pressure and content [17]. A Schematic view of the Finite element model representing nodes, segments, and stress distribution is shown in Figure 2.

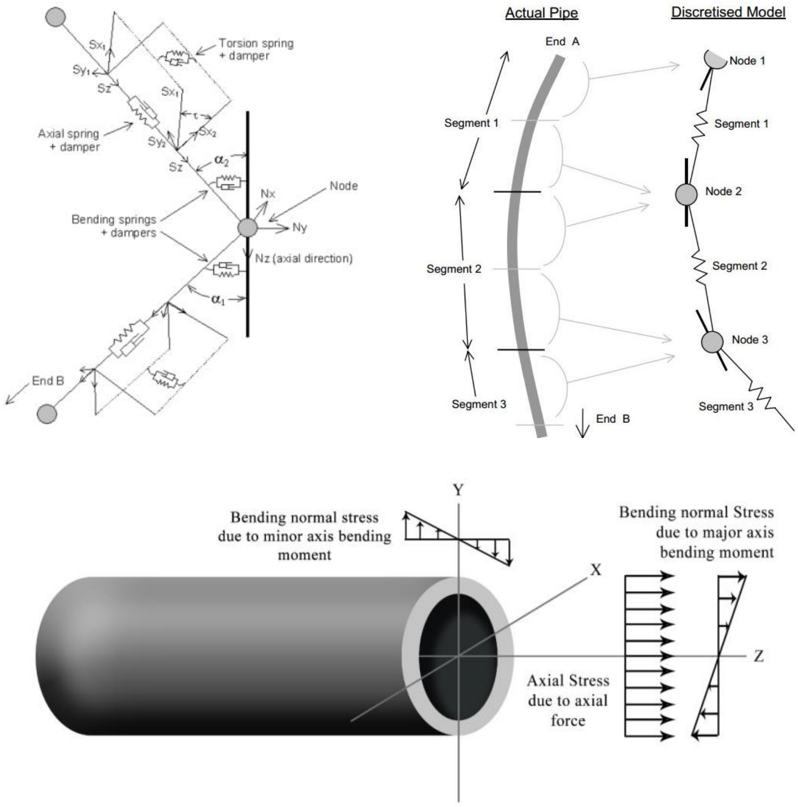

Figure 2. Representation of line FE model and stress distribution

3. Modelling

Different comparative models of riser and mooring system combinations are selected for investigating the effects of mooring system on riser performance. For this study, a deepwater FPSO is modeled with four feasible combinations of riser and mooring system as presented in Table 1.

The riser is limited to two of the most conventional compliant riser solutions for deepwater production including free hanging steel catenary and lazy wave steel catenary risers. Figure 3 shows a schematic of the models consisting of mooring systems and riser configurations. All properties and characteristics of mooring line and riser are considered to be the same, according to Table 2, for all models in order to allow the comparison and investigation of the effects of spread and turret mooring system on riser

Table 1. Model naming table

Model Number	Riser Type		Mooring Type	
	SCR	LWSCR	Spread	Turret
1	●	-	●	-
2	●	-	-	●
3	-	●	●	-
4	-	●	-	●

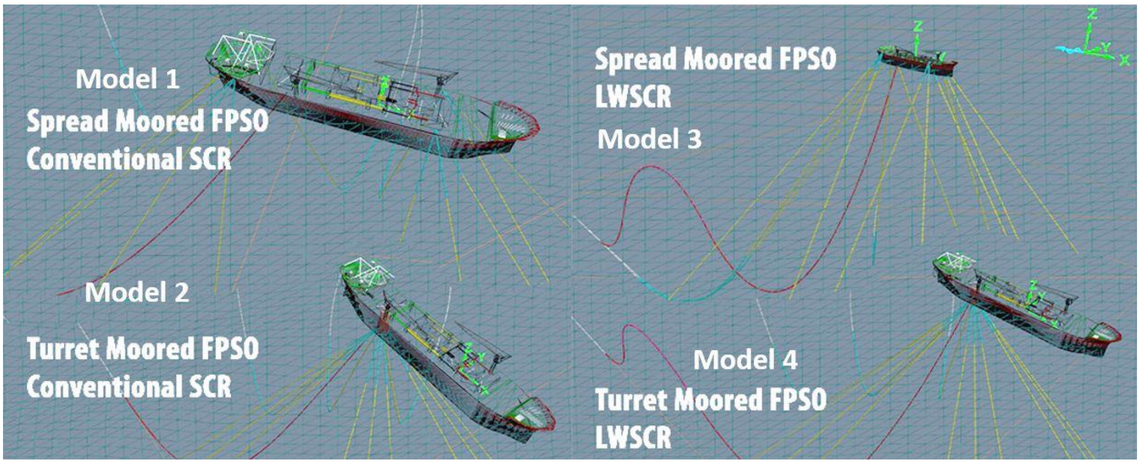

Figure 2. Schematic of mooring and riser models

Table 2 Line input data

Line Data (SCR & LWSCR)

Line type	Homogeneous pipe			
Material	Steel X-65			
Structure				
Riser type	SCR		LWSCR	
Line Length	2346 m		2346 m	
Number of Sections	4		5	
	Length of Sections	Number of Segments	Length of Sections	Number of Segments
Sec.1	96 m	8	430 m	10
Sec.2	1100 m	22	600 m	200
Sec.3	300 m	115	850 m	150
Sec.4	850 m	17	320 m	100
			146 m	8
Pipe Geometry and Content				
Outer Diameter	0.273 m		Content Pressure	Survival
Inner Diameter	0.191 m			89.6E3 (kN/m^2)
Thickness	0.041 m			
Hang off angle	10.5 degree Azimuth		Content Density	0.80063755 (te/m^3)

Line Data (Mooring)

Line type	Catenary (Chain - Rope - Chain)		
Material	Steel - Polyester - Steel		
Structure			
Mooring Type	Catenary Mooring		
Material	Chain	Rope	Chain
Length	30 m	630 m	1175 m
Number of segments	1	15	29
Geometry			
Diameter	Chain	Rope	Chain
	0.238 m	0.237 m	0.238 m

performance for both cases of SCR and LWSCR.

Harsh environment characteristics such as wave and current are considered to be a survival condition using a 100-year hurricane wave as listed in Table 3

Table 3 Wave & current data
100 Year Hurricane Wave & Current data

Environment	
Water Depth	1000 m
Water Density	1.025 (te/m^3)
Wave	
Direction	180 degree (Ahead)
Spectral	Jonswap
Spectral Data	Survival
Hs	13.4 m
Tp	14.9 s
H max	23.6 m
T max	13.4 s
Current	
Depth	Current velocity
0 m	0.93 m/s
50 m	0.68 m/s
300 m	0.47 m/s
1000 m	0 m/s

4. Results

The effect of two mooring systems – spread and turret – was studied on dynamic response and fatigue of SCR and LWSCR by OrcaFlex finite element software package which is fully 3D non-linear time domain finite element software capable of dealing with arbitrarily large deflections of the flexible from the initial configuration.

Figure 4 shows a block diagram of the analyses and their results. Three categories of analyses were carried out: static, dynamic and fatigue. Static analysis finds the initial position and configuration of the systems before starting the dynamic stage.

Preamble to the dynamic stage is the build-up period during which the wave and the current are formed and the simulation gets ready for the time response analysis; this stage is represented by minus time (from -14s to 0s) in time history diagrams. Finally, dynamic analysis is applied for 20 minutes and the system is faced with a continuous 100-year hurricane. For fatigue analysis of the risers as a post-processing analysis, it is required to define the material S-N curve and its fatigue limit. For this purpose, the DNV F1 classification is considered as the characteristic for weld grooves of these SCR and LWSCR models. [18] The structure is also considered a high-risk structure with a design fatigue factor of 10 so that its critical damage is defined to be 0.1. [19]

The prediction of the displacement ranges of the TDP which is commonly called Touch Down Zone (TDZ) is important in riser analysis in which floater movement is an important factor influencing TDZ.

As shown in Figures 5a and 5b, it would be remarkable that the changes in mooring system from turret to spread has more influence on TDZ in steel catenary riser (215 m to 157 m) than on TDZ in lazy wave steel catenary riser (remains about 8.9 m).

Distribution of maximum von-misses stress in riser length for SCR and LWSCR which is normalized by 448 MPa API as maximum allowable stress [20, 21] is illustrated in Figures 5g and 5h. The allowable stress was calculated for steel x-65 considering its minimum yield stress; 1.2 as design factor for extreme environmental conditions and 0.66 as an allowable stress factor.

The comparison of two graphs in Figures 5g and 5h shows that the use of turret mooring systems reduced maximum von-misses stress, particularly in TDZ for SCR, whilst in LWSCR, stress is not affected by mooring. However, it should be noted that maximum von-misses stress is considerably increased in TDZ and the prior scope to as high as 2.6 times as great as allowable stress during dynamic analysis time interval in SCR. Although the increase is for a short time period corresponding to dynamic buckling of the riser, it is effective on the riser's fatigue life.

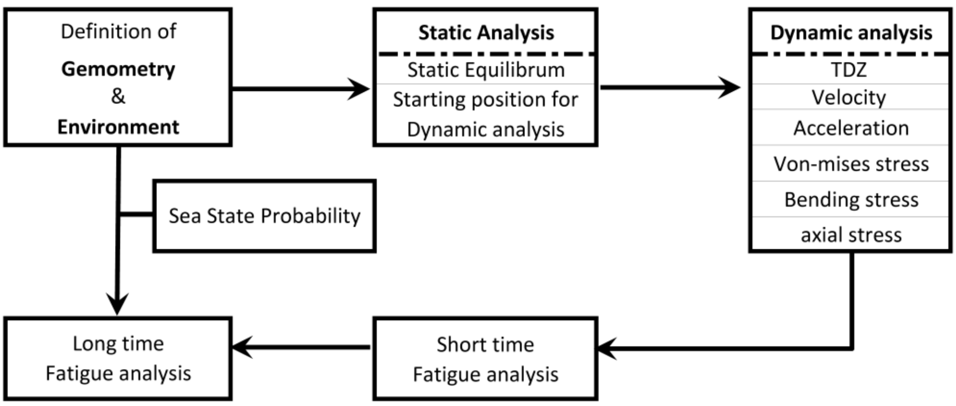

Figure 4. Block diagram of present analysis

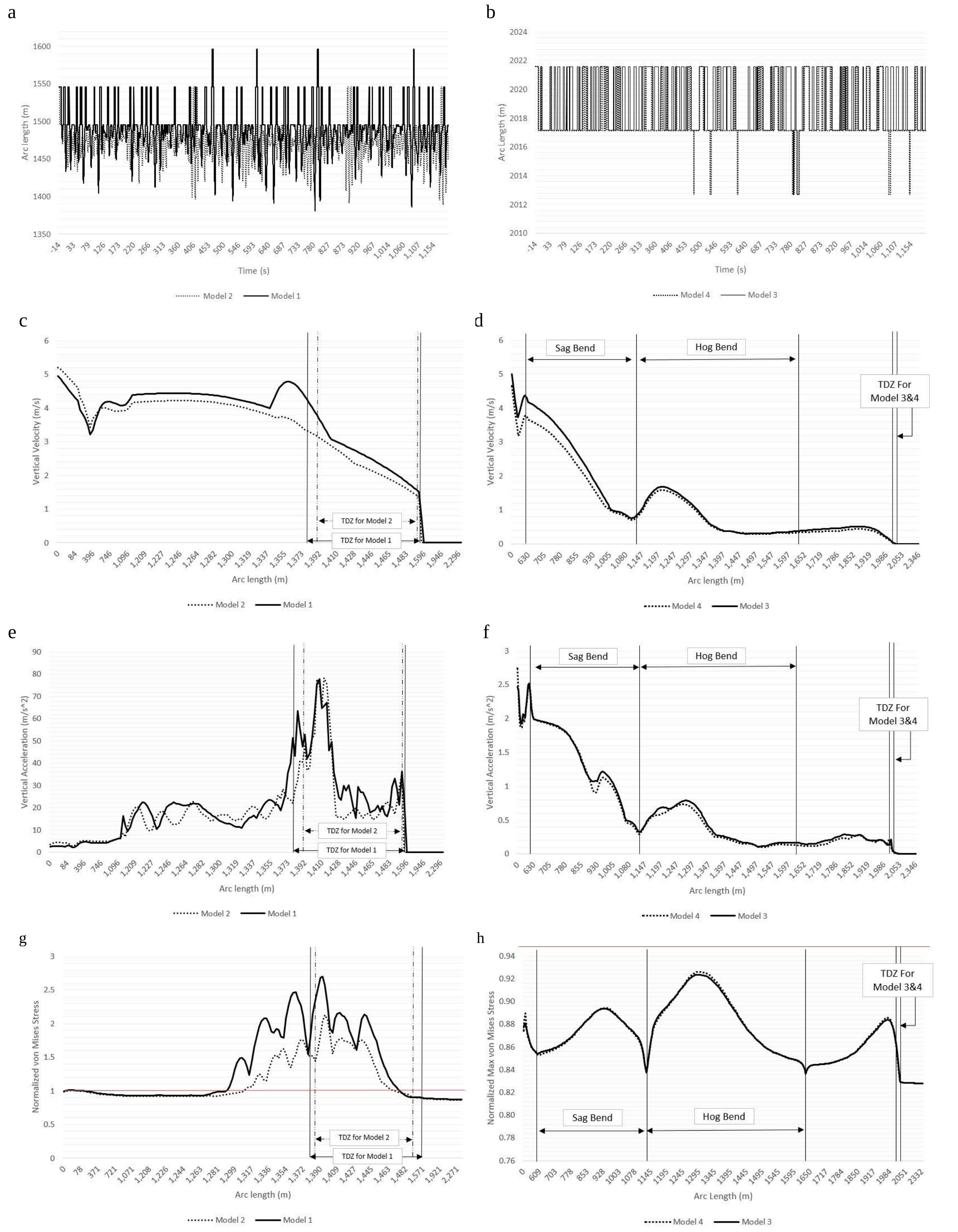

Figure 3. TDZ in arc length of a) an SCR and b) a LWSCR connected to a FPSO. Vertical velocity in arc length for c) an SCR and d) a LWSCR. Vertical acceleration in arc length for e) an SCR and f) a LWSCR. Normalized Maximum Von-mises stress for g) an SCR and h) a LWSCR

Figures 5c, d, e, and f show that the LWSCR has less vertical velocity and considerably less vertical acceleration in its arc length in comparison with the SCR. For the turret moored FPSO both SCR and LWSCR, models 2 and 4, has less vertical velocity and accelerations in comparison with the spread moored ones, models 1 and 3.

As can be seen in Figures 5c and e, there is a sudden abnormal change in vertical velocity and acceleration of the upper portion of the TDZ in SCR, for both mooring systems, models 1 and 2, which can definitely be the cause of dynamic buckling as a result of sudden increase or decrease in compression inertial loading at a point near the upper portion of the TDZ.

Figure 6 shows maximum bending moment for models. The similarity of bending moment curve with von-misses curve shows that the stress governing factor for a riser is bending moment and it can also be measured that bending moment for the SCR is five times as large as bending moment for the LWSCR. For the SCR the point 1393 m (1392 m – 1395 m) in arc length undergoes the maximum bending moment and bending stresses. As shown in Figure 7, the buckling phenomena can also be traced as negative stresses in the axial stress vs. time diagram for the point with maximum bending moment and stress.

According to Figure 7, SCR buckles more quickly, around 400 s, when FPSO is moored with turret mooring system than when it is moored with spread mooring system, 800 s. By tracing the vertical and longitudinal position of nodes in related buckling time intervals, the buckling curvature in SCR configuration is revealed as shown in Figure 8.

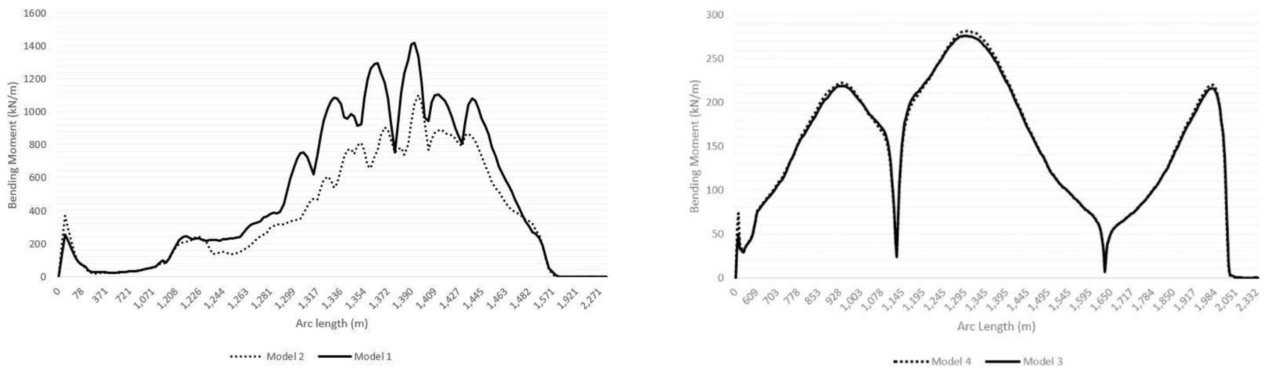

Figure 4. Maximum Bending moment for an SCR and a LWSCR

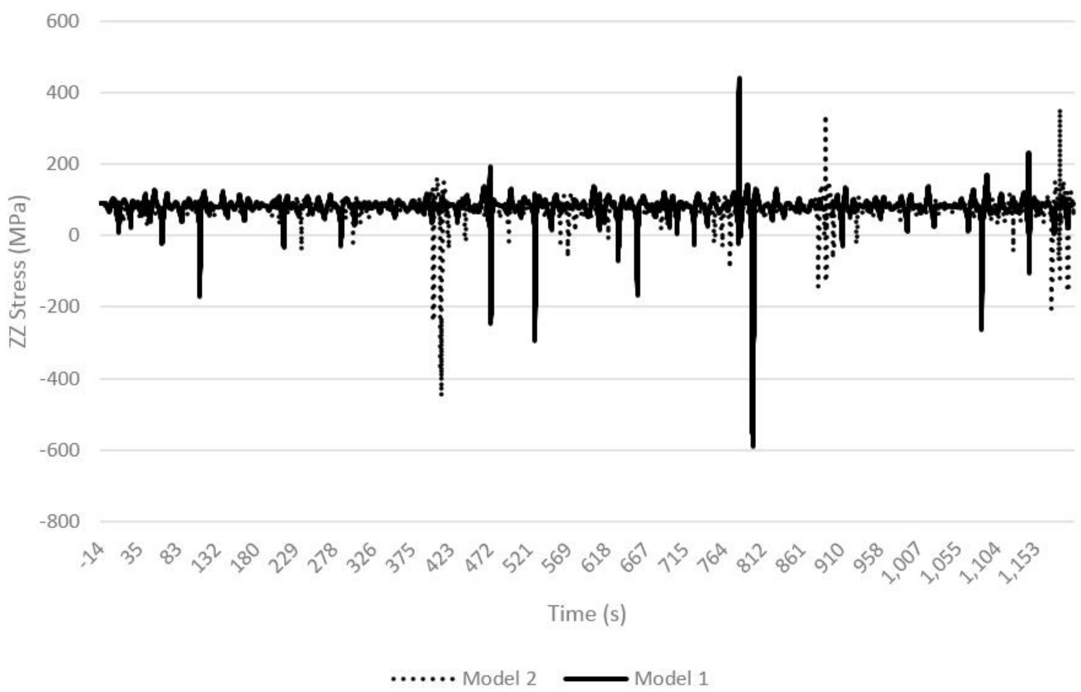

Fig. 5 Axial Stress at the point with maximum bending moment

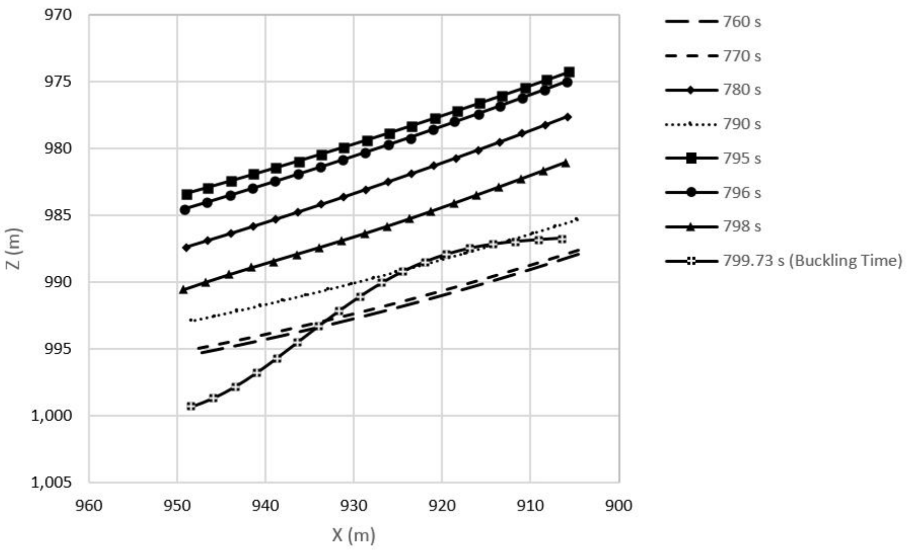

Fig. 6 Buckling phenomena traced in time

In the third stage of the analysis, the risers are first assumed to be exposed to a continuous 100-year hurricane for a constant time (1.5 hrs for SCR and 500 hrs for LWSCR).

According to the results of fatigue analysis, as is evident in Table 4, SCR exhibits a behavior completely different from LWSCR relative to the position corresponding with the fatigue-induced failure as well as the effect of mooring system on fatigue life.

In SCR, the first point related to fatigue failure is in the position corresponding to maximum bending moment, whilst in LWSCR it is at the joint point to FPSO (hanging point). The conversion of the mooring system from spread to turret in SCR increased fatigue life, whereas it generated a reverse response in LWSCR reducing the riser's fatigue life. Considering critical damage of 0.1 for a high-risk structure and performing short-term fatigue analysis [19], the first fatigue damage for the case of SCR happened at 1.6 hrs in the spread moored case, and 2.9 hrs for the turret, both near the maximum bending moment point. In the case of LWSCR, the first fatigue happened at 4261.5 hrs and a point near 63 m in arc length for the turret mooring system, while in the spread mooring system, the first fatigue occurred at the same point but in 7505.7 hrs.

For the real conditions considering the probability of the assumed sea state, long fatigue life of the risers is estimated for the first fatigue damage, as shown in Table 4. Figure 9 shows normalized maximum von-misses stress and long-time fatigue life for a section of the SCR connected to the spread moored FPSO around its TDZ. The point proportion to maximum von-misses stress is the first point that reaches the critical fatigue damage in the case of an SCR.

Table 4. TDZ, max BM and fatigue analysis

Riser Type	SCR				LWSCR			
Mooring Type	Spread (1)		Turret (2)		Spread (3)		Turret (4)	
TDZ Range	from	To	from	to	from	to	from	To
	1,381 m	1,596 m	1,389 m	1,546 m	2,012.7 m	2,021.6 m	2,012.7 m	2,021.6 m
	215 m		157 m		8.9 m		8.9 m	
(BMP) Point with Max. BM	1,392.957 m		1,395.565 m		1,295 m		1,295 m in arc length	
	At	799.73 s	At	411.27 s	At	803.73 s	At	804.23 s
Fatigue Analysis Critical damage (0.1)	Max Damage for 1.5 hrs. at BMP				Max Damage in 500 hrs. at BMP			
					0.000077	Theta 0	0	Theta 0
					Max Damage in 500 hrs. at 63m			
	0.09	Theta 180	0.05	Theta 180	0.006	Theta 180	0.01	Theta 180
	First fatigue				First fatigue			
	0.101	1.6 hrs.	0.1002	2.9 hrs.	> 0.1	7505.7 hrs.	> 0.1	4261.5 hrs.
	At (in Arc length)		At (in Arc length)		At (in Arc length)		At (in Arc length)	
	1,390.348 m		1,395.565 m		63 m		63 m	
	Estimated Long Life				Estimated Long Life			
	480 year		870 year		2,251,710 year		1,278,450 year	

5. Conclusion

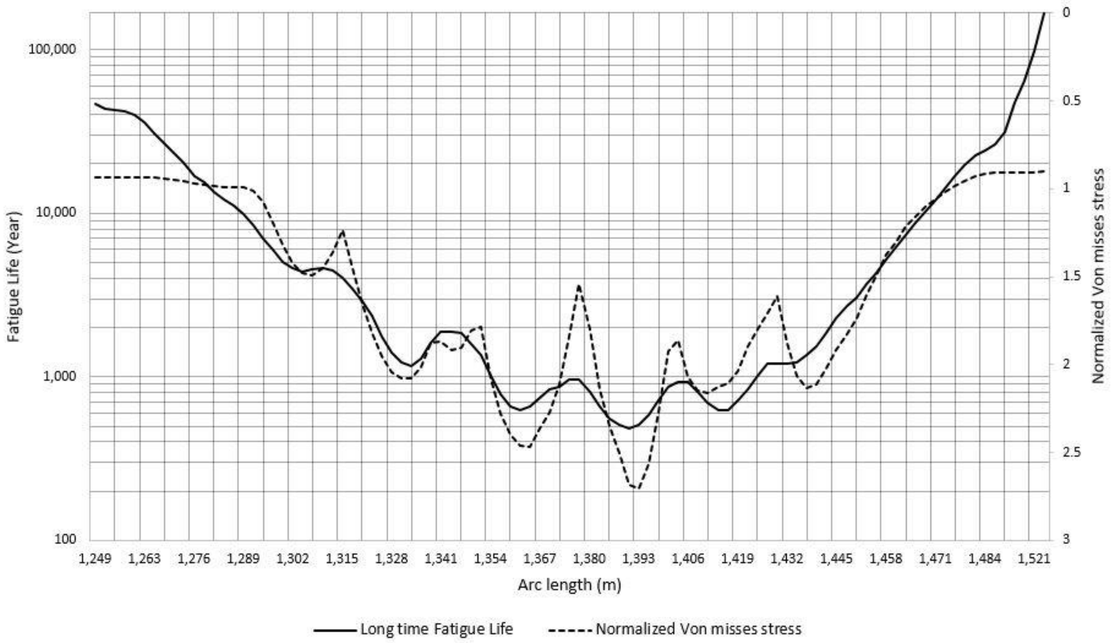

Figure 7. Long time Fatigue life and Normalized von misses stress for Model 1

The effects of the application of mooring system are studied on dynamic performance and fatigue life of two conventional deep-water risers, SCR and LWSCR. Given the placement of LWSCR and the isolation of its movements from floater dynamic movements, the dynamic performance of this riser is least influenced by mooring system type.

Dynamic analysis is applied for 20 minutes and the system is faced with a continuous 100-year hurricane. The changes in the mooring system from turret to spread are more effective on TDZ in steel catenary riser than on TDZ in lazy wave steel catenary riser. Maximum von-misses stress, particularly in TDZ for SCR, is reduced by the application of turret mooring systems whilst in LWSCR, stress is not affected by mooring. The similarity of the bending moment curve with the von-misses curve shows that the stress governing factor for a riser is bending moment.

Dynamic buckling of riser caused in a short time period resulted in considerably higher von-misses stress at TDZ for SCR. Consequently, it increases riser's fatigue life. SCR's behavior completely differs LWSCR's behavior relative to the position corresponding with the fatigue-induced failure as well as the effect of mooring system on fatigue life. In SCR, the first point related to fatigue failure is in the position corresponding to maximum bending moment, whilst in LWSCR it is at the joint point to FPSO (hanging point). The conversion of the mooring system from spread to the turret in SCR resulted in longer fatigue life while generating a reverse response in LWSCR resulting in a shorter riser's fatigue life

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