# New Frontiers in the Design of Steel Catenary Risers for Floating Production Systems

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*The steel catenary riser (SCR) concept has recently been used in almost every new deepwater field development around the world. Shell pioneered the implementation of the SCR concept in 1994 on its Auger tension leg platform (TLP) in 872 m (2860 ft) water depth. Since then, SCRs have been vital to deepwater field developments. Their use has given a new dimension to oil exploration and transportation in water depths where other riser concepts could not tolerate the environmental loads or would have become very costly. SCR designs are very sensitive to floating support platform or vessel motion characteristics to which they are typically attached. In addition to pipe stresses, the main design issue for the SCR concept is fatigue related. There are two main sources for fatigue: random wave fatigue and vortex-induced vibration (VIV) fatigue. The former is due to wave action and the associated platform motion characteristics. The VIV fatigue is mainly due to current conditions. Fracture mechanics assessment is also an essential issue that must be addressed in the design of SCRs. This paper presents a brief history in the use and development of SCRs since the first project implementation on Auger TLP in 1994. The paper also summarizes major steps that must be considered in the design of SCRs and how to explain their behavior in different water depths and environmental conditions. Existing design boundaries for SCRs are discussed with emphasis on the capabilities of new technologies that enable engineers to go beyond these boundaries. Projects with unique SCR features and their implementation are compiled and presented.*
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## Introduction

With the offshore industry moving into deeper waters, floating facilities have become an integral part of many field developments acting as an oil and gas production facility and/or as a hub for developments of several remote wells or fields. Steel catenary risers (SCRs) for deepwater developments have become a viable option for oil and gas export from floating production facilities to shore, shallow water platforms, or to subsea pipeline hubs. SCRs have been less expensive than other types of risers such as flexible pipe, which has a complex set of layers and not as strong as rigid steel in resisting hydrostatic pressure. The preferred use of SCRs with floating structures has created the need to understand their behavior during installation and operation, and when subjected to extreme environmental conditions.

The catenary shape of SCRs imposes high stresses in the touchdown/sagbend area. The level of these stresses in most cases is within acceptable limits if no platform motions exist; but this is not the case with SCRs attached to floating structures with varying degrees of motion. The compliance of floating structures usually causes the SCRs to move back and forth by stretching (floating structure in far position with shorter section on the seabed) and kneeling (floating structure in near position with longer section on the seabed), as shown in Fig. 1. This kind of shape variation, and due to the direct effects of waves, fatigue damage and high stresses caused by dynamic motions become important aspects of the SCR design. The existence of a loop current, particularly in the Gulf of Mexico, adds another dimension to the SCR design because of its VIV fatigue effect.

This paper represents an overview of SCR design, installation and operation as a concept that has been increasingly used with floating support structures. A brief history of SCR design and installation developments is presented. The main steps required for the SCR design are also discussed. Some important limitations and boundaries that have been overcome or are being examined and studied to take the SCR applications to new frontiers are introduced and discussed.

## History of Steel Catenary Risers

The first SCRs were installed on the Auger tension leg platform for oil and gas export [1]. The SCRs were installed in a water depth of 872 m (2860 ft) with a flexjoint connection to the TLP pontoon at 21 m (70 ft) below the water surface. According to Phifer et al. [1], the SCRs were selected because they were, among other factors, less expensive than flexible pipe risers. These first oil and gas export SCRs were 12.75-in. diameter and 0.688-in. wall thickness. Since they were the first SCRs, an extensive design and analysis effort was undertaken. Full-scale fatigue tests were performed to verify feasibility for the Gulf of Mexico environment and TLP motion characteristics.

J-lay installation method was used to install the Auger SCRs and attach them to the receptacles at the TLP pontoons. The J-lay method was selected for cost effectiveness and ease of installation. The Auger SCR installation was part of the J-lay export pipelines installation that started from water depth of 366 m (1200 ft) to the TLP location. Several calculation steps were taken to insure the length accuracy, and consequently, the departure angle of the SCRs. Helical strakes were added to the top 152 m (500 ft) of the SCRs for VIV suppression.

Since Auger, SCRs have been installed on many TLPs and Spar-type structures. These two types of floating structures share a common feature in their small heave motion, which consequently can cause detrimental fatigue damage to the SCRs, particularly in the touchdown area. SCRs have been installed not only as means to connect oil and gas export pipelines to floating production structures, but also as flowline SCRs connecting remote subsea wells to production facilities. Flowline SCRs usually have thermal

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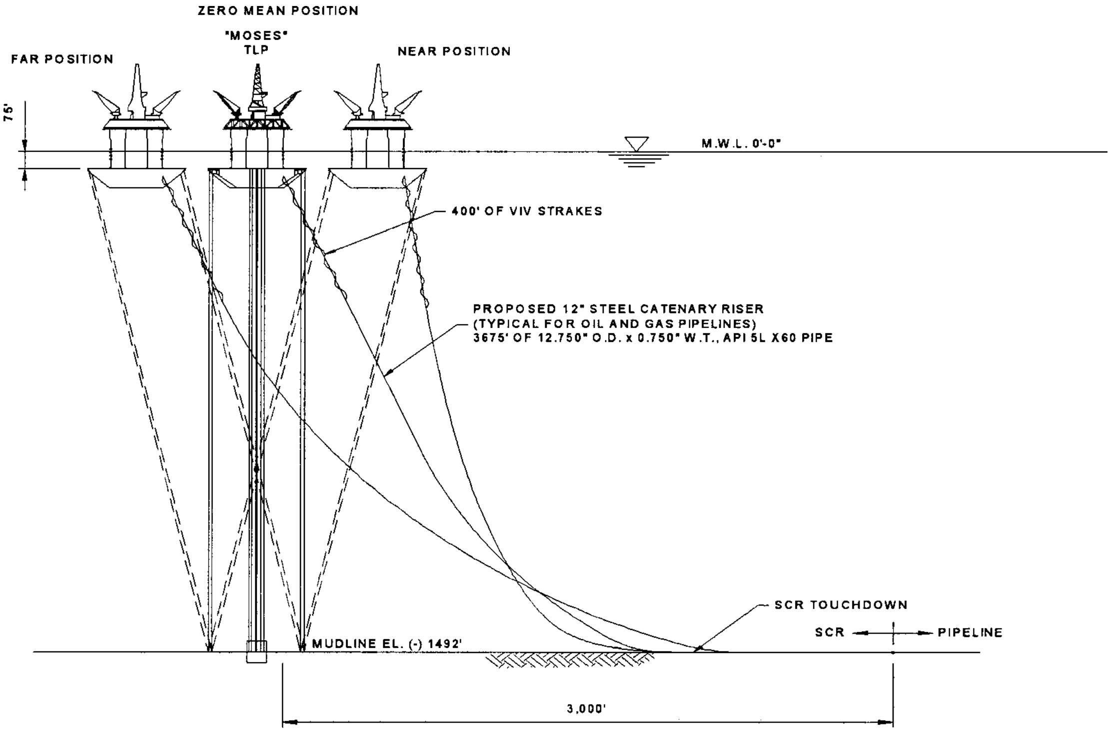

**Fig. 1 Typical SCR configurations for the Prince project**

insulation and operate under much higher internal and shut-in pressures than the operating pressure for export SCRs. The Allegheny SeaStar TLP, for example, has both export and flowline SCRs in water depth of 1000 m (3290 ft). A pipe-in-pipe SCR is a technically viable option, but yet to be implemented. It was first considered for the King/King's Peak Spar project in the Gulf of Mexico in water depth of approximately 1500 m (5000 ft), but the project was cancelled and replaced by a different field development scenario.

The following represents the industry firsts related to the development of the SCR concept:

- First SCR to a floating structure: The SCRs connected to Auger TLP in water depth of 872 m (2860 ft) in Green Canyon Block 426 in the Gulf of Mexico [1].
- First SCR installed by S-lay/J-lay combination: The SCRs connected to the Morpeth SeaStar TLP in water depth of 510 m (1670 ft) in Ewing Bank Block 965 in the Gulf of Mexico. The J-lay method was used only for the SCR top section with strakes [2].
- First SCR to a semi-submersible: The SCR connected to the P-18 semi-submersible for Petrobras in water depth of 910 m (1985 ft) in the Marlim Field offshore Brazil [3].

The Prince Project in water depth of 455 m (1490 ft) in Ewing Bank Block 1003 in the Gulf of Mexico sets SCR industry records in many aspects:

- First SCR installed in water depth of less than 457 m (1500 ft)—see Fig. 1.
- First SCR installed with 24-deg departure angle and ±20-deg flexjoint angle variations—see Fig. 2.
- First SCR completely installed using S-lay method with strakes attached prior to laying. Typical VIV strakes are shown in Fig. 3.

The installation of the first SCRs has indeed started a new era in oil and gas production and transportation in deeper water than what other pipe materials can withstand. Now, the oil industry is considering ways to improve and invent new technologies to go to even deeper, 3000 m (10,000 ft) and beyond [4].

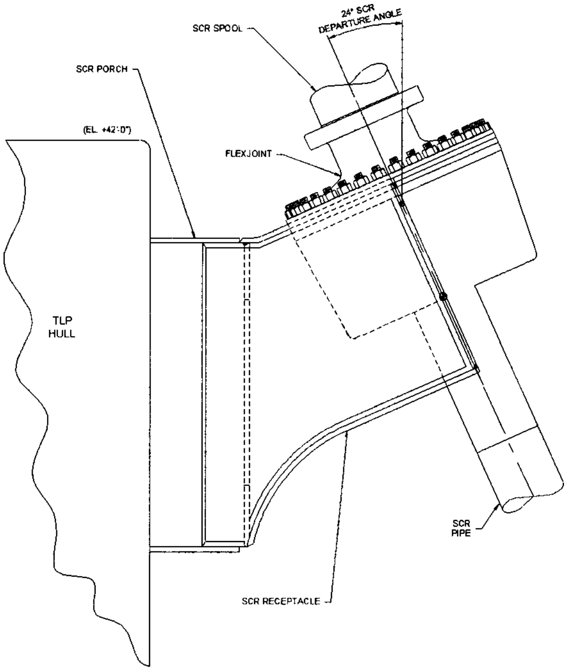

**Fig. 2 Flexjoint attachment to the TLP hull for the Prince project**

## Design Requirements

**Wall Thickness and Configuration.** The first step in every pipeline and riser design is to determine the minimum wall thick-

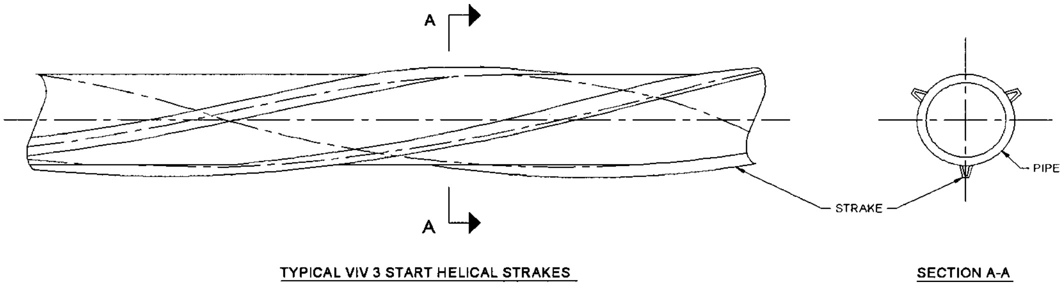

**Fig. 3 Typical VIV strakes for SCRs**

ness required to withstand external and internal pressure according to applicable codes. However, in most SCR design cases, the wall thickness value is governed by fatigue life, wave actions, and platform dynamics [2]. Corrosion allowance is typically added to the overall wall thickness.

At this stage of the design, sensitivity analyses to optimize SCR configuration, including length and departure angle, should be performed. Determination of the most suitable top connection type (flexjoint, stress tapered joint, etc.) to the floating support structure should also be decided at this stage.

The sensitivity analysis should include the SCRs with different positions of the floating support structure. The most common positions for the floating support structure, which are shown in Fig. 1, include:

- Zero mean offset position: The floating structure is in its initial position without displacement in any direction.
- Far offset position: The structure is displaced in the plane of the SCR away from the SCR touchdown area causing the departure angle to increase with a shorter section of the SCR laying on the seabed.
- Near offset position: The structure is displaced in the plane of the SCR towards the SCR touchdown area causing the departure angle to decrease with a longer section of the SCR laying on the seabed.
- Cross offset position: The structure is displaced out of the plane of the SCR with the structure in the in-plane zero mean offset position. It is not expected that the cross-offset position will change the departure angle. It is mainly considered to determine the SCR lateral forces on the receptacle and porch and to investigate if there is any clashing and interference with other risers in some cases. Rotational and twisting effects may also be considered.

It is expected that a preliminary VIV analysis should also be performed at this stage of the design to determine the need for VIV suppression devices such as helical strakes, which are commonly used for SCRs.

**Static Analysis.** Static analysis with the correct SCR material and configuration parameters should be performed to verify that the stresses at the most critical areas are within the allowable limits specified by the applicable loads such as API RP 2RD [5]. It should be noted that the SCR dynamic stresses and forces due to wave action and platform motions are always higher than those produced by the static analysis. Thus, some allowance in the range of 15 to 35 percent for dynamic amplification should be incorporated in the static result comparisons. The aforementioned percentages depend upon the cases investigated, and the amount of the dynamic amplification expected from the wave action and the associated platform motions. Static analysis should cover cases mentioned in the previous section that relate to the floating structure position with respect to the direction of waves, winds, and currents.

**Dynamic Analysis.** Unlike risers connected to fixed platforms, SCRs suspended from floating support structures have to sustain amplification to static forces and stresses imposed by dynamic motions of the floating structures caused by waves, winds, and currents. The dynamic motion of a floating support structure is a combination of first-order response at the wave frequencies and second-order nonlinear response at the sum and difference wave frequencies, and at the structure natural frequencies. The slow-drift (low-frequency) response at a very long period or high-frequency response at a short period compared to the natural period of the floating structure are examples of the nonlinear behavior of floating compliant structures. The dynamic response of floating structures is usually presented by response amplitude operators (RAOs) in all applicable wave directions.

The behavior of the SCRs is nonlinear in nature. Thus, a time domain simulation is better suited than frequency domain analysis to capture possible nonlinear effects associated with wave forces and structural motions.

Because of available software limitations and their boundary condition capability, dynamic analysis is usually performed by applying waves and RAOs at the floating structure displaced position that is associated with the environmental condition under consideration. The displaced positions of the floating structure mainly encompass the surge offset displacement, the associated heave displacement (e.g., setdown for TLPs) and pitch rotation in the SCR plane. The maximum surge offset typically consists of the quasi-static offset due to current plus slow-drift offset (second-order motion) and the first-order wave offset. The dynamic analysis is performed with the floating structure displaced by the amount of the current and drift mean offsets. The first-order offset will be accounted for in the response results of the applied wave and RAO motions.

Time histories of dynamic simulations are statistically interpreted to determine the possible extreme response values based on selected probability of exceedance value during the life of the SCRs.

**Fatigue Analysis.** Fatigue-related aspects are attributed to the contribution of random sea state waves and vortex-induced vibration (VIV). The former is the result of direct wave action and floating vessel motion. The latter is caused by the effect of currents, particularly loop currents and eddy formations in the Gulf of Mexico. There are other contributors to fatigue damage such as vessel VIV, as in the case of Spars, and functional loads such as slugging [6].

The two major SCR areas where fatigue damage should be assessed are the lower or touchdown section and the top section close to the top connection. Fatigue damage input from all sources should be added along the SCR length.

Random sea state wave fatigue is based on a series of one-half to 1-h dynamic simulations of sea states from a scatter wave diagram that also includes sea states annual probability of occurrence. The wave sea states in the scatter diagram can be grouped in blocks to reduce the computation time and effort [6]. Rainflow counting technique or any acceptable statistical method is applied to calculate fatigue damage associated with each sea state. Miner's rule should then be used to calculate the overall fatigue damage along the SCR pipe.

The VIV fatigue analysis is mainly based on the effect of loop currents. Scatter diagrams for loop currents are usually developed from the site metocean data. In most Gulf of Mexico SCR designs, VIV strakes are added to the top 90 m (300 ft) to 215 m (700 ft) section of the SCR pipe. Longer sections with strakes may be feasible where loop currents are stronger along deeper water columns. VIV strake effectiveness is about 85 percent or more in suppressing VIV. Therefore, the mix-layer current in the top 100 m (300 ft) of water that accompanies waves will have little or no effect on SCR fatigue, and VIV will be suppressed effectively by the strakes.

The magnitude and frequency of fluctuating lift force caused by VIV is dependent on the component of flow perpendicular to the SCR pipe. The fatigue damage due to VIV increases with increasing perpendicular flow velocity. For currents perpendicular to the plane of the SCR, the current velocity is always perpendicular to the pipe. For currents parallel to the SCR plane, the velocity component perpendicular to the pipe is equal to the current speed multiplied by the cosine of the SCR slope from vertical. Close to the seabed, where the SCR is nearly horizontal, the perpendicular component of the flow is substantially less than the full speed, resulting in reduced VIV and fatigue damage. Therefore, it would be conservative to assume that all currents are perpendicular to the SCR plane.

The VIV analysis of SCRs is typically performed using the SHEAR7 Program [7]. SCR's natural frequencies and corresponding mode shapes are obtained from a finite element program. The mode shape curvatures are then calculated numerically from the normalized mode shapes [8]. Risers in SHEAR7 Program are usually modeled as a straight beam with length equal to that of the suspended riser. Modeling of the SCRs in this manner has previously been shown to give accurate results, particularly for higher modes of vibration [8,9].

The calculation of the random sea state and VIV fatigue damage is based on one of the $S$-$N$ curves as specified in a variety of design codes such as API RP 2A [10]. Fatigue life is calculated as the reciprocal of the maximum fatigue damage rate for each riser.

**Fracture Mechanics Assessment.** Fracture mechanics assessment is becoming a more integral part of the overall SCR design. In almost every SCR project to date, a set of full-scale fatigue tests have been conducted to simulate operational and installation conditions of the SCRs. The acceptance or the rejection of the SCR pipe welds is based on weld acceptance criteria that should be established according to the engineering critical assessment (ECA) procedure. Weld acceptance criteria provide guidelines to either accept or reject flaws that would be detected during the nondestructive examination (NDE) of the welds. A combination of flaw length and height is considered in the flaw evaluation, as well as the position of the flaw with respect to the weld profile (surface flaws or subsurface flaws).

## Floating Support Structures

SCRs can be installed on a variety of fixed and floating structures. However, the motions of floating structures significantly influence SCR behavior and fatigue life expectancy. The four main types of the floating structures considered herein are tension leg platforms (TLPs), Spars, semi-submersibles, and tanker-based floating production, storage, and offloading (FPSO) vessels. All other floating structures can be categorized in one of the aforementioned types as far as behavior is concerned.

TLPs and Spars have favorable motion characteristics for SCRs in comparison with semi-submersibles and FPSOs. Since Auger TLP in 1994 to date, SCRs have been installed on several Gulf of Mexico TLPs, and Spar-type structures such as Marlin TLP, Allegheny SeaStar TLP, and Hoover/Diana–DDCV in water depth of 897 m (2950 ft), 1000 m (3290 ft), and 1460 m (4800 ft), respectively. TLPs and Spars have small heave and pitch motions, but the latter is larger for Spars. Surge and sway motions are relatively large and measure approximately 6 to 10 percent of the water depth in extreme conditions. Long-period (low-frequency) surge and sway motions of TLPs and Spars have, however, only benign effects on the SCR behavior.

There are also SCRs installed on the P-18 semi-submersible FPS in the Marlim Field in water depth of 910 m (2985 ft) [3] and on the P-36 semi-submersible FPS in the Roncador Field in water depth of 1340 m (4400 ft) [11]. Both semi-submersibles are operated by Petrobras offshore Brazil. Petrobras pioneered in utilizing a load monitoring system to measure stresses and strains of SCRs on their 10-in. SCR installed on the P-18 semi-submersible in the Marlim Field, offshore Brazil [12].

Although there have been many studies to include SCRs as part of field developments using FPSOs or FSOs, they are still in the design phase. West Africa and offshore Brazil areas with their benign environmental conditions are expected to see the first SCRs installed on permanently moored FPSOs.

Feasibility studies have already been performed to install SCRs on FPSOs for the Barracuda project in water depth of 800 m (2630 ft) and for the Espadarte project in water depth of 1000 m (3290 ft). Both projects are also for Petrobras offshore Brazil.

For weather vaning permanently moored FPSOs where SCRs have to be connected to the turret, this concept has been investigated for several projects such as Girassol for West Africa [13]. Other projects are also considering similar options. Connection types and installation issues in addition to SCR configuration and behavior are still under study.

## Water Depth Limitations

SCRs as the name infers usually have a catenary shape with the largest curvature being at the touchdown area (smallest radius). There are many factors that control the catenary configuration of an SCR. These include the SCR pipe diameter and wall thickness, departure angle, water depth, and the riser content (oil or gas). Stresses in the SCRs must be maintained below certain allowable limits as specified in applicable design codes. These stresses must also have some margin of flexibility to account for dynamic stress amplification caused by the motions of the floating structure, and consequently changing SCR configuration. Changes in stresses also influence fatigue life of the SCRs. Accordingly, SCRs would have lesser restrictions in relation to moving into deeper water. The water depth of 455 m (1490 ft) for the Prince 12-in. oil and gas export SCRs in the Gulf of Mexico represents the shallowest water depth to date. The Morpeth SeaStar TLP 12-in. export SCRs installed in water depth of 510 m (1670 ft) had held the previous record for the shallowest water depth for SCR connected to a floating structure [2]. The Prince SCRs have been designed with a departure angle of 25 deg with $\pm 20$ deg variation to limit stresses in the touchdown area to be below the allowable limits specified by applicable codes.

The SCR water depth limit mainly depends on a combination of parameters:

- Pipe size: The smaller the pipe diameter, the shallower the water depth. The wall thickness requires optimization to satisfy design, curvature and fatigue requirements.
- Departure angle: The feasibility of top connections with large departure angles, particularly with large diameter pipe and the capability of the top joint to handle large angle variations.
- Floating support facility motion behavior: The motion behavior includes all six degrees of freedom (surge, sway, heave, pitch, roll, and yaw).

The importance of the last parameter on SCR touchdown area increases as the SCR moves to shallower water. Having longer SCRs in deeper water, the motion of the floating support structure will be dampened during its propagation through the SCR pipe and the seawater column, and will not be totally felt in the SCR touchdown area. On the contrary, in relatively shallow water, the motion of the floating support structure will have a pronounced interaction with the behavior of the SCR touchdown area. In this regard, soil-structure interaction between the SCR sagbend/touchdown area and the seabed stiffness becomes even more sensitive to the motion of the floating structure. In deeper water, the heave motion of a floating support structure will have less detrimental fatigue effect on the SCRs.

Despite motion and configuration advantages when moving into deeper water, there are also some limitations that have to be considered in the design of the SCRs and the floating support facility. In deep water, the SCR will be longer and require larger wall thickness to withstand the external hydrostatic pressure. This will lead to heavier riser weight that has to be supported by the floating structure. Other issues such as flow assurance and soil-riser interaction could also be important factors to investigate.

To reduce the riser weight on the floating support structure, some innovative concepts have been developed such as integration of flexible and steel pipes for risers [14]. The use of a lazy wave rigid riser for a turret-moored FPSO in harsh environment has also been investigated [15]. It is believed that some type of lazy wave-shaped rigid risers will be used for turret-moored FPSO to reduce the weight supported by the turret.

## Installation Methods

Installation of SCRs is one of the major considerations to achieve a complete and successful design. J-lay has been the leading method for SCR installation. It presents some advantages compared to other installation methods such as S-lay or reel methods. Benefits include imposing the minimum amount of stresses and tensions in the SCR pipe, particularly in the touchdown and top joint sections, and facilitating installation of the VIV strakes without the need to retrofit by divers. The first SCRs on the Auger TLP were installed using the J-lay method [1]. However, the J-lay method may be more expensive than other installation methods, and only few vessels have J-lay capability.

A hybrid installation approach was introduced to mitigate the cost disadvantage of the J-lay method and to satisfy the stress and fatigue design requirements and VIV strake installation if applicable. The Morpeth SeaStar TLP 12-inch export SCRs were installed in 1998 using a combination of S-lay and J-lay methods [2]. The entire export pipeline system including the SCRs was installed using the S-lay method with the exception of the top 160 m (520 ft) section of the SCRs where the VIV strakes were needed. This top 160 m (520 ft) section with strakes was installed using the J-lay method. The Morpeth SCRs are the first to be installed using the S-lay method. Special attention had to be given to the fatigue behavior of the SCRs because of residual stresses and strains that were imposed on the SCR pipe during the S-lay installation.

Petrobras also used a hybrid reel/J-lay method for the installation of the two 10-in. oil and gas export SCRs on the P-36 semi-submersible FPS offshore Brazil in water depth of 1340 m (4400 ft) [11]. The SCR intermediate section between the touchdown section and the top joint section (where fatigue is not critical) and the export pipeline system was installed using the reel-lay method. The J-lay mode of the same installation vessel was used for installation of the SCR's two fatigue critical areas (touchdown and top joint section). More details of this hybrid method are contained in other publications [16,17].

An attempt to install the Marlin SCRs using the S-lay method including the top joint section with strakes attached did not succeed because of damage to the strakes when passing over the rollers of the S-lay vessel stinger. The SCR installation was completed, but without strakes that were retrofitted after the SCRs final installation stage of setting the SCRs in the TLP receptacles. The Prince 12-in. oil and gas SCRs in water depth of 455 m (1490 ft) are the first to be installed entirely using the S-lay method including the sections with strakes. Prior to the decision to install the strakes with the SCRs by the S-lay method, tests were performed to demonstrate the feasibility of strakes passing over the rollers of the S-lay vessel stinger, and withstanding the loads imposed on the strakes without damage. The Prince SCRs were also designed to accomodate residual stresses and strains during installation using the S-lay method.

The installation of SCRs using the reel lay method has been under consideration for some time. However, the SCR concept is relatively new and time has been needed to understand the overall behavior of the SCRs connected to floating structures. As mentioned before, fatigue is a major issue in SCR design, thus having SCRs installed that already plastically strained to about 200 percent of the yield strain is a major concern. To determine the detrimental or maybe the advantageous effects on fatigue life of plastically strained SCR pipes, several joint industry projects (JIPs) have been initiated. So far minimal results have been made public. However, the papers that have been published about the subject to date indicate the feasibility of the reel-lay method for SCRs [18,19]. It is expected that the reel-lay method will be used to install the export pipeline systems including the SCRs for the Nansen and Boomvang Fields in water depth of 1060 m (3500 ft) in the Gulf of Mexico in 2001. The export SCRs for the Nansen Field are two 12-in. oil and gas and for the Boomvang Field are 16-in. oil and 18-in. gas.

## Conclusions

SCRs have become a viable and reliable option for every deepwater field development project. The less expensive, but stronger steel materials utilized for SCRs has in fact started a new era in the oil industry. Oil companies and design engineers are striving to better understand the behavior of SCRs so they can utilize available resources or develop new methodologies if necessary for SCR design, installation and operation.

The design of SCRs must satisfy many static, dynamic and fatigue requirements. Wall thickness is usually controlled by dynamic and fatigue factors. Fracture mechanics assessments to develop weld acceptance criteria have become an integral part of the overall design scope of work.

Significant improvements have been accomplished since the installation of the first SCRs on the Auger TLP in the Gulf of Mexico. S-lay and reel-lay methods have been considered and used for installation of SCRs after conducting full-scale tests to verify the effect of plastically strained pipe with regard to fatigue aspects. SCRs, which, not long ago, were not considered as an option for semi-submersibles and FPSOs, have already been installed on semi-submersibles and are now being designed for FPSOs.

In closing, the development and utilization of steel catenary risers is one of the most significant achievements in the realization of deepwater field development projects.

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