Dynamic Plastic Deformation of Deepwater Steel Catenary Risers Under Extreme Cyclic Compressive Loading

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Summary

Steel catenary risers (SCRs) on a large-heave-motion vessel are susceptible to compression in the riser touchdown zone (TDZ). Dynamic compression can lead to overstress under extreme or abnormal weather conditions. The response of an SCR under compression is highly nonlinear and sensitive to various factors. However, the current available industry design codes and practices do not provide a clear guidance to address the acceptability of compression, overstress, and the resulting plastic strains. In addition, the current analysis method used in industry common practice cannot capture accurately the nonlinear behavior of an SCR involving accumulated plastic deformation, hysteresis effects, and local buckling.

In this paper, a finite-element-analysis modeling method that uses combined beam and solid elements is presented. This method enables simulation of large plastic deformation, pipe ovality, and local pipe buckling in the TDZ of a deepwater SCR. The model is developed with Abaqus (Dassault Systèmes 2009). The SCR nonlinear response is examined through dynamic analysis of a deepwater SCR that is hung from a semisubmersible. The key analysis results are compared with a nonlinear beam-element model. Moreover, dynamic-ratcheting analysis under multiple plastic-strain cycles by use of the proposed solid-riser model is conducted to understand the plastic-strain accumulation and to check the acceptability of the survival response of a deepwater SCR under a series of severe hurricanes in its service life.

This paper presents the methodology for evaluating the compression and plastic deformation that could be experienced by deepwater SCRs, including the modeling approach, analysis results, possible failure modes, and conclusions. The impact of the study findings on the robustness and suitability of SCRs for deepwater application is discussed.

Introduction

Steel catenary risers (SCRs) have been used successfully with a range of floating host facilities and geographical locations, and have been an attractive choice, especially for high-temperature and high-pressure production and exports. The application of SCRs on large-heave-motion vessels presents design challenges because of the severe wave-induced motions and large vessel offsets from wind, current, and drift motions. Under such extreme conditions, SCRs are susceptible to significant compression in the touchdown zone (TDZ), leading to overstress and plastic behavior. Assessment of riser response under compressive loading is required to ensure that SCRs will not fail globally and locally under such conditions.

However, the latest industry design codes and practices do not provide a clear guidance on addressing the acceptability of compression, overstress, and the resulting plastic strains. In addition, the analysis method used in industry common practice cannot accurately capture the local behavior of the riser pipe under such extreme global response because of the limitation of the traditional riser-modeling method. The limitations include

- Pipe local buckling because of a combination of compression, bending, and external pressure from global analysis cannot be checked directly through the analysis. The local-buckling check must be performed separately, with other tools.
- The initial imperfections and defects from pipe manufacturing and installation cannot be taken into account during global analysis. These include ovality, wall-thickness tolerance, and dents.
- Stress and plastic-strain distribution on the riser pipe along the circumferential direction cannot be obtained.
- Large riser plastic strain produced during riser installation (reel-lay, S-lay) cannot be included accurately in the global riser analysis, and thus the accumulated plastic strain can be underestimated.
- Stress and strain concentration because of geometric discontinuities cannot be captured from global analysis. Inaccuracy could be introduced through a separate local model that has inappropriate load and boundary conditions.
- In most of the commercial finite-element-analysis programs, a nonlinear kinematic-hardening-material model cannot be applied to beam elements, but this material model is very important for cyclic-loading analysis.

This paper introduces a finite-element-analysis modeling method that combines beam and solid elements. This model captures geometric, contact, and material nonlinearity to simulate the global riser response with local detailed 3D solid modeling. The methodology presented herein is implemented for a 10-in. production SCR that is hung from a semisubmersible in the deep water of the Gulf of Mexico. The behavior of the SCR TDZ under extreme loading is investigated with az severe-vessel-motion time series. The analysis results obtained by use of this model are verified by the traditional beam-element model, considering nonlinear riser behavior.

In addition, in the service life of an SCR, it is possible that the riser will experience a series of severe hurricanes. Therefore, there is a need to understand and assess SCR behavior under multiple cycles of plastic strain. In this paper, an accumulated plastic-strain analysis under extreme loading conditions with three cycles of severe motions is conducted for the same production SCR.

Steel-Catenary-Riser (SCR) Finite-Element Model

Riser Data. A 10-in. production SCR mounted to a deep-draft semisubmersible in a water depth of 7,500 ft in the Gulf of Mexico is evaluated as an example to illustrate the riser model and analysis methodology. The SCR outer diameter is 10.75 in., with nominal
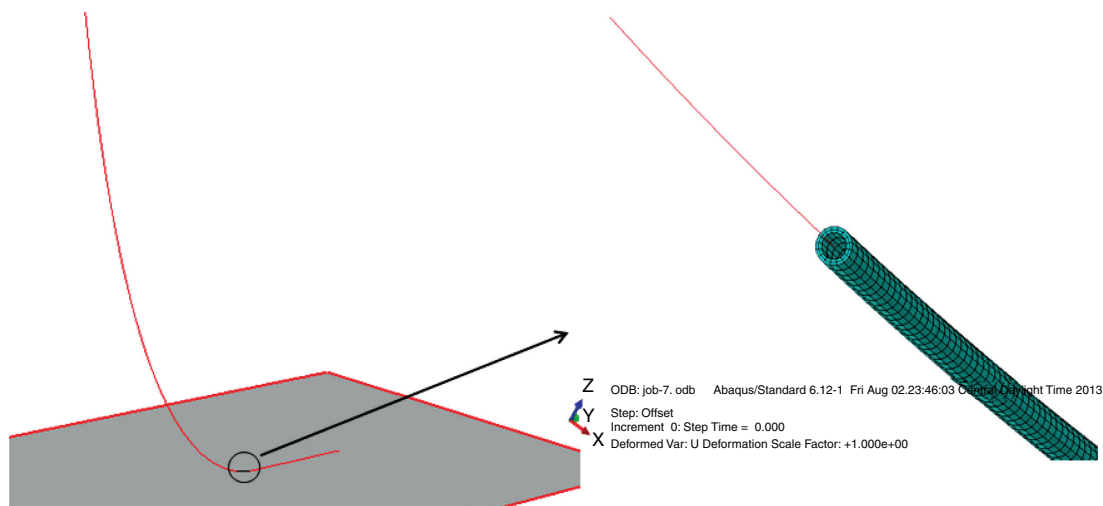
Fig. 1—Beam/solid global SCR finite-element model.

wall thickness of 1.5 in. The riser is fully straked, and the steel pipe is covered by 2.5-in. thermal insulation. A flex joint is used at hang-off, and the hang-off angle is 11.5°. This riser is selected to represent a typical high-pressure production SCR in deep water.

Beam-Element Model. A global model of the SCR is developed in the general-purpose finite-element-analysis package Abaqus (Dassault Systèmes 2009). The assembly is meshed with 2-node hybrid beam elements in space (3D); these have one integration point at the center of the element. A refined mesh (element lengths ≈ 0.5 to 1.0 m) is defined for the critical locations along the length of the riser, including the riser touchdown zone (TDZ) and hang-off regions. The element lengths in other regions along the midsection of the SCR do not exceed a maximum of 10.0 m (32.8 ft). The flex-joint-extension piece is modeled as a series of short beam elements, with constant inner diameter and variable outer diameter to simulate the tapered sections.

The model consists of two parts—the SCR and the seabed. The seabed is modeled as an analytical rigid plane with appropriate soil properties. The interaction of the riser and seabed is simulated through the definition of a contact region between the nodes on the pipe and the analytical plane. The contact between the pipe and seafloor is modeled with a pressure-overclosure relationship.

A fixed boundary condition has been used at the end of the riser on the seabed to represent the interface between riser and flowline.
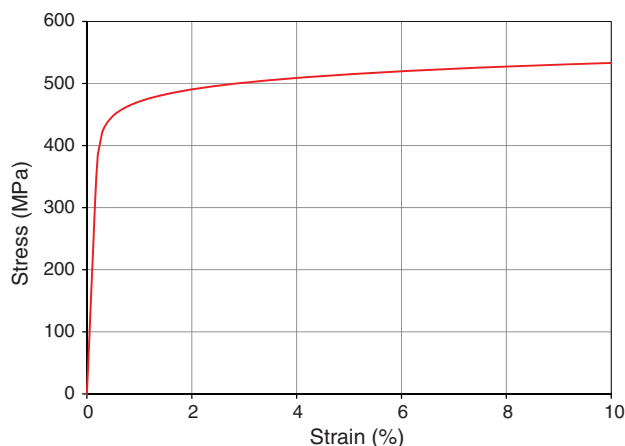
The riser on the seabed is modeled long enough to achieve negligible reaction force at this interface location.

Beam-/Solid-Element Model. To accurately capture the local behavior of the TDZ region during the dynamic analysis, a portion of the beam-element model in the TDZ region is replaced by a detailed model containing 8-node linear solid elements, as shown in **Fig. 1.** The remaining portions of the SCR are still modeled by beam elements to save computational cost. A rigid transition between beam elements and solid elements is assumed. Contact behavior between the solid elements and analytical plane is also modeled to simulate the interaction of the riser and the seabed. The total length of the riser section with solid elements is 75 m. The model contains 9,600 solid elements with 16 element slices distributed equally along the circumference. Two layers of elements are used along the thickness of the pipe wall. The maximum element-length/width aspect ratio is 5.5. The beam-element length adjacent to the solid elements is 1 m. An extensive number of convergence studies have been conducted with several models of different mesh sizes to ensure that the mesh size is sufficient for required accuracy but with acceptable computational cost.

Material Model. A nonlinear material property is considered for the two global models. A Ramberg-Osgood stress/strain relationship for X65 steel is used, as shown in **Fig. 2.** The stress/strain relationship is applied directly into the Abaqus model instead of converting it into a moment/curvature curve. In this way, both axial loads and bending moments will contribute to the nonlinear behavior of the riser. Pipe mass, stiffness, and hydrodynamic properties are also appropriately modeled for the solid-element portion with a 2H Offshore proprietary modeling approach.

Analysis Methodology

Extreme-storm analysis is conducted with the models described in the preceding subsections. Vessel motion is applied directly to the center of gravity of the hosting vessel at 6 degrees of freedom. Pressure effect is not a major concern of this study; therefore, the riser is considered to be in a depressurized condition. Hence, the stress and deformation of the pipe are mainly caused by riser dynamic motion.

Typical Gulf of Mexico environmental data are used in the analysis. A vessel-motion time series, which is equivalent to the conditions of a 100-year hurricane in the Gulf of Mexico (Joint North Sea Wave Project wave, H_s = 14.8 m, T_p = 14.7 seconds, γ = 2.6), is applied, and the mean vessel offset is assumed to be 5% of water depth. A previous study shows the magnitude of compression is highly correlated with axial downward-heave velocity at porch location (Foyt

Fig. 2—Nonlinear stress/strain curve of steel for riser pipe.

Model	Maximum Compression (kN)	Maximum VM Stress (MPa)	Maximum Plastic Strain (%)
Beam	715	458.4	0.17
Solid	718	458.0	0.16

Table 1—Model-comparison summary.

et al. 2007). Therefore, only a 200-second window, which encompasses the maximum axial downward porch velocity of the entire vessel motion, is selected for this study. Collinear currents associated with the seastate are also applied through water depth.

The key outputs from the analysis are stress and strain, as well as forces and deformations at critical riser locations. In this study, the von Mises (VM) stress is used to measure the material stress level and equivalent plastic strain is used to measure the material plastic deformation. The equivalent plastic strain depends on the history of deformation so as to represent the hardening of the material or the plastic work performed on the material. Therefore, it can also be considered as a measurement of the damage.

In Abaqus (Dassault Systèmes 2009), the equivalent plastic strain is defined as

$$\bar{\varepsilon}^{pl} = \int_0^t \dot{\bar{\varepsilon}}^{pl} dt, \quad ....(1)$$

where, for VM plasticity,

$$\dot{\bar{\varepsilon}}^{pl} = \sqrt{\frac{2}{3} \dot{\varepsilon}^{pl} : \dot{\varepsilon}^{pl}} . \quad ....(2)$$

It is clear from Eq. 1 that the equivalent plastic strain is always positive, and keeps increasing over plastic-strain history.

Model Evaluation
The key analysis results for the extreme strength response for the two models are compared in **Table 1.** The results of the solid model match quite well with those of the beam model. The steel catenary riser (SCR) experiences a large compression at the touchdown point (TDP), when the downward porch velocity reaches its peak. The maximum compression is 718 kN. The riser deformation and

the von Mises (VM) stress distribution near the TDP that were obtained at the critical time instant with the solid-element model are shown in **Fig. 3.** It can be observed that the maximum VM stress at the pipe outer surface is beyond yield strength of the pipe steel (448 MPa for X65 steel), and occurs on the compression side of the pipe because of the combination of global bending and compression. Similarly, the maximum equivalent plastic strain can be obtained at the exact same time, and the equivalent-plastic-strain distribution at this instant is shown in **Fig. 4.** The maximum plastic strain is 0.16%, and it occurs on the compression side of the pipe.

It is clear from this model comparison that the two SCR models will generate almost identical riser global response at the critical location. However, some important parameters, such as the stress and strain distribution and local pipe deformation, can only be captured by the solid model. Therefore, for riser pipe experiencing large nonlinearity, the solid-riser model is more appropriate. Further, as discussed in the preceding, initial pipe imperfections such as ovality, nonuniform wall thickness, and dents can also be built into the solid model and evaluated.

Extreme Cyclic Loading
To understand the steel-catenary-riser (SCR) touchdown-zone (TDZ) response under a series of severe hurricanes in its service life, the motion time series used in the preceding analysis is repeated to create a new 600-second time series (the same extreme vessel motion repeats three times). In addition, to obtain a more-pronounced plastic deformation on the riser pipe, the heave motion is intentionally increased by 30% in the cyclic-loading analysis, and this reasonably represents a 1,000-year hurricane in the Gulf of Mexico, which is typically a robustness check case for riser analysis.

On the basis of the previous study (Foyt et al. 2007), the maximum porch heave motion is a reliable indicator to capture the minimum effective tension and maximum stress for a semisubmersible. A recent study by 2H Offshore shows the riser bending stress at the touchdown point (TDP) has a linear relationship with a downward porch velocity along the riser axial direction. Therefore, the combined downward-velocity components from all vessel 6-degree-of-freedom motions along the riser axial direction provide the contribution to riser bending stress at the TDP. For an SCR that is hung from a semisubmersible, the small hang-off angle makes the heave motion the primary contributor to TDP bending stresses.

In this analysis, the same production SCR and stress/strain curve are considered, but the beam-/solid-element model only is used.
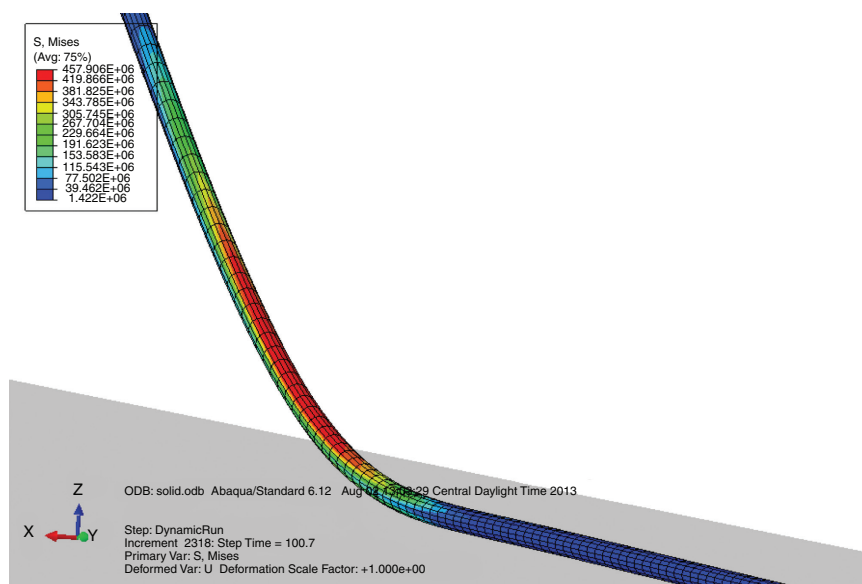

S, Mises
(Avg: 75%)
457.906E+06
419.866E+06
381.825E+06
343.785E+06
305.745E+06
267.704E+06
229.664E+06
191.623E+06
153.583E+06
115.543E+06
77.502E+06
39.462E+06
1.422E+06

ODB: solid.odb Abaqua/Standard 6.12 Aug 02 13:33:29 Central Daylight Time 2013

Step: DynamicRun
Increment 2318: Step Time = 100.7
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +1.000e+00

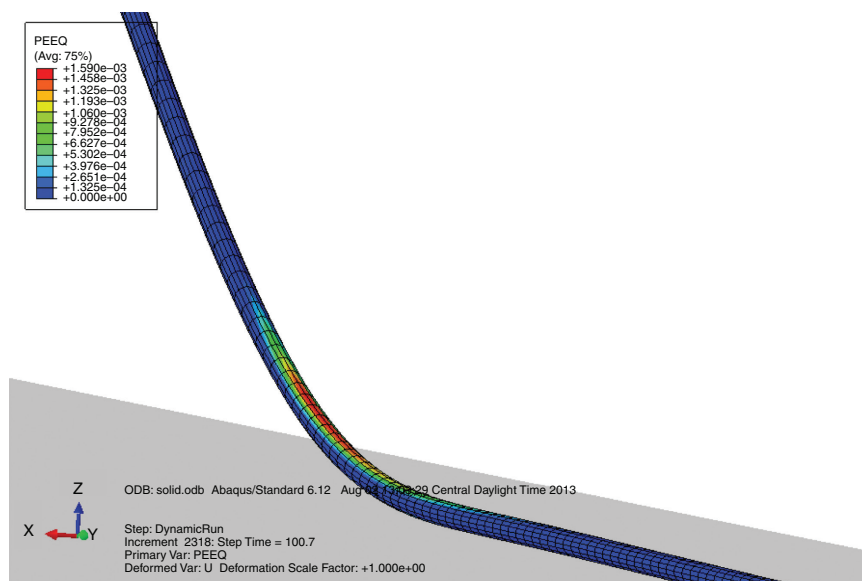Fig. 3—Deformation and VM-stress contour at riser touchdown point (TDP).

Fig. 4—Deformation and equivalent-plastic-strain contour at riser TDZ at riser peak motion.
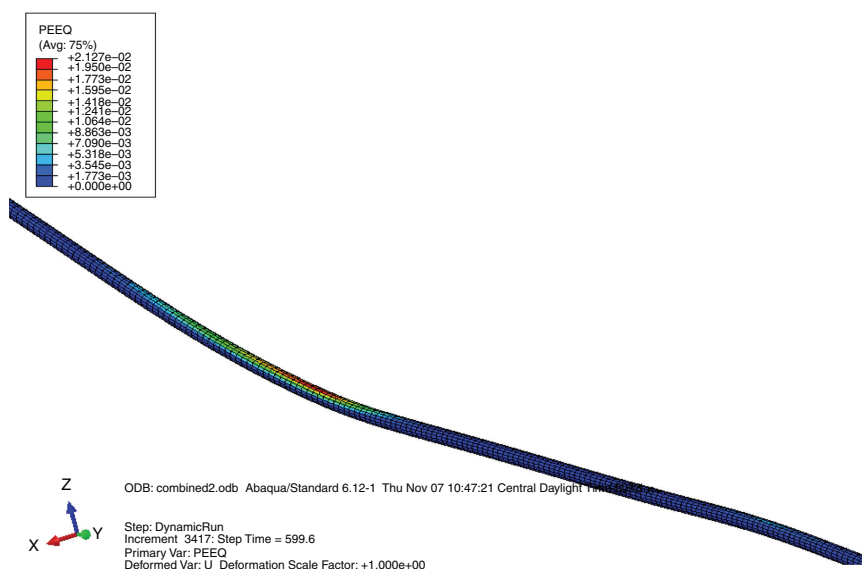

Fig. 5—Deformation and equivalent-plastic-strain contour at riser TDZ after three extreme loading cycles.

Nonlinear isotropic/kinematic hardening is used in the material model for cyclic response.

The key output parameters are extracted from the analysis. The maximum compression occurs during the peak motion in the first cycle. Maximum compression of 975 kN is obtained at the riser TDP. Because the pipe steel goes well beyond the yield strength at the TDP, plastic strain and deformation are of more interest than von Mises stress. The deformation shape and plastic-strain contour of the riser TDZ after the three extreme cycles is shown in **Fig. 5.** It is clear from this figure that noticeable permanent deformation appears in the riser after these plastic cycles. The accumulated equivalent plastic strain is 2.1% at the compression side and 1.3% at the tension side, as shown in **Fig. 6.** From this figure, it is also noted that among the three plastic cycles, the first cycle develops the most plastic strain and the third cycle develops the least.

To further understand the riser-response history during the plastic cycles, the plastic-strain components are extracted. Among these components, the axial strain contributes the most to the riser global dynamic analysis. The axial plastic-strain time series at critical location is shown in **Fig. 7.** It can be noted that for both the compression side and the tension side of the pipe, the maximum axial plastic strain occurs during the first cycle. The magnitude of peak axial plastic strain decreases from the first cycle to the second cycle, and then to the third. The axial-stress hysteresis loops for the critical location at the pipe compression side and the pipe tension side are obtained and shown in **Figs. 8 and 9,** respectively. It can be noted that the peak strain decreases from the first cycle to the third.

Observations from the dynamic-analysis animation show that the curvature of the pipe at the most-critical location displays a sharp angle at the first peak motion. During the second and third peak motions, the curvature becomes smoother. This observation also indicates that the largest bending curvature and stress occur at the first peak during the entire time history. One possible reason for this is that the deformed and yielded pipe spot forms a weak
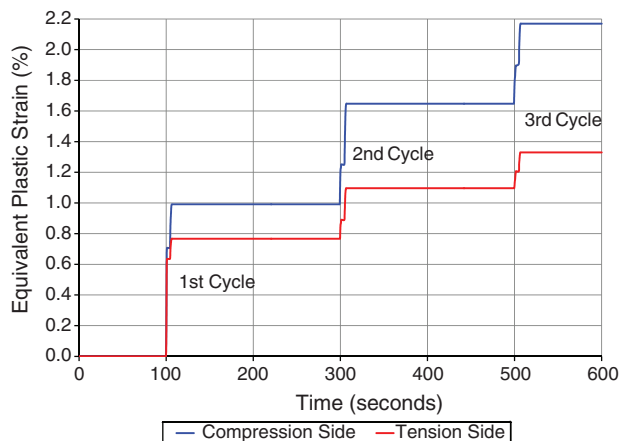
Fig. 6—Time series of accumulated equivalent plastic strain at critical location.
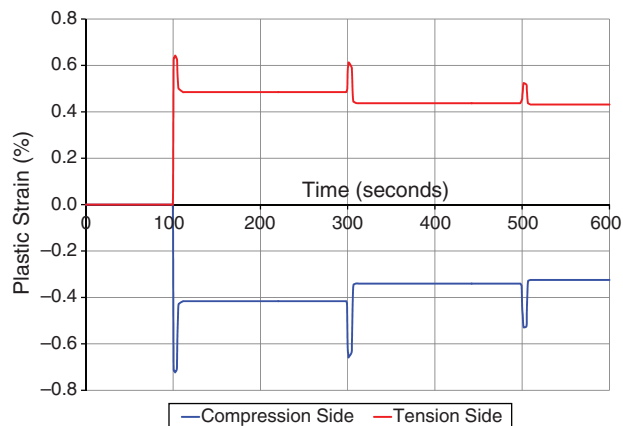

Fig. 7—Time series of axial plastic strain at critical location.
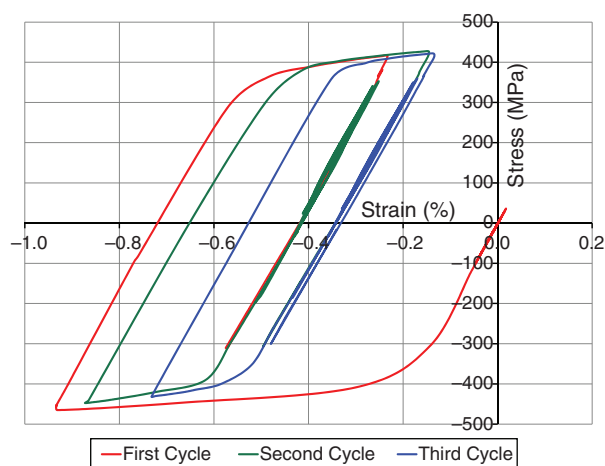

Fig. 8—Stress hysteresis loop for the critical location at the pipe compression side.
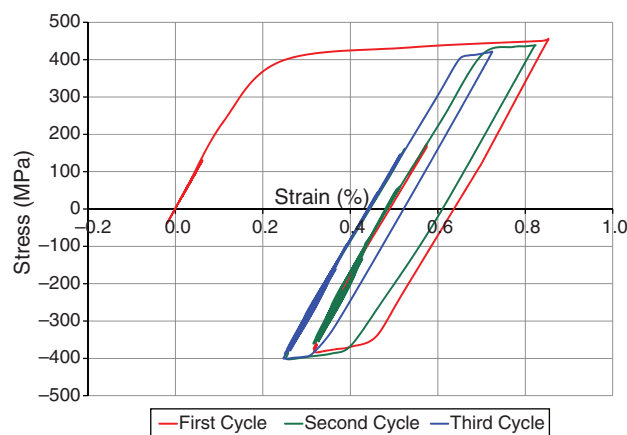

Fig. 9—Stress hysteresis loop for the critical location at the pipe tension side.

link after the first plastic-strain cycle, which prevents it from receiving extreme bending and compression again during the second and third cycles. Instead of accumulating the plastic deformation at one spot, the axial plastic strain spreads out along the pipe length near the critical spot. To prove this hypothesis, a node 6 m away from the most-critical location toward hang-off is selected, and the axial-plastic-strain time series at this node is shown in **Fig. 10.** It is noted that the axial plastic strain increases from the first cycle to the third, which confirms the assumption that the plastic deformation spreads along the pipe length for multiple plastic-strain cycles.

The pipe cross section at the critical location after the first peak motion is shown in **Fig. 11.** It is observed that deformation of the cross section because of the extreme bending is not significant for the thick-walled production riser.

Discussions

For risers under extreme conditions, riser robustness and failure resistance are the major concerns. The analysis carried out in this study provides a new methodology for steel-catenary-riser (SCR) robustness assessment. It is anticipated that some of the SCR failure behavior and modes can be well-studied with further developed models.

One of the possible strength failures of SCRs under extreme conditions is incremental plastic deformation under cyclic loading (ratcheting). The conducted cyclic analysis in this study indicates that the plastic-strain accumulation from multiple cycles will not concentrate on one spot of the pipe; instead, it will spread along the pipe length after the first plastic hinge forms. In the worked example, after three extreme cycles, the maximum equivalent plastic strain reaches approximately 2%. This strain level is typically smaller than the allowable bending strain in the current design codes (*DNV-OS-F101* 2013; *DNV-OS-F201* 2001; *API RP 1111* 2000). Actually, the SCR-installation process can also generate large pipe strain to a similar level (e.g., reel-lay) (*DNV-RP-F108* 2009). Considering that the possibility of more than two extreme cycles in one 3-hour storm is extremely low, it seems the probability of production-SCR failure under such extreme cyclic plastic loading is not likely to be high.

Local buckling and collapse because of combined bending and compression form another possible failure mode for an SCR at the touchdown zone. Although thick-walled production risers are not generally susceptible to this failure mode, it is still a concern for SCRs with high *D/t* ratio, such as a deepwater export riser. The proposed finite-element-analysis model in this study is capable of capturing this riser-failure mode. Further study with this modeling technique will be carried out to understand this failure mode, and the results will be compared with the industry design codes.

Another possible failure mode of an SCR is ductile fracture under large tensile strain. Previous studies show the pipe fracture can occur at relatively low strain level if there are initial defects or cracks in the pipe and if other factors such as high internal pressure and undermatched welds come into play (Pipeline Research Council
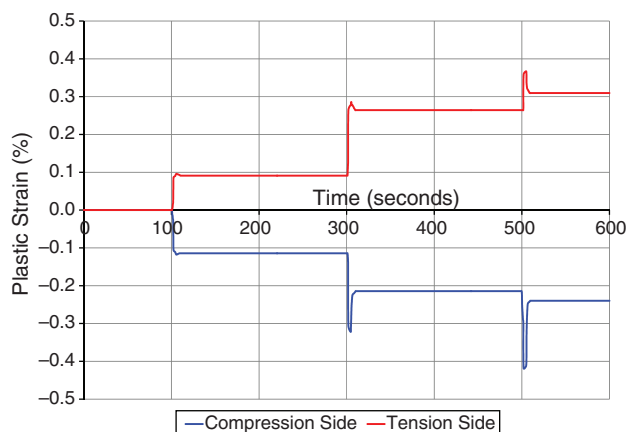
Fig. 10—Time series of axial plastic strain at 6 m away from critical location.

International 2011a, b). Undermatched welds can result in strain concentration at the weld. The effects of pressure are manifested by means of crack-face pressure effects and because the biaxial stress field caused by the pressure will reduce the fracture capacity (Cerkovnik and Akhtar 2013). While strains caused by reeling installation may reach 2% or more, those risers are designed to be reeled, and special weld qualification is required to ensure that the strains will not result in excessive damage. Moreover, installation strains are seen only at the beginning of life, before deterioration from corrosion and fatigue loading has occurred. If a riser design includes the possibility of strains above yield, then the tolerance of the riser to the loads should be investigated and sufficient testing should be performed to qualify it for strains.

While this type of problem is very complicated typically, some of these complicated behaviors can be well-simulated with the developed finite-element model. With the predicted time history of the extreme tensile strain, the fracture acceptability can be assessed with a Level 3 engineering-critical-assessment fracture-mechanics check (*BS 7910* 2005).

Conclusions

This paper proposes a new modeling methodology for assessing the behavior of deepwater steel catenary risers (SCRs) under extreme compressive loading. From the conducted analysis, the following conclusions can be drawn:

- The proposed SCR model containing solid elements can be used to simulate the SCR global behavior, and the key results agree well with those obtained from the traditional beam model.
- The limitations of the traditional beam model, such as pipe local deformation, pipe-to-seabed contact, stress and strain distribution along the pipe circumferential direction, and pipe cross-sectional behavior, can be overcome with the new model.
- If the yield limit is exceeded, the pipe steel will accumulate plastic strain for multiple extreme-motion cycles, and the riser will display permanent deformation after the cycles.
- The plastic-strain accumulation from repeated plastic cycles does not concentrate on the same riser spot; instead, it spreads along the riser length near the critical location.
- The probability of production-SCR failure at the touchdown zone because of multiple extreme-motion cycles is not likely to be high.

The proposed analysis model and methodology provide a high level of confidence for SCR behavior under extreme loading and cyclic loading. It is recommended that the proposed nonlinear riser model be developed further and applied to SCR design and analysis.

Nomenclature

D = diameter
H_s = significant wave height
t = pipe wall thickness
T_p = peak wave period
γ = peakedness parameter
$\dot{\varepsilon}^{pl}$ = plastic strain component
$\overline{\varepsilon}^{pl}$ = equivalent plastic strain
$\dot{\overline{\varepsilon}}^{pl}$ = equivalent plastic strain rate
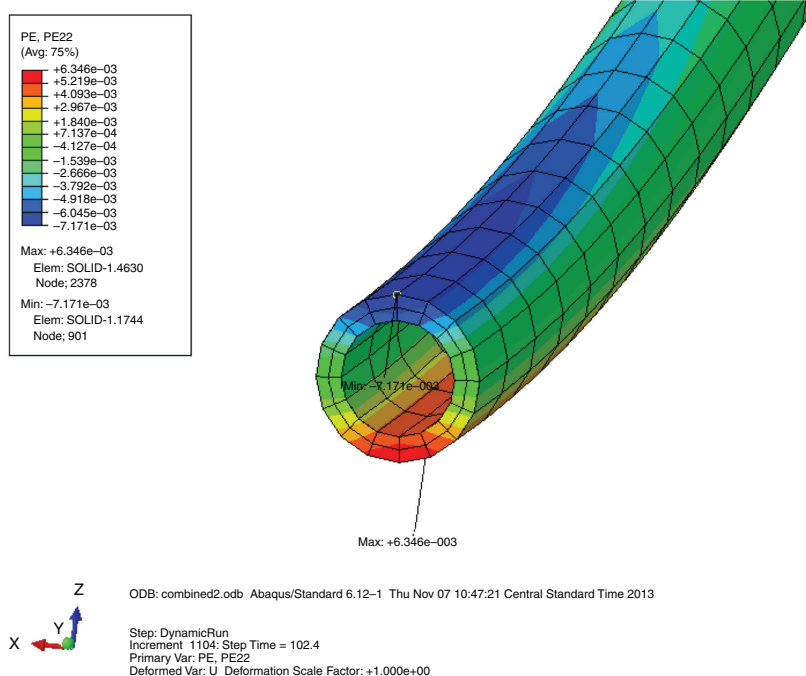

Fig. 11—Pipe cross-sectional shape at largest axial strain.

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