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Static Strength Analysis of a Top-Tensioned Riser in the Gendalo–Gehem Oil and Gas Field

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Abstract

A Top-Tensioned Riser (TTR) is a key structural component that connects subsea facilities to floating production platforms and plays an essential role in ensuring production continuity in deepwater oil and gas exploitation systems. To maintain structural integrity, a TTR must satisfy the design requirements specified in API ST 2RD, particularly with respect to its ability to withstand hydrostatic pressure, internal fluid pressure, ocean current loads, and axial forces generated by top tension. This study aims to analyze the static strength of a TTR under deepwater conditions in the Gendalo–Gehem Field using a numerical approach based on the finite element method. The environmental loads considered include hydrostatic pressure at a water depth of 1,823 m, internal operating pressure, and hydrodynamic forces induced by ocean currents. The riser model was analyzed to determine stress distribution, deformation, and safety performance, which were then evaluated against the allowable stress limits defined in API ST 2RD. The analysis results indicate that the TTR exhibits a stable structural response, with the maximum stress remaining below the material yield strength. Although the maximum stress approaches the operational stress limit under conservative loading conditions, the riser still satisfies the ultimate limit state requirement. This study provides a preliminary basis for evaluating the feasibility of TTR design for deepwater operations in Indonesia and may serve as a reference for vertical riser design in floating production facilities.

Keywords: Riser; hydrostatic pressure; stress; structure; regulation

1. INTRODUCTION

The development of deepwater oil and gas production systems requires reliable vertical connection structures capable of maintaining integrity under complex environmental and operational loads. A Top-Tensioned Riser (TTR) is one of the main riser systems used to connect subsea wells or seabed facilities to floating production platforms. In deepwater environments, the riser must resist hydrostatic pressure, internal fluid pressure, ocean current loading, axial tension, and bending effects without exceeding allowable design limits.

The design of risers for floating production systems is commonly guided by API RP 2RD, which provides recommended practices for risers used in floating production systems and tension-leg platforms [1]. In addition to strength requirements, offshore riser systems must also consider fatigue, long-term cyclic loading, and environmental load variations, as discussed in offshore fatigue design standards and fatigue analysis theories [2], [3]. For deepwater applications, risers are exposed to current-induced vibration, irregular waves, and hydrodynamic loading, which may significantly affect long-term structural performance [4]–[9].

Previous studies have shown that fatigue and dynamic response are important in riser assessment. Cai et al. [4] investigated fatigue behavior of unbonded flexible risers under combined wind, wave, and current effects. Li et al. [6] analyzed the dynamic and fatigue characteristics of deep-sea mining risers under irregular waves and currents. Other studies also emphasized the influence of wave-induced vibration, vortex-induced vibration, and strain monitoring on fatigue life prediction of riser-related offshore structures [7], [8], [10]. These studies indicate that riser reliability should not be evaluated only from a static perspective, especially for long-term deepwater operation.

However, static strength analysis remains an essential initial stage before dynamic and fatigue assessments are carried out. Static analysis provides a basic understanding of whether the riser can withstand primary operational loads such as hydrostatic pressure, internal pressure, top tension, and current-induced lateral force. Therefore, this study focuses on the static strength evaluation of a Top-Tensioned Riser in the Gendalo–Gehem deepwater oil and gas field. The analysis is performed using the finite element method, and the structural response is evaluated based on deformation, equivalent stress, and strain distribution with reference to API RP 2RD.

2. METHODS

2.1 Study Area

The Gendalo–Gehem Field is one of Indonesia's deepwater oil and gas fields located in the Rapak and Ganal Blocks, offshore East Kalimantan. The field is situated at approximately 0.4638° S latitude and 118.1277° E longitude based on the WGS 84 coordinate system. This area is characterized by deepwater conditions, with a water depth of approximately 1,823 m. Such environmental conditions make the field relevant for evaluating the structural behavior of a Top-Tensioned Riser under high external pressure and offshore environmental loading. The environmental characteristics of the study area were identified using oceanographic and meteorological data, including water depth, ocean current velocity, wave period, significant wave height, and surface wind speed. Figure 1 shows the spatial condition of wave and current distribution around the Gendalo–Gehem oil and gas field. This figure provides a general representation of the marine environment surrounding the study location and supports the selection of environmental parameters used in the riser analysis.

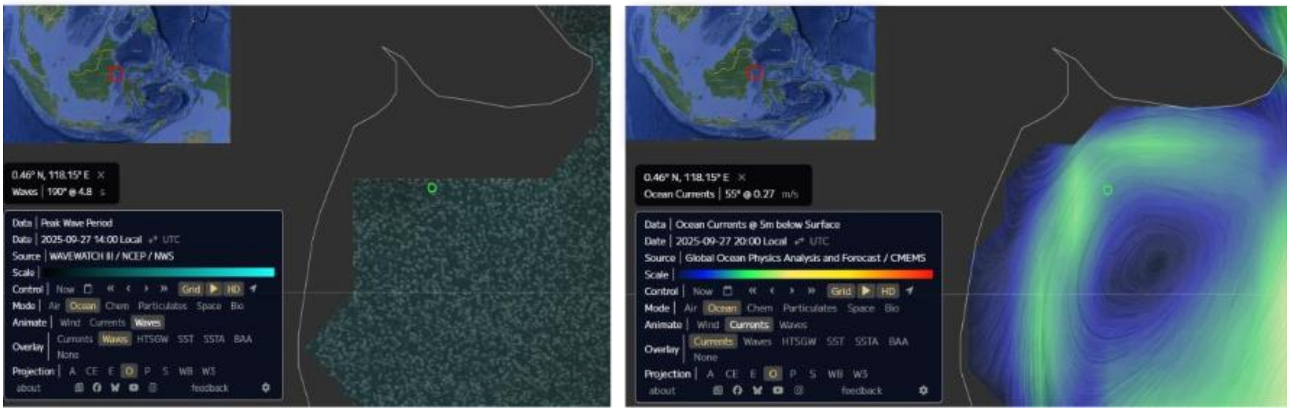

Figure 1. Wave and current condition map of the Gendalo–Gehem oil and gas field

Based on the environmental condition shown in Figure 1 and supported by secondary oceanographic data, the main environmental parameters used in this study are summarized in Table 1. These parameters were then used as the basis for estimating the hydrostatic pressure and hydrodynamic loads acting on the riser. Water depth was used to calculate hydrostatic pressure, while current velocity, wave period, significant wave height, and wind speed were used to represent the offshore environmental loading condition.

Table 1. Environmental conditions of the Gendalo–Gehem oil and gas field

Parameter	Observed Value	Data Source
Water depth	1,823 m	NES-FIRCROFT
Ocean current velocity	0.5 m/s	Global Ocean Physics Analysis and Forecast, CMEMS
Peak wave period	4.8 s	WAVEWATCH III, NCEP/NWS
Estimated significant wave height	2.5 m	INA-WAVE, BMKG
Surface wind speed	2.4 m/s	GFS/NCEP, Earth Nullschool

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The data in Table 1 indicate that the riser is subjected to a combination of high hydrostatic pressure and current-induced hydrodynamic loading. Therefore, these environmental parameters are essential inputs for the subsequent hydrodynamic load estimation and finite element analysis conducted in this study.

2.2 Top-Tensioned Riser Design Data

The Top-Tensioned Riser used in this study was modeled as a vertical cylindrical steel pipe designed for deepwater operation. The riser dimensions and material properties were selected based on typical deepwater riser design parameters and the design philosophy of API RP 2RD [1]. The selected material was API 5L Grade X65 steel pipe because this material is commonly used for offshore pipeline and riser applications due to its high strength and suitability for pressure-containing structures.

The main geometric and mechanical properties of the riser are summarized in Table 2. These parameters were used as the primary input for the finite element model, including the riser length, outer diameter, wall thickness, material density, yield strength, and ultimate tensile strength. The riser length was defined based on the water depth of the Gendalo–Gehem Field, while the outer diameter and wall thickness were used to calculate the structural stiffness and pressure resistance of the riser.

Table 2. Top-Tensioned Riser design data

Parameter	Value
Material	API 5L Grade X65 steel pipe
Riser length	1,823 m
Outer diameter, OD	0.45 m
Wall thickness, t	0.03 m
Steel density	7,850 kg/m³
Yield strength	450 MPa
Ultimate tensile strength	535 MPa

The data in Table 2 indicate that the riser has a long slender geometry with sufficient wall thickness to resist the combined effects of hydrostatic pressure, internal pressure, and axial top tension. The yield strength of 450 MPa was used as the main reference for evaluating the maximum equivalent stress obtained from the finite element analysis. Therefore, the structural response of the riser was assessed by comparing the simulated stress with the material strength limit.

In addition to the static material properties listed in Table 2, the material fatigue characteristic is represented by the S–N curve shown in Figure 2. The S–N curve describes the relationship between stress range and the number of loading cycles that the material can withstand before fatigue failure occurs. Although the present study focuses on static strength analysis, the S–N curve is included as supporting material information because deepwater risers are also exposed to cyclic environmental loads during long-term operation.

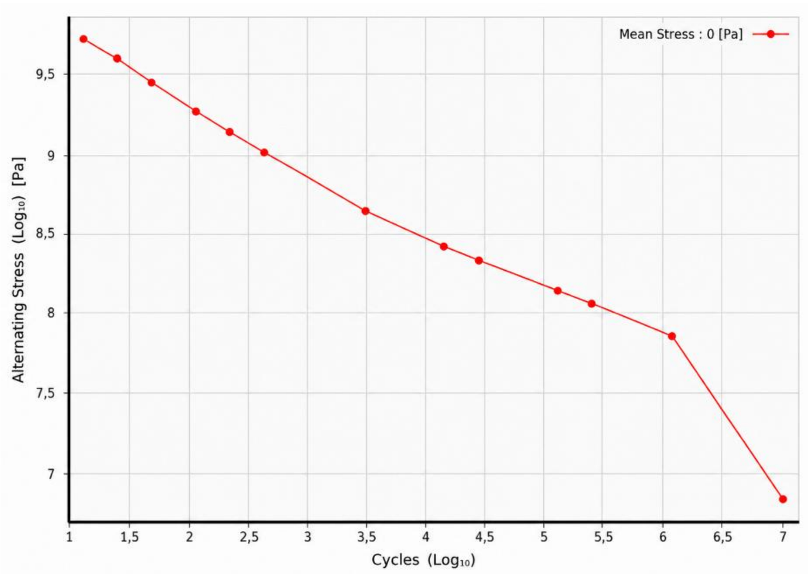

Figure 2. S-N Curve Material

The use of the S–N curve provides a preliminary basis for future fatigue assessment of the riser. In the present static analysis, the main evaluation was conducted using yield strength and equivalent stress. However, for long-term reliability evaluation, the stress response obtained from the static and dynamic analyses can be further related to the S–N curve to estimate fatigue life under repeated wave and current loading.

2.3 Hydrodynamic Load Estimation

The hydrodynamic loading acting on the riser was estimated using the Morison equation. This approach is commonly used to estimate wave- and current-induced loads on slender offshore cylindrical structures. The total hydrodynamic force is expressed as the sum of drag and inertia components:

$$F(t) = F_D + F_I \tag{1}$$

$$F(t) = \frac{1}{2}\rho C_D D \mid u \mid u + \rho C_I \frac{\pi D^2}{4} a_x \tag{2}$$

where $F(t)$is the total hydrodynamic force, $F_D$is the drag force, $F_I$is the inertia force, $\rho$is the seawater density, $C_D$is the drag coefficient, $C_I$is the inertia coefficient, $D$is the riser outer diameter, $u$is the flow velocity, and $a_x$is the fluid acceleration. The estimated hydrodynamic loading was then used as input for numerical simulation. The trial simulation data are presented in Table 3.

Table 3. Trial-and-error CFD simulation data

Trial	Flow Speed, U (m/s)	Pressure, P (MPa)	Total Force, Ft (MPa)
1	0.27	12	17.93
2	0.35	14	30.13
3	0.40	16	39.36
4	0.45	18	49.82
5	0.50	20	61.50
6	0.75	30	138.81
7	1.00	40	246.00

The fluid simulation was used to observe the interaction between the surrounding flow and the riser body. The hydrodynamic force obtained from the Morison equation and CFD simulation was then applied as lateral loading in the finite element model. This staged procedure allowed the theoretical hydrodynamic estimation to be refined before being incorporated into the structural analysis.

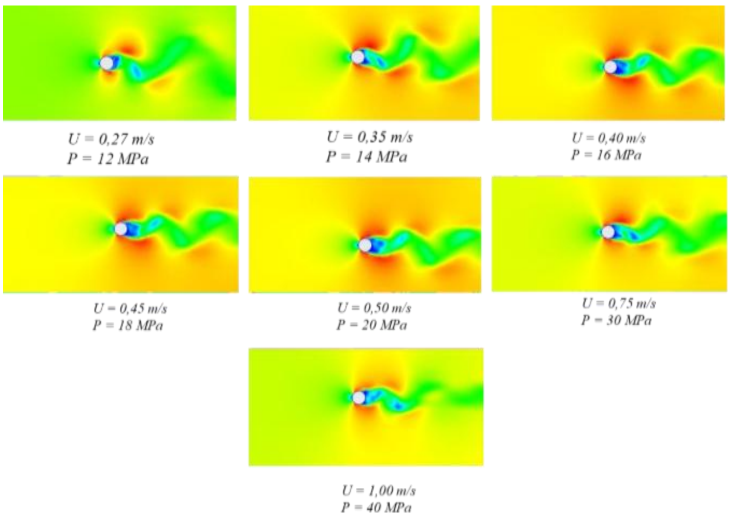

Figure 3. CFD Simulation with Ansys Fluent

2.4 Finite Element Modeling

The structural analysis of the Top-Tensioned Riser was conducted using the Finite Element Method. The riser was modeled as a long vertical cylindrical structure subjected to hydrostatic pressure, internal pressure, current-induced lateral loading, and top tension.

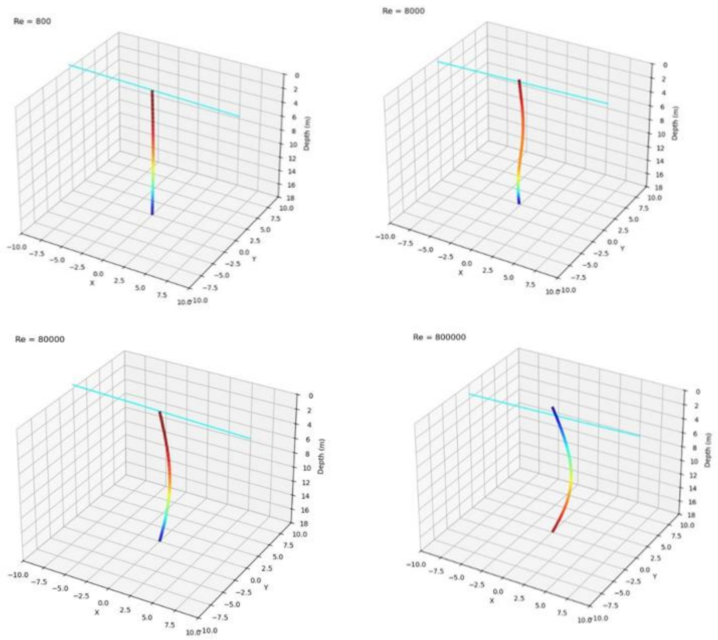

Figure 4. Defleksi Riser akibat beban gelombang dan arus

Top tension was applied as a constant axial tensile force at the upper end of the riser. This force was assumed to be greater than the effective submerged weight of the riser, following the general design approach for top-tensioned riser systems [1]. The application of top tension helps maintain vertical alignment and reduces the risk of axial instability. The upper end of the riser was modeled with rotational freedom but restricted lateral movement due to the tension system. The lower end was assumed to be connected to the subsea wellhead with full translational restraint. The riser joints were modeled as continuous connections without local stiffness variation, so the structural response was assumed to be uniform along the riser length.

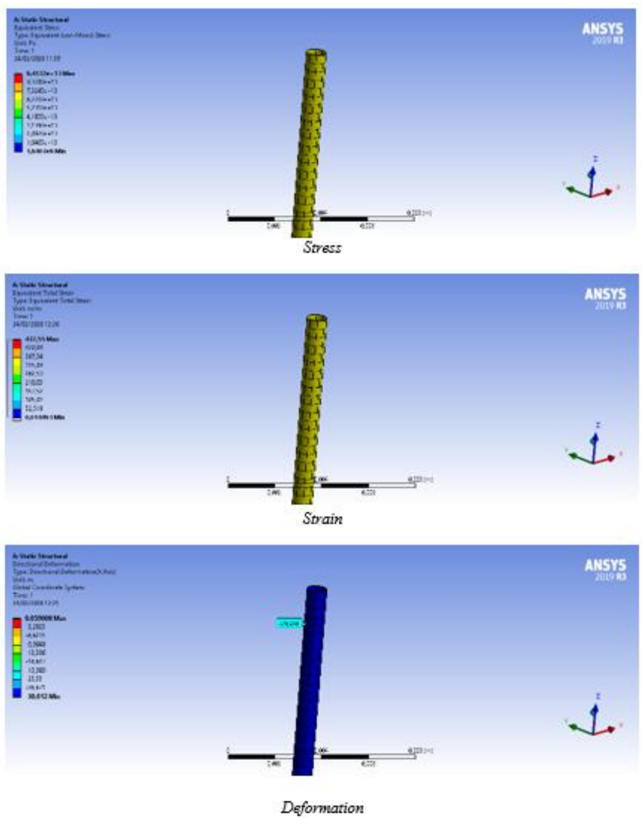

Figure 5. Simulasi FEM dengan Ansys Mechanical

The finite element analysis was used to obtain the distribution of deformation, equivalent stress, and equivalent strain along the riser. The results were then evaluated against the material yield strength and API RP 2RD design philosophy.

Table 4. FEM simulation results

Parameter	Minimum	Maximum	Average
Deformation	0.003 m	0.06 m	0.014 m
Equivalent stress	16 MPa	388 MPa	355 MPa
Equivalent strain	1.90	3.73	2.99

Table 5. Trial-and-error FEM simulation data

Trial	Flow Speed, U (m/s)	Hydrostatic Pressure, Ph (MPa)	Internal Pressure, Pint (MPa)
1	0.27	18.3245	5
2	0.35	18.3245	7
3	0.40	18.3245	9
4	0.45	18.3245	10
5	0.50	18.3245	12
6	0.75	18.3245	18
7	1.00	18.3245	25

3. RESULTS AND DISCUSSION

3.1 Environmental Loading Characteristics of the Gendalo–Gehem Field

The environmental conditions of the Gendalo–Gehem Field indicate that the riser operates in a deepwater environment with a water depth of 1,823 m. This condition produces a high external hydrostatic pressure acting along the riser length. In addition, the presence of ocean current, wave period, significant wave height, and surface wind speed contributes to the environmental loading acting on the riser system.

Based on the field condition data, the hydrostatic pressure used in the FEM simulation was 18.3245 MPa. This value represents the external pressure acting on the riser wall due to the deepwater condition. Although hydrostatic pressure does not directly cause large lateral deformation, it contributes to the external compressive loading on the cylindrical riser structure. Therefore, hydrostatic pressure becomes an important parameter in evaluating the static strength of the Top-Tensioned Riser.

The current velocity used in the baseline environmental condition was 0.5 m/s. This current generates lateral hydrodynamic force on the riser and may cause bending deformation along the water column. Compared with internal pressure and hydrostatic pressure, the effect of current loading is more significant in influencing lateral displacement rather than increasing direct axial or hoop stress.

3.2 Hydrodynamic Load Response Based on Morison Equation and CFD Simulation

The hydrodynamic loading was estimated using the Morison equation, which separates the total hydrodynamic force into drag and inertia components. This approach is suitable for slender cylindrical offshore structures such as risers. The calculated hydrodynamic load was then supported by CFD simulation to observe the interaction between fluid flow and the riser body. The trial simulation results show that the hydrodynamic response increased with flow speed and pressure. At the lowest flow speed of 0.27 m/s and pressure of 12 MPa, the total force was 17.93 MPa. When the flow speed increased to 1.00 m/s and the pressure increased to 40 MPa, the total force reached 246.00 MPa. This result indicates that hydrodynamic loading is strongly affected by flow velocity because the drag component in the Morison equation is proportional to the square of velocity.

The increase in hydrodynamic force also indicates that the riser becomes more vulnerable to lateral loading when exposed to stronger current conditions. However, in the static analysis, the current-induced load mainly affects the lateral deformation pattern rather than becoming the dominant contributor to equivalent stress. This finding is consistent with the general behavior of vertical risers, where current loading primarily produces bending and lateral displacement. The use of CFD simulation provided additional insight into the pressure distribution and flow interaction around the riser. The CFD result was not used as a final structural response but as a supporting step to refine the hydrodynamic load input before it was applied in the finite element model. Therefore, the hydrodynamic analysis served as a bridge between environmental data and structural simulation.

3.3 Finite Element Modeling Response of the Top-Tensioned Riser

The finite element model was developed to evaluate the structural response of the Top-Tensioned Riser under combined hydrostatic pressure, internal pressure, current-induced hydrodynamic load, and top tension. The riser was modeled as a vertical cylindrical steel pipe with API 5L Grade X65 material. The upper end of the riser was subjected to top tension, while the lower end was restrained at the subsea wellhead. The application of top tension plays an important role in maintaining riser stability. By applying axial tensile force at the upper end, the riser is kept in a relatively straight vertical configuration. This condition reduces the possibility of excessive lateral displacement and helps prevent axial instability or buckling. The FEM results show that the riser maintained its global stability under the applied static loading conditions.

The simulation produced three main structural outputs: deformation, equivalent stress, and equivalent strain. These parameters were used to assess whether the riser can satisfy the static strength requirement. The results show that the riser response remained within acceptable structural limits, although the maximum equivalent stress requires careful interpretation because it approaches the operational stress limit.

3.4 Deformation Response

The FEM results show that the riser experienced limited deformation under the simulated static loading conditions. The maximum deformation was 0.06 m, while the total riser length was 1,823 m. The ratio between maximum deformation and riser length is approximately:

$$\frac{0.06}{1823} = 3.29 \times 10^{-5}$$

This very small ratio indicates that the riser maintained its vertical alignment and did not experience excessive lateral displacement. The result also confirms that the top-tension system was effective in controlling the global deformation of the riser. The deformation pattern is expected to be larger around the middle portion of the water column because this region is more affected by distributed current-induced drag force. However, the magnitude of deformation was still very small and did not disturb the overall configuration of the top-tension system. Therefore, from the deformation perspective, the riser can be considered structurally stable under the simulated static loading scenario.

3.5 Equivalent Stress Evaluation

The maximum equivalent stress obtained from the FEM analysis was 388 MPa, while the minimum stress was 16 MPa and the average stress was 355 MPa. The maximum stress was compared with the yield strength of API 5L Grade X65 steel, which is 450 MPa. Since the maximum equivalent stress remains below the material yield strength, the riser satisfies the ultimate strength requirement under the simulated loading condition. However, the maximum stress value is relatively close to the yield strength. If evaluated under normal operational criteria, this stress level may exceed the recommended operational stress limit. Therefore, the maximum loading condition should be interpreted as a conservative or extreme loading scenario rather than a normal continuous operating condition.

The high equivalent stress is mainly influenced by the combined effect of internal pressure, hydrostatic pressure, and axial top tension. Internal pressure contributes directly to hoop stress and axial stress, while hydrostatic pressure provides external compressive action on the riser wall. The current-induced hydrodynamic load contributes mainly to bending stress due to lateral displacement. Therefore, the equivalent stress response is the result of combined pressure, axial, and bending effects. Based on the API RP 2RD design philosophy, a riser must be able to maintain structural integrity under combined pressure, axial, and environmental loading. The present result indicates that the riser can still satisfy the ultimate limit state requirement, but further assessment is required to ensure safe long-term operation.

3.6 Equivalent Strain Response

The equivalent strain result shows that the maximum strain value was 3.73, while the minimum and average values were 1.90 and 2.99, respectively. The strain distribution indicates that the riser response remained within the elastic behavior assumed in the finite element model. No indication of permanent deformation or local plastic failure was observed from the static simulation result. The strain response supports the stress evaluation result. Although the maximum equivalent stress approaches the operational limit, the riser still behaves elastically under the simulated loading condition. This means that the structure can return to its original configuration after the static load is removed, provided that the material remains within the elastic range.

Nevertheless, strain response should not be evaluated only from a static perspective. In real deepwater operation, cyclic strain may occur due to wave action, current variation, vortex-induced vibration, and platform motion. Repeated cyclic strain may lead to fatigue damage even when the static stress remains below the yield strength. Therefore, strain-based monitoring and fatigue evaluation are recommended for further study.

3.7 Sensitivity of Riser Response to Internal Pressure and Current Velocity

The trial FEM data show that the riser response is affected by variations in both internal pressure and current velocity. However, the influence of internal pressure on equivalent stress is more dominant than the influence of current velocity. The increase in internal pressure from 5 MPa to 25 MPa produces a stronger effect on the stress response because internal pressure directly increases hoop and axial stresses in the cylindrical riser wall.

In contrast, the increase in current velocity from 0.27 m/s to 1.00 m/s mainly affects the lateral loading and deformation response. This occurs because current-induced hydrodynamic force acts as a distributed lateral load along the riser. As a result, current velocity has a stronger effect on bending and lateral displacement than on direct pressure-induced stress. This finding indicates that internal pressure should be treated as a critical parameter in static strength evaluation, while current velocity should be carefully considered in deformation, bending, and dynamic response analysis. For deepwater TTR design, both parameters must be evaluated together because their combined effects determine the overall structural safety of the riser.

3.8 Design Implication and Limitation of Static Analysis

The results indicate that the Top-Tensioned Riser in the Gendalo–Gehem Field demonstrates acceptable static structural performance. The maximum deformation is very small relative to the total riser length, and the maximum equivalent stress remains below the material yield strength. Therefore, the riser can be considered safe under the simulated static loading scenario. However, static analysis has several limitations. First, the analysis assumes steady-state loading does not include time-varying wave and current effects. Second, vortex-induced vibration was not directly modeled, although it may significantly affect fatigue life in long slender risers. Third, the analysis does not consider corrosion, material degradation, weld defects, or long-term fatigue damage.

Therefore, the present static analysis should be viewed as an initial design verification stage. Although the riser satisfies the static strength requirement, further investigation is needed to confirm long-term reliability. Future studies should include time-domain dynamic analysis, vortex-induced vibration assessment, fatigue-life evaluation, corrosion allowance, and nonlinear material behavior. These additional analyses are necessary to ensure that the riser is not only safe under static loading but also reliable under actual deepwater operating conditions.

4. CONCLUSION

This study evaluated the static strength of a Top-Tensioned Riser in the Gendalo–Gehem deepwater oil and gas field by considering hydrostatic pressure, internal pressure, current-induced hydrodynamic loading, and top tension. The analysis was conducted using the finite element method, and the results were assessed based on deformation, equivalent stress, and equivalent strain. The results show that the maximum deformation of the riser was 0.06 m, which is very small compared with the total riser length of 1,823 m. This indicates that the riser maintained its vertical alignment and structural stability under the simulated static loading conditions. The maximum equivalent stress reached 388 MPa, which is below the material yield strength of 450 MPa. Therefore, the riser satisfies the ultimate strength requirement based on the API RP 2RD design philosophy.

However, the maximum stress approaches the operational stress limit under conservative loading conditions. This indicates that the analyzed condition should be considered as an extreme loading scenario rather than a normal continuous operating condition. The strain response remained within the elastic range, indicating that no permanent deformation occurred during the static analysis.

Overall, the Top-Tensioned Riser shows acceptable static structural performance for the simulated conditions of the Gendalo–Gehem Field. The combination of top tension, material strength, and applied loading characteristics provides adequate resistance against static failure. Nevertheless, further studies are required to evaluate the long-term reliability of the riser. Dynamic analysis, vortex-induced vibration assessment, fatigue-life evaluation, and corrosion assessment should be conducted to ensure that the riser remains safe under actual deepwater operating conditions.

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