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A Novel Steel Lazy Wave Riser Configuration for Ultra-Deepwater

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Abstract

A steel lazy wave riser (SLWR) configuration combines buoyancy modules with a traditional steel catenary riser (SCR). The buoyancy section at the riser separates the floater's motion and acts as a damper toward the critical area in the touchdown point, improving the strength and fatigue performance. In ultra-deepwater environments, the substantial payload of risers due to extreme riser length imposes considerable tension and stress, challenging the limits of traditional configurations such as SLWR and SCR. The effective tension, maximum stress, and minimum bend radius at ultra-deep depths of these conventional risers would exceed the allowable limits, leading to potential structural failure. To address these limitations, this study proposes a novel riser configuration, the shaped steel lazy wave riser (SSLWR), specifically for ultra-deepwater conditions. By introducing an additional buoy section, SSLWR effectively reduces the effective tension while ensuring allowable stress distribution across the riser length, enhancing structural reliability and operational feasibility over traditional risers. OrcaFlex, a fully 3D non-linear finite element software widely used in maritime structure analysis, was used to simulate the effective tension, maximum stress, and minimum bend radius of the SCR, SLWR, and SSLWR configurations at 3000 m depth. The SSLWR shows a maximum effective tension that is less than half of that observed in the SCR, and it remains consistently lower than SCR and SLWR, suggesting that SSLWR holds promise as a robust alternative for ultra-deepwater applications. This study offers new insights into how modifying riser shape and buoy placement can effectively balance tension reduction with stress distribution, providing an alternative to traditional riser designs. The SSLWR's specific responses to buoy placements and varying currents expand an understanding of riser performance under varying conditions, guiding future advancements in offshore riser engineering.

Keywords: Riser Configuration; Steel Lazy Wave Riser; Ultra-Deepwater.

1. Introduction

An offshore field development is considered a deepwater field if the water depth is 500 m to 1500 m, while an ultra-deepwater field is for field developments with water depths greater than 1500 m [1]. Transporting oil and gas from ultra-deepwater wells to land through submarine pipelines is challenging, with risers being a good alternative. Steel catenary riser (SCR) has been widely applied in oil and gas development for its structural simplicity, reliability, and availability in a large range of diameters [2]. A typical SCR configuration is shown in Figure 1-a. However, it has reduced fatigue life at the touchdown zone; therefore, its application is limited in harsh environments. SLWR is a variation of SCR, with buoyancy modules attached near its touchdown point at the seabed (Figure 1-b). The buoyancy modules help to reduce the payload and improve its strength and fatigue performance [3].

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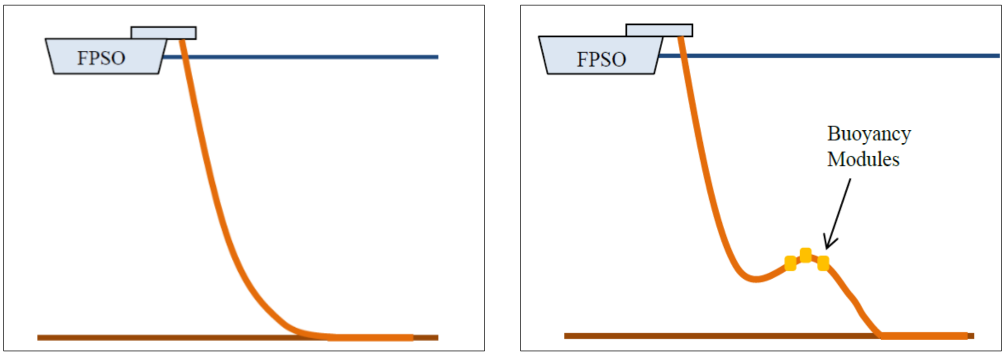

Figure 1. Typical (a) SCR (b) SLWR configurations

The first SLWR was installed in 2008 in Brazil's BC-10 field [4]. Since then, it has become a popular and competitive riser solution for applications in deep water fields. Ruan et al. [5] developed a finite element model based on the rod model to investigate the global dynamic behavior of SLWR. They found that the local maximum effective tension occurs at the riser top and the maximum bending moments at the sag bend, hog bend, and touchdown zones. They also found that as the buoyancy segment moves down along the riser, the maximum bending moment in the sag bend, hog bend, and touchdown zone reduces. Work on riser structural analysis based on numerical methods includes that by Trapper [6], who considered the buoyancy section of an SLWR partially suspended and partially laid on the seabed as a single segment. Roveri et al. [7] developed 6440 geometric configurations of an SLWR and found only six configurations are feasible based on static, dynamic, and fatigue analysis. Cheng et al. [8] compared the top riser departure angle, top tension, and bottom tension experimentally and numerically based on a model scale SLWR, concluding that adjustments in the hydrodynamic coefficient database are necessary to improve the prediction accuracy.

On the effect of buoyancy modules on structural integrity. Oh et al. [9] found that the riser connection and the buoyancy magnitude were the important parameters affecting the SLWR's dynamic behavior. da Silva et al. [10] investigated the possibility of buoyancy reduction for SLWR and its effect on fatigue damage based on structural reliability methods. They analyzed four different buoyancy length ratios and found that buoyancy length could be decreased by 25% while maintaining safety. Cheng et al. [8] investigated the addition of synthetic foam modules to the lower section of an SLWR to reduce the riser payload and to decouple the floater's dynamic motion from the touchdown zone of the riser.

Recent studies have examined the durability and load management of production risers in ultra-deepwater environments. Subsequent advancements in configurations, such as hybrid risers that use advanced buoyancy modules to redistribute load, have resulted in improved fatigue life under extreme environments compared to traditional Steel Catenary Risers (SCRs) and Steel Lazy Wave Risers (SLWRs) [11]. Additionally, buoy optimization enables precise tension and stress modeling, which is essential for safe ultra-deepwater operations [12]. These innovations and refinements in materials, coupled with advanced structural analyses, have improved riser performance to the point where the full service life of structures is 30 years [13]. However, with increasing length, traditional riser configurations such as SCR and SLWR will experience excessive tension and stresses at the hang-off, especially for SCRs. To reduce the strength requirements and improve the fatigue life of risers for ultra-deepwater applications, an alternative configuration, a shaped steel lazy wave riser, is proposed for ultra-deepwater applications, as shown in Figure 2.

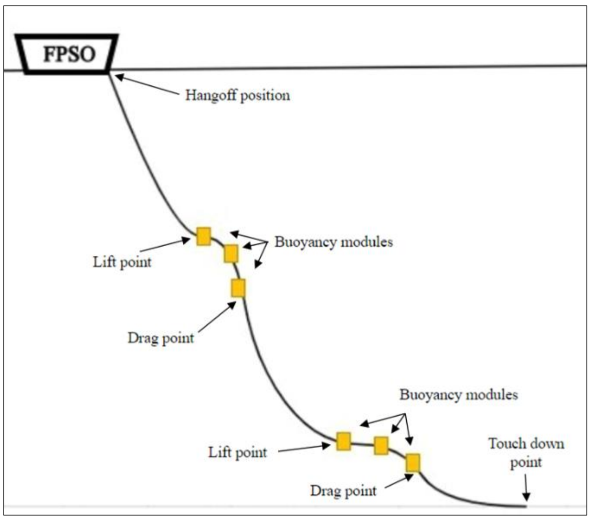

Figure 2. Shaped steel lazy wave riser

2. Research Methodology

In this paper, three riser configurations are simulated at a depth of 3000 meters to verify their feasibility in ultra-deepwater. SSLWR, SCR and SLWR configurations of a 10-inch steel flexible riser with equivalent dimensions and material properties were simulated in OrcaFlex to compare their performance. Table 1 lists the properties of the riser. For the SSLWR configuration, buoyancy modules were added in two sections. Upper buoys with a larger outside diameter are used to support the weight of the riser, and lower buoys with a smaller outside diameter are used to decouple vessel motions at the touchdown position. The detailed properties of the two types of buoys are shown in Table 2.

Table 1. 10" Steel Riser Properties

Quantity	Value	Unit
Riser	10	inch
Outer Diameter	0.356	m
Inner Diameter	0.256	m
Mass per unit length	0.184	te/m
Minimum Yield Stress	448	MPa
Allowable Tension	5000	kN
Minimum Bend Radius	3.675	m
Bending stiffness	124.869	$kN.m^2$

Table 2. Buoy Properties

Quantity	Large buoy	Small buoy	Unit
Outer Diameter	0.77	0.679	m
Inner Diameter	0.248	0.248	m
Mass Per Unit Length	0.12	0.096	te/m

Figure 3 illustrates the research methodology flowchart. Simulations were performed at a depth of 3000 meters, considering ocean currents and seabed interaction with current velocities ranging from 0.5 to 2.0 m/s. The risers were connected to a semi-submersible platform positioned 7° from the vertical, with the ocean current direction varying from 0° to 180°. To prevent excessive stress at the hang-off position, a flexible joint was adopted as a local reinforcement to the riser wall (see Table 3).

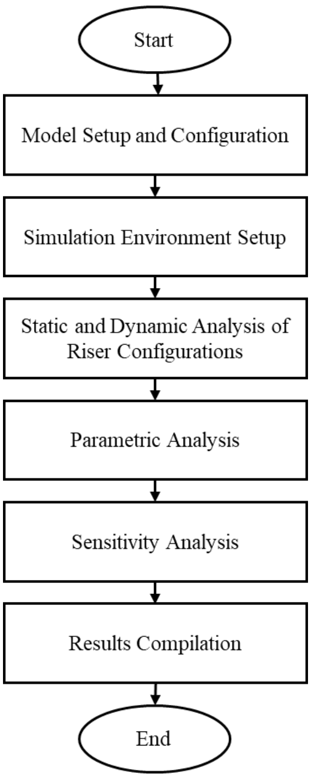

Figure 3. Methodology flowchart

Table 3. Flexible Joint Properties

Quantity	Value	Unit
Diameter	0.305	m
Mass Per Unit Length	0.175	Te/m
Bending stiffness	4.65 × 104	$kN.m^2$
Axial Stiffness	4.73 × 106	kN/m
Poisson Ratio	0.3	-
Added mass coefficient Normal	1	-

Both static and dynamic simulations were conducted to determine the maximum effective tension, von Mises stress, and minimum bend radius across the riser configurations. The simulation outputs were compared against API RP-2RD standards to ensure that the SSLWR meets industry safety and reliability thresholds. A parametric study was performed to determine the optimal placement of the upper buoy module to minimize tension and stress concentrations across the riser. Various buoy positions were tested by moving the upper module closer to or farther from the hang-off point. For each buoy position, the effective tension, maximum von Mises stress, and minimum bend radius were recorded. A comparative analysis focused on how SSLWR's performance metrics differ from SCR and SLWR under identical load conditions. The results were analyzed to determine the factors contributing to SSLWR's improved performance.

3. Numerical Studies

3.1. Model Overview

A numerical simulation (Figure 4) was performed using OrcaFlex, a non-linear finite element software widely used in marine engineering, to determine that the maximum effective tension, maximum stress, and minimum bend radius are within limits specified by API RP-2RD criteria.

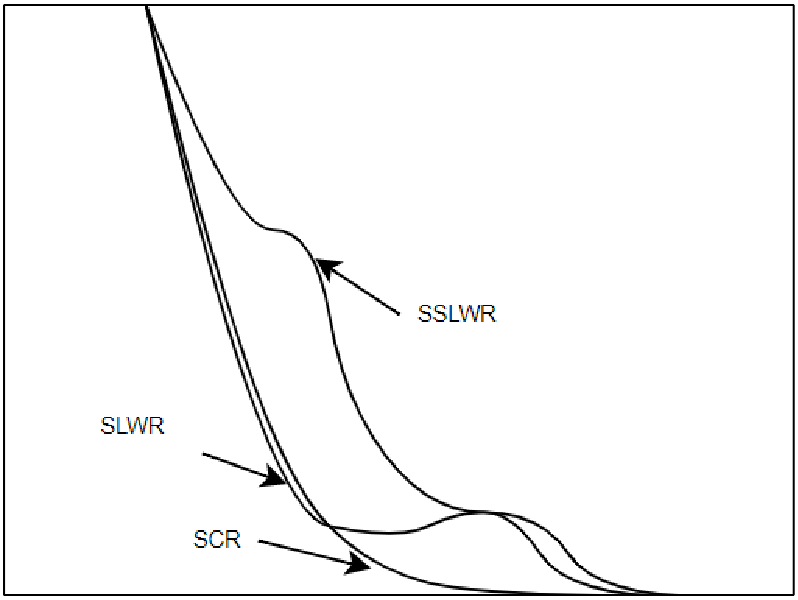

Figure 4. The finite element analysis of SCR, SLWR, and SSLWR in OrcaFlex

Owing to their geometric shape, the SCR, SLWR, and SSLWR connected to a semi-submersible platform have a length of 4585 m, 5102 m, and 5102 m, respectively. The overall configuration of SCR, SLWR, and SSLWR is shown in Figure 5.

3.2. Comparison Between SCR, SLWR, and SSLWR

Figure 6 shows the effective tensions of SCR, SLWR, and SSLWR along the risers, with the maximum effective tension at the hang-off location. The maximum effective tension of SCR is more than twice that of SSLWR. The effective tension of the SSLWR is significantly lower compared to the other two riser configurations, although because of bending, the tension increases sharply at the lift point.

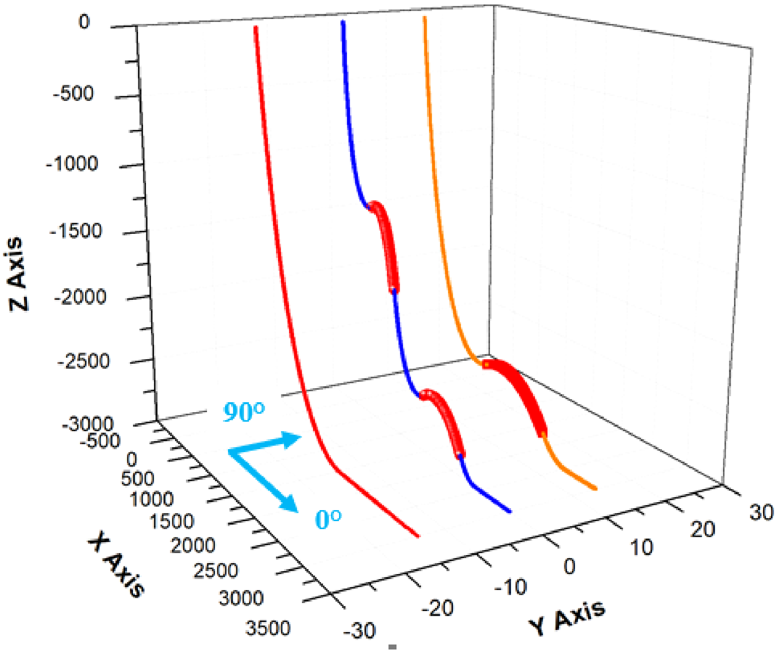

Figure 5. The overall configuration of SCR, SLWR, and SSLWR

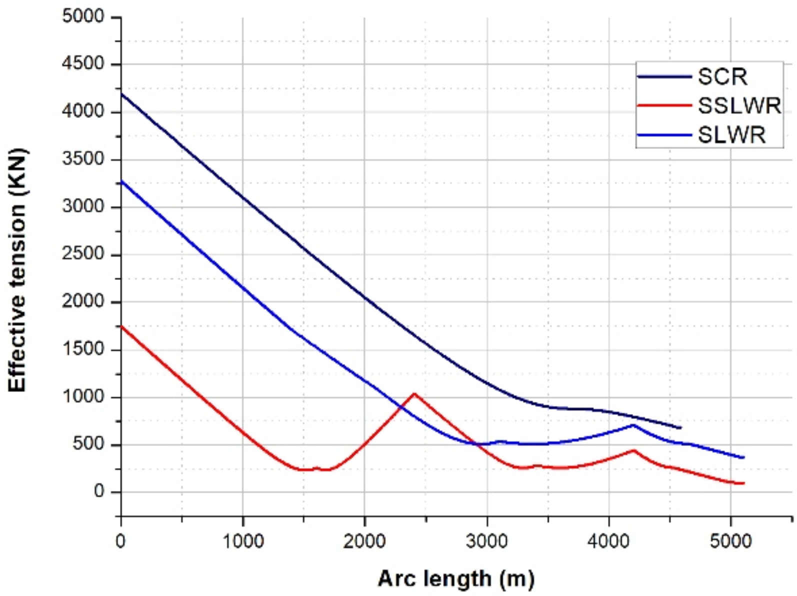

Figure 6. Effective tension of SCR, SLWR, and SSLWR

Figure 7 shows the Max von Mises stresses of the three different riser configurations. In contrast to the stresses of SCR and SLWR, the maximum stress of the SSLWR appears at the lift and drag points due to the large deformation caused by the buoys. Compared to SLWR, the von Mises stress of SSLWR is higher in the buoy sections. The higher stress is inevitable as the additional buoy module results in additional bends, although the effective tension decreases at the hang-off location. Although the stress in SSLWR rises significantly, it is still comparable to that experienced by SCR and much lower than its stress limit, which is 448 MPa.

Overbending is a key factor that must be considered in the design process. In an SSLWR, overbending is more likely to arise because there are two arches along the pipeline. To establish if the minimum bend radius requirement is met, the bend radius was simulated, shown in Figure 8. The results indicate that the bend radius in SSLWR is 175 m, which is much larger than the minimum bend radius limit of 3.75 m.

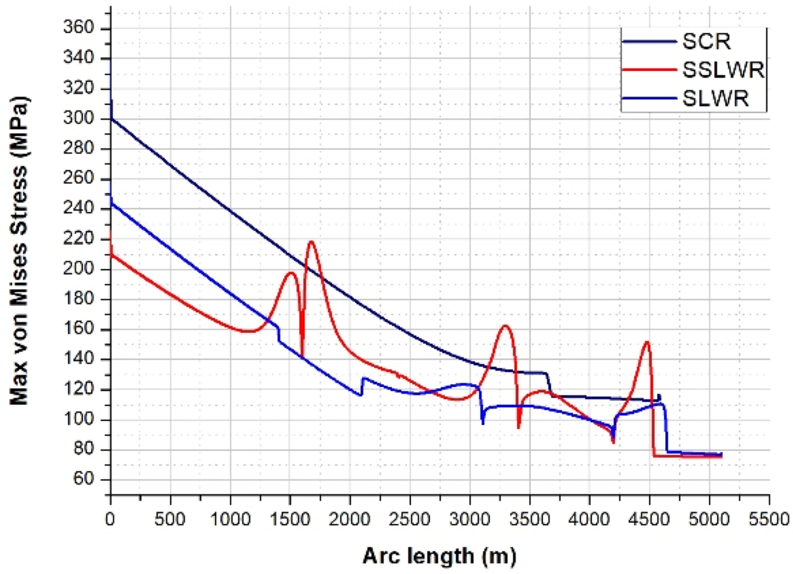

Figure 7. Max von Mises stress of SCR, SLWR, and SSLWR

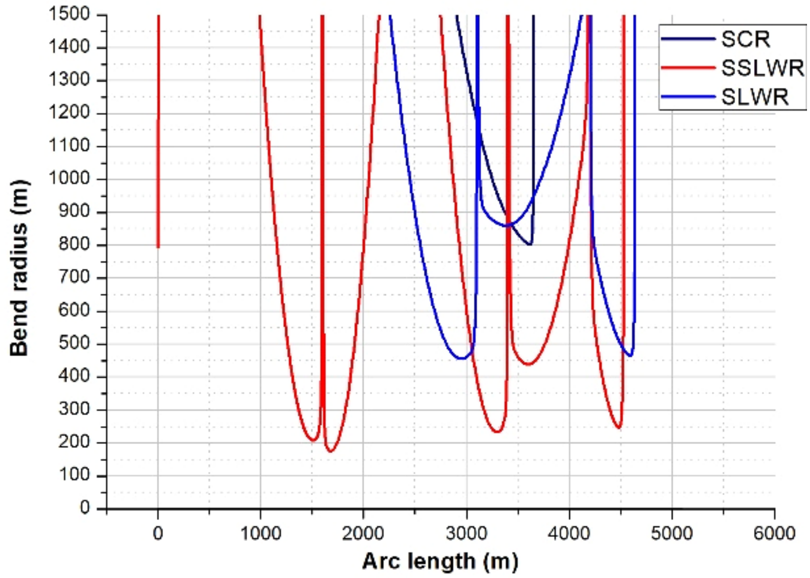

Figure 8. Minimum bend radius of SCR, SLWR, and SSLWR

4. Parametric Study

4.1. Current Velocity

Ocean currents significantly affect the force and stress distribution of risers, especially for risers with a complicated shape such as the SLWRs [14-16]. To further verify the feasibility of SSLWR in ultra-deepwater, it is necessary to simulate its mechanical properties at varying currents. Based on the same SSLWR model, the effective tension and maximum von Mises stresses along the risers were obtained at various currents.

Figure 9 shows the distribution of effective tension along the SSLWR for various current velocities. In general, the current velocity in the South China Sea is less than 2 m/s, so current velocities from 0.5 m/s to 2.0 m/s at the sea surface are considered. The maximum force is at the hang-off position, with the second peak at the lift point. The effective tension increases as the current velocity increases, with the maximum effective tension of 1850 kN occurring at a current velocity of 2.0 m/s. The variation in current velocity does not significantly affect the tension distribution, with the variation in tension more noticeable at the lower section than at the upper section.

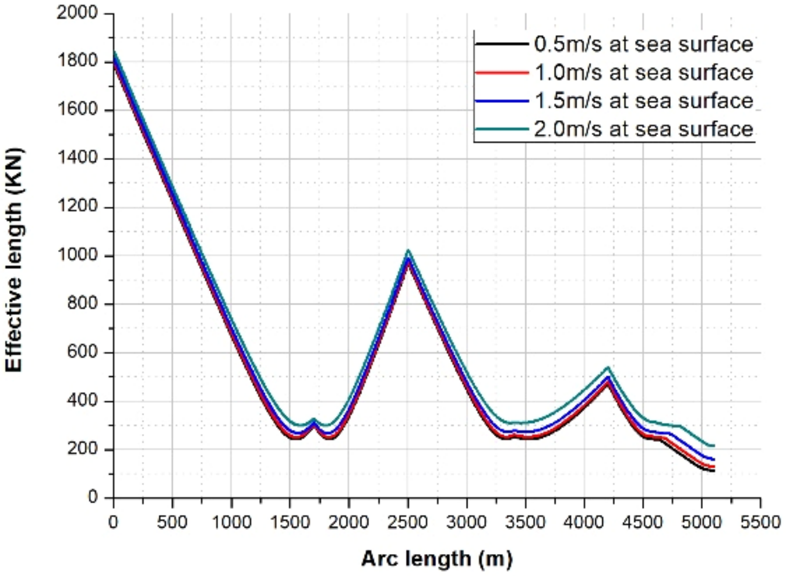

Figure 9. Effective tension along the riser

Figure 10 shows the maximum von Mises stresses for SSLWR at different current velocities. The stress variation is much more apparent than the effective tension at varying current velocities, especially at the hang-off point. It should be noted that the stress at 2.0 m/s rises sharply, up to 305 MPa, and may result in failure at the hang-off position. Interestingly, the stress reduction rate is higher than the stress reduction at a lower current speed.

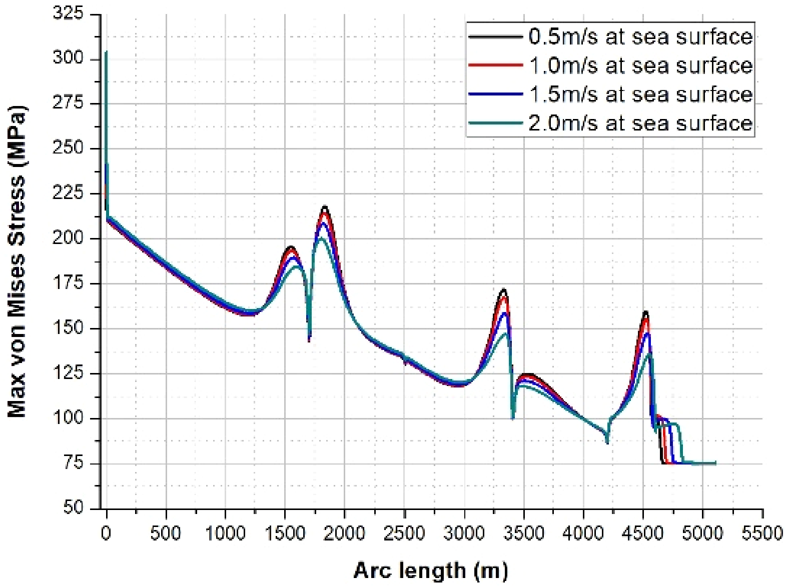

Figure 10. SSLWR maximum von Mises stress

4.2. Current Direction

A series of simulations was conducted to evaluate the mechanical properties of an SSLWR at varying current directions. The hang-off angle is set at 7 degrees, and the current velocity at the sea surface is 2 m/s. Owing to the configuration's symmetry, the current direction varies from 0 degrees to 180 degrees. The coordinate system is illustrated in Figure 5.

The tension and stress distribution along the riser are more sensitive in the lower section than the upper section, as was the case when the current velocity was varied. Figure 11 shows the effective tension along the riser with the current direction varying from 0 to 180 degrees. It shows that the effective tension increases as the current direction increases, with the maximum tension at 180 degrees.

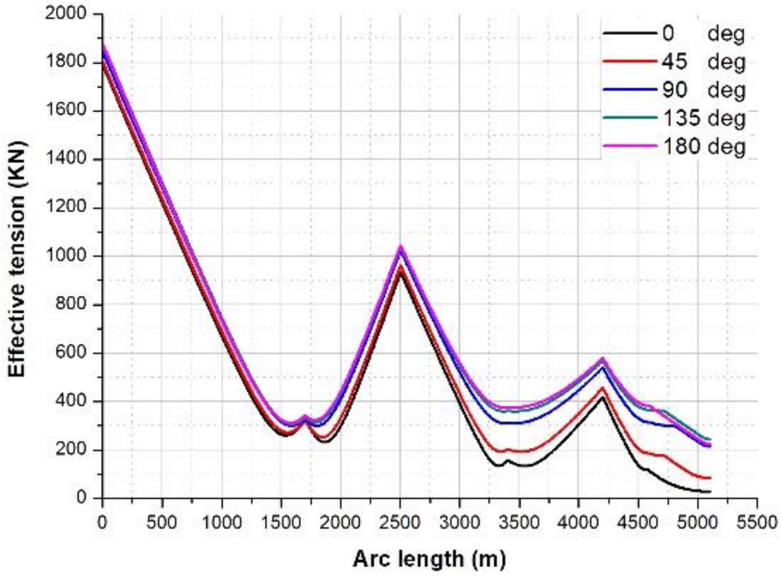

Figure 11. Effective tension along the SSLWR

Figure 12 shows the maximum von Mises stress of an SSLWR for various current directions. The maximum stress is at the hang-off, when the current is 90 degrees, as the riser has the biggest drag area and will experience a bigger drag force. It should be noted that the stress goes up sharply at the arch bend section when the current is at 0 and 45 degrees due to excessive deformation at the lift and drag points.

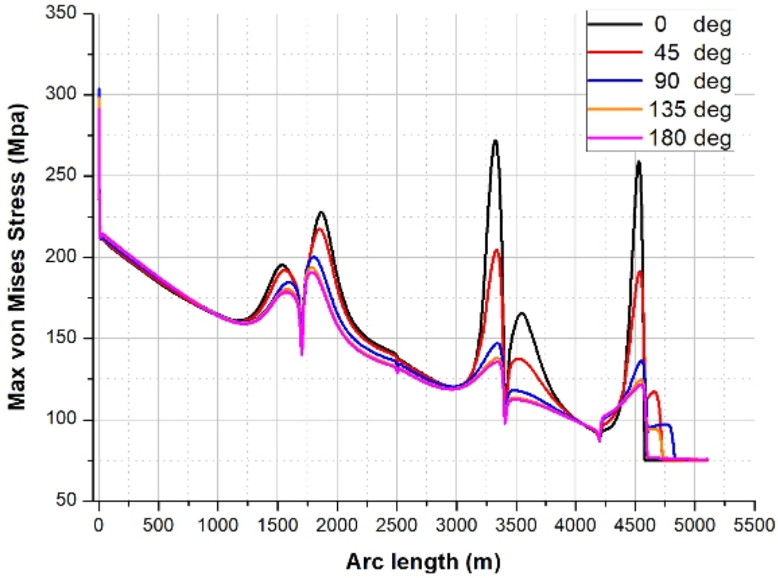

Figure 12. SSLWR maximum von Mises stress

4.3. Optimization of Upper Buoy Position

Various upper buoy locations with the same lower buoy location were simulated in OrcaFlex to determine the optimal upper buoy position. The different configurations are shown in Figure 13. If the upper buoy is installed closer to the hang-off point, the sag bend will be closer to the seabed.

The riser with its upper buoy at 1702.7 m has the longest section between the hang-off position and the upper buoy and the shortest section between the upper buoy and lower buoy, so it has the highest tension at the hang-off position and lowest tension at the arch bend position, as shown in Figure 14. It means that top tension can be reduced by moving up the position of the upper buoy.

The change in the position of the upper buoy significantly affects the stress distribution. Compared with SCR, the maximum stress of SSLWR appears at the arch bend section and touchdown point, shown in Figure 15. The maximum stress increases with increasing distance between the upper buoy and the hang-off position. The maximum stress reaches 220 MPa when the upper buoy is 1702.7 m.

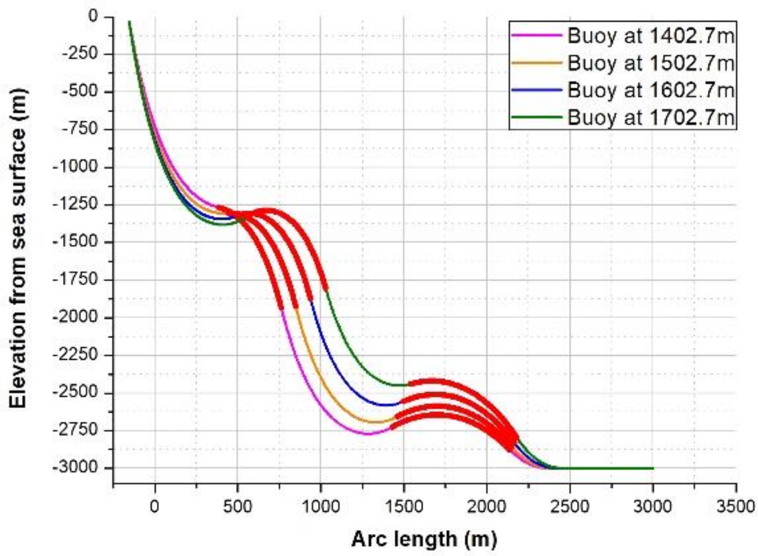

Figure 13. Riser shapes at different buoy positions

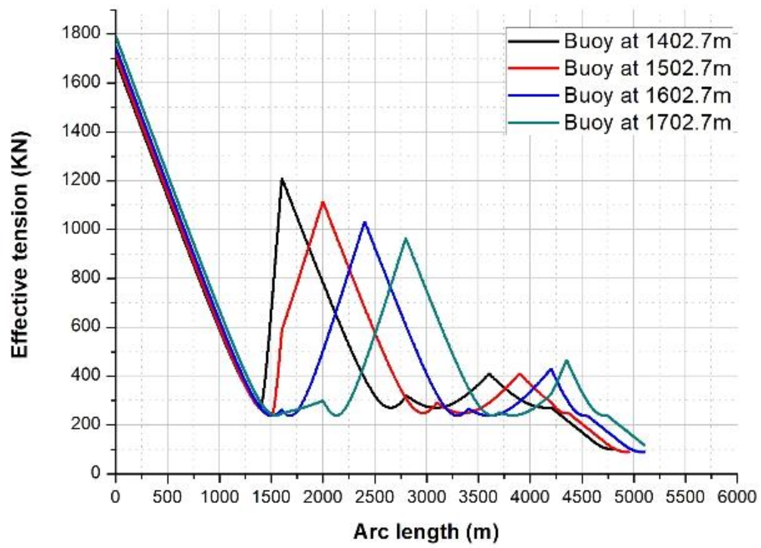

Figure 14. Effective tension of riser

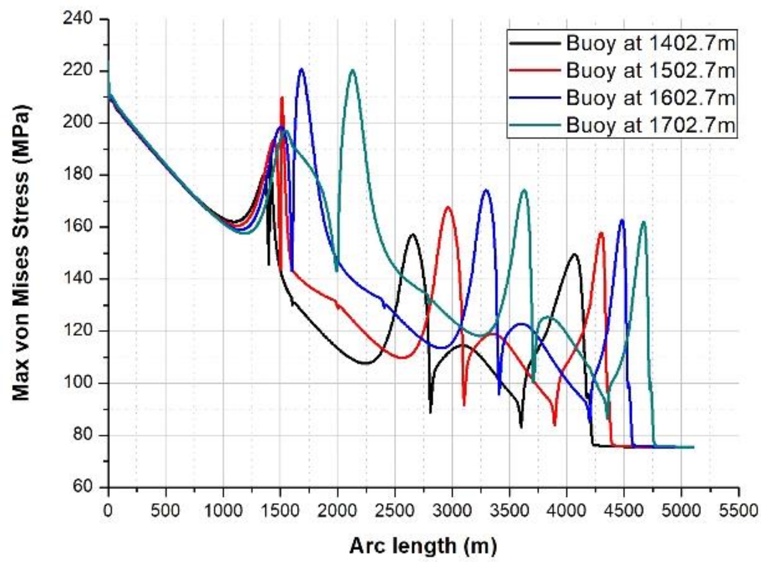

Figure 15. Max von Mises stress of riser

The SSLWR configuration showed substantial improvements over traditional SCR and SLWR risers in deepwater environments, especially for ultra-deepwater applications. This improvement is due to decreased effective tension and a more uniform stress distribution, leading to enhanced structural integrity. When installed, the bend radius of SSLWR is significantly larger than in conventional designs, helping to prevent overbending and reduce fatigue, which is crucial for extending the component's operational life. This setup reduces stress to less than half of that measured in the SCR configuration, keeping stresses well below 448 MPa and supporting SSLWR's suitability for continued safe use. The SSLWR configuration also demonstrates improved tension and stress distribution, making it ideal for ultra-deep environments, where increased depth intensifies loads.

At the lift and drag points for SSLWR, increased stress concentrations are created due to the need for larger buoy modules. While regions of lower tension experience buoyancy-induced deformation, these locations will face higher bending stress levels, which may require close monitoring or strengthening to ensure an extended service life for SSLWR. Additionally, natural variability in the marine environment, such as thermal gradients or uneven seabed terrain, may adversely affect the efficiency of SSLWR, indicating that more rigorous simulations should be performed under dynamic oceanic conditions.

5. Conclusion

This paper proposes a novel riser configuration, the shaped steel lazy wave riser, to enhance the riser performance for ultra-deepwater. To assess its feasibility compared to SCR and SLWR, a series of finite element simulations under different conditions were performed. The SSLWR shows a maximum effective tension that is less than half of that observed in the steel catenary riser (SCR), and it remains consistently lower than both SCR and steel lazy wave riser (SLWR) configurations. While bending at the lift point increases tension sharply, and large deformation near buoys causes higher von Mises stress at the lift and drag points, SSLWR's stress remains within acceptable limits, well below the 448 MPa threshold. The study also reveals that the tension and stress distribution in the SSLWR are more sensitive in the lower section, with significant effects from current velocity and direction. Effective tension peaks at 180 degrees, while maximum stress occurs at a 90-degree current due to increased drag force on the riser. Stress rises sharply at the arch bend section with currents at 0 and 45 degrees due to deformation at lift and drag points. The SSLWR with an upper buoy at 1702.7 m experiences the highest tension at the hang-off and the lowest at the arch bend, suggesting that moving the upper buoy closer to the hang-off position can reduce top tension. This buoy position also impacts stress, with maximum stress reaching 220 MPa when the upper buoy is at 1702.7 m.

These findings highlight the potential for optimizing buoy placement to control tension and stress distribution, enhancing SSLWR performance in ultra-deepwater environments. This configuration balances effective tension reduction and stress, suggesting that SSLWR holds promise as a robust alternative for ultra-deepwater applications. Despite promising findings, this study has several limitations. First, the simulations are based on idealized conditions that may not fully capture complex, real-world ocean environments, such as varying temperature gradients or seabed interactions. Additionally, while this study optimizes the buoy position, further detailed optimization is required to enhance performance. Future work will address these limitations by including fatigue life analysis and comprehensive cost assessments. Additionally, exploring different buoy placements and configurations in real-world scenarios will be critical for determining the practical feasibility of SSLWR in diverse operating conditions. This study offers new insights into how modifying riser shape and buoy placement can effectively balance tension reduction with stress distribution, providing an alternative to traditional riser designs. The SSLWR's specific responses to buoy placements and varying currents expand an understanding of riser performance under varying conditions, guiding future advancements in offshore riser engineering.

6. Declarations

6.1. Author Contributions

Conceptualization, C.H. and F.L.; methodology, C.H. and M.O.; software, C.H.; validation, C.H., M.O., and V.P.; formal analysis, C.H. and S.K.; investigation, C.H. and S.K.; resources, V.P.; data curation, C.H. and V.P.; writing—original draft preparation, M.O.; writing—review and editing, S.K. and S.D.V.K.; visualization, C.H. and M.O.; supervision, M.O., S.K., and V.P.; project administration, M.O. and S.K.; funding acquisition, M.O. and S.K. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

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