Numerical Study on Mechanics and Thermodynamics of Ocean Riser with Smart Buoyancy Materials

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Abstract. With the gradual shift of oil and gas resource exploitation from shallow waters to deep waters worldwide, traditional steel risers are gradually unable to meet the demand for deep water use. Compared to metal risers, smart composite material risers have advantages such as corrosion resistance, high specific strength, and good thermal insulation performance, which are more in line with the needs of deep-sea oil and gas resource exploitation. This article is based on the research hotspot of applying hollow glass microbeads as a new type of composite buoyancy material to deep-sea oil production risers. Aiming at the different performances between smart material risers and traditional steel risers, finite element method is used to conduct static and thermodynamic analysis on various forms of ocean oil production risers. The study found that using composite materials instead of some metal materials can reduce platform top tension and engineering costs while meeting functional requirements. In addition, using composite material risers can reduce heat loss while ensuring a constant flow rate, thereby increasing the transportation temperature of internal oil and gas.

Keywords: Smart Marital; Hollow Glass Microspheres; Production Riser; Intelligent Analysis.

1. Introduction

In recent years, to meet the increasing demand for oil and gas supply, the water depth involved in offshore oil and gas extraction has been continually expanding. According to the latest statistics from the International Energy Agency, 44% of the global oil and gas reserves are located in deep-sea areas with water depths exceeding 2,000 meters, and 241 deep-water floating platforms have been constructed abroad [1]. With the further development of China's offshore oil and gas industry, an increasing number of oil and gas resources will be explored and extracted from greater water depths [2]. The deep sea has not only become a new energy base and a frontier for scientific and technological innovation but also symbolizes humanity's proactive advance into uncharted territories.

The marine riser system is an important component of modern offshore structural engineering. Its upper part is directly connected to oil storage vessels or platforms, while its lower part extends into the seabed, serving as a crucial conduit for material exchange between the sea and land. The risers used for offshore oil and gas extraction are not only subjected to the influence of external forces such as waves and currents, but also experience significant internal pressure due to the flow of high-temperature fluids. Additionally, as oil and gas exploration progressively moves into deeper waters, the increasing working depth of risers leads to more severe environmental conditions during their service life. This is primarily manifested in the extremely high hydrostatic pressure, which imposes higher demands on the strength and stability of risers; the lower temperatures in deep-sea areas can also affect the fluidity of the fluids inside the risers to a certain extent. Moreover, traditional metallic materials not only make cost control difficult but also lead to the failure of riser components during service, potentially causing oil spills and even explosions, which pose severe threats to the marine ecological environment and personnel safety. Therefore, traditional steel risers are gradually becoming inadequate for deep-water development requirements, and the exploitation and development of deep-sea oil and gas urgently need new materials and technologies that are more cost-effective and reliable.

The hollow glass microspheres (HGMs) composite material, with its unique advantages, holds broad application prospects in the field of deep-sea oil and gas exploitation, primarily due to its lightweight, high strength, and excellent thermal insulation properties [4]. This material not only outperforms traditional steel in mechanical and thermodynamic properties [5], but also addresses the widespread issue of corrosion in metallic materials, making it the ideal choice for subsea oil extraction risers [6]. Currently, numerous scholars both domestically and internationally have conducted research on the mechanical properties of deep-sea risers, with most studies focusing on traditional steel risers and fiber-reinforced composite risers. In contrast, research on risers made of HGM/epoxy resin composite foam materials and fiber-reinforced composite foam materials is relatively limited. McNamara [7] performed a finite element simplification analysis on traditional steel flexible risers, assuming that the layers of the flexible riser were in a bonded state, thereby neglecting the contact and friction between layers. Bai [8] analyzed and optimized the mechanical properties and structure of composite risers. Yoshiyasu [9] conducted a mechanical analysis of traditional risers and those with an external carbon fiber-reinforced composite cladding, finding that the tensile strength of the enhanced riser could reach twice that of the standard type. In addition to mechanical loads, due to the flow of high-temperature fluids inside, there is a significant temperature gradient between the inner and outer layers of the riser, making thermal loads an indispensable factor. Kemmochi [10] provided an elastic solution for a sandwich structure riser composed of isotropic core and orthotropic shell layers under thermal loads, based on the classical lamination theory. Hastie [11] used finite element analysis to calculate the stress in thermoplastic composite risers under thermal loads, and observed the effects of varying parameters such as inner wall temperature and relative wall thickness on the results. In summary, this paper innovatively applies HGMs composite materials to risers, conducting static and thermal steady-state analyses based on their material properties. The study aims to explore the superior performance of the new material in riser structures and provide a design basis for its future application in practical engineering projects.

2. Numerical Model and Method

2.1 Steel Riser Model

To conduct finite element analysis and calculations on the steel riser, it is necessary to first establish the geometric model and finite element model. The completed finite element model is shown in Figure 1. The steel riser model is constructed as the control group, with the dimensions and material parameters of the model detailed in Table 1.

The steel riser consists of five layers of materials, arranged from the inside to the outside as follows: steel pipe layer, fiber-reinforced rubber layer, two helical armor layers (+55° and -55°), and a rubber layer. The five layers of the riser are numbered from the outside to the inside as Layer 1, Layer 2, Layer 3, Layer 4, and Layer 5, respectively. In the model construction process, the steel pipe layer and the rubber layer are simplified as isotropic layers, while the fiber-reinforced rubber layer and the two helical armor layers are simplified as orthotropic layers. The mechanical parameters and geometric dimensions of each layer are shown in Table 2

Table 1. Dimensions and material parameters of the steel riser model

Riser Type	Outer Diameter (mm)	Inner Diameter (mm)	Length (mm)	Density (kg/m³)	Elastic Modulus (GPa)	Poisson's Ratio
Steel Riser	188	176	1000	7850	207	0.3

Composite Riser	variable	184	1000	929	0.54	0.3

Table 2. Dimensions and mechanical parameters of each layer of the steel riser

Layer Number	Material	Inner Diameter (mm)	Thickness (mm)	E (N/mm²)	Poisson'sRatio
(i)	Rubber Layer	125	10	15	0.49
(ii)	Helical Armor Layer (5 mm diameter, α = +55°)	120	5	2000000	-
(iii)	Helical Armor Layer (5 mm diameter, α = -55°)	115	5	2000000	-
(iv)	Fiber-Reinforced Rubber Layer	101	10	780	0.49
(v)	Steel Pipe Layer	100	1	2000000	0.28

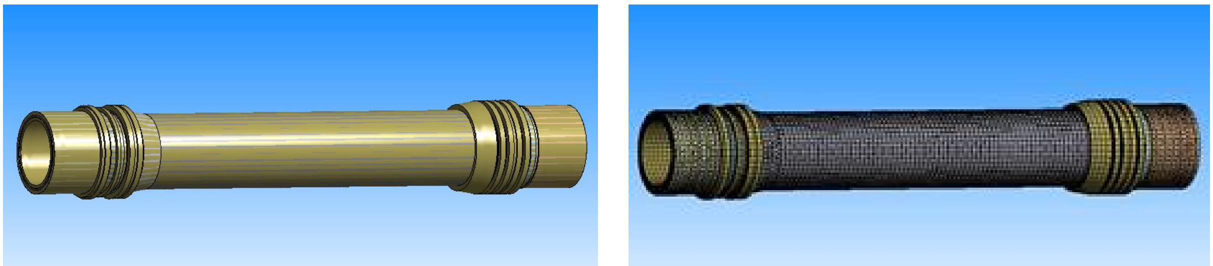


Fig. 1 Geometric model and finite element model

2.2 Composite Riser Model

To enhance computational efficiency, the riser model was simplified. The hollow glass microsphere/epoxy resin composite riser was reduced to a bilayer structure, removing the outer steel layer while retaining the inner steel layer. The established model is shown in Figure 2. The dimensions and material parameters of the model are shown in Table 1.

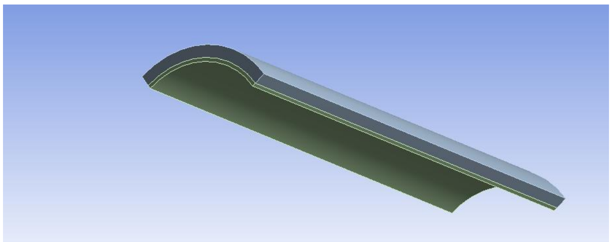


Fig. 2 Finite element model of bilayer composite riser

3. Static Analysis

The working condition is set with an external pressure of 40MPa and an internal pressure of 50MPa. The stress distribution cloud map and longitudinal distribution map of the equivalent stress steel riser obtained through calculation and analysis are shown in Figure 3.

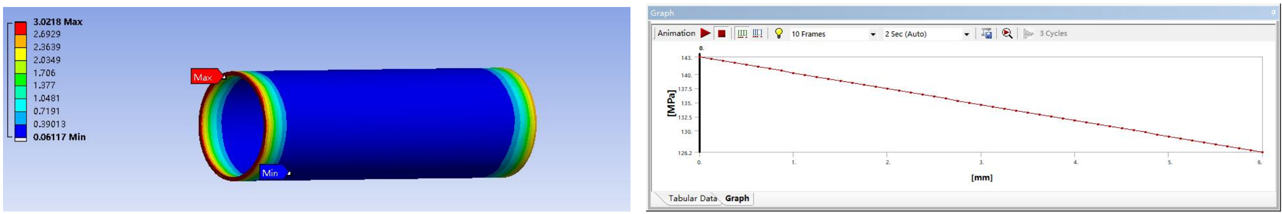
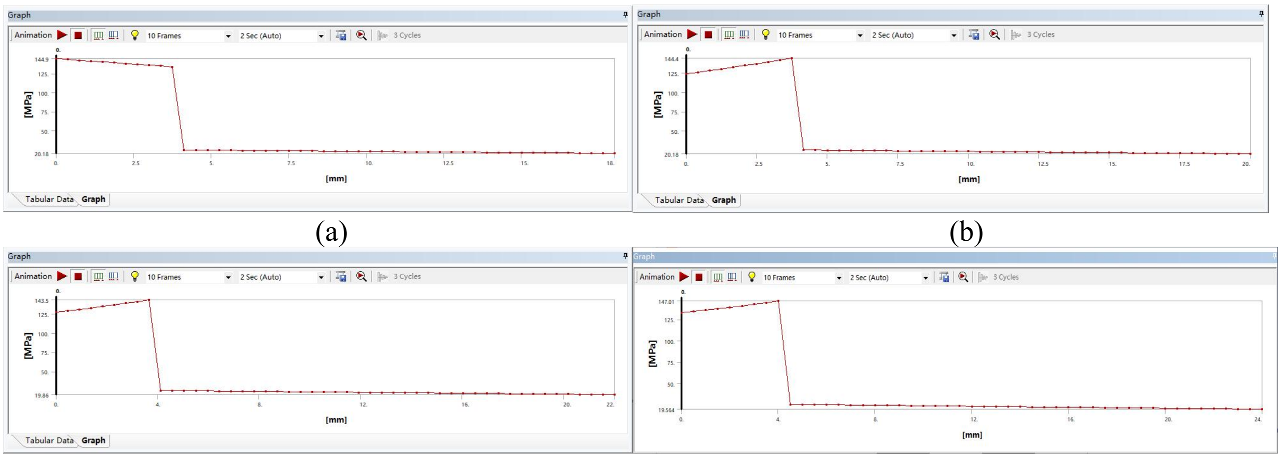


Fig. 3 The stress distribution cloud map and longitudinal distribution map of the equivalent stress

As shown in the above figure, the equivalent stress of the traditional steel riser in the control group decreases from the inner layer to the outer layer, and there is no significant jump. The maximum value is 143 MPa, which serves as the criterion for determining whether the experimental group and the control group can meet the same functional requirements. To further investigate the variation law of the maximum equivalent stress of the steel layer with the thickness of the composite material layer, an increment of ± 2mm was set at around 20mm thickness of the composite material layer. The series of calculation results are shown in Figure 4.



(a) (b) (c) (d)

Fig. 4 The Stress results of composite material riser (a) 14mm; (b) 16mm; (c) 18mm; (d) 20mm

As shown in the Fig. 4, in the series of calculation results with an increment of 2mm, the maximum stress of the steel layer shows a minimum value of 143.7MPa and 143.5MPa when the thickness of the composite material layer is 16mm and 18mm, respectively. Due to the fact that the maximum stress of the steel layer when the thickness of the composite material is 18mm is slightly less than 16mm, and the maximum equivalent stress of the composite material layer is also relatively small. A composite material riser with a thickness of 18mm is selected. It is believed that it can meet the same functional requirements as the control group's traditional steel riser. Furthermore, based on this, calculate the wet weight per unit length of the riser separately. The comparison results show that the wet weight per unit length of 18mm HGMs composite pipes is smaller than that of steel pipes. Therefore, it can be considered that using HGMs/epoxy resin composite materials to replace part of the steel layer of traditional steel pipes can reduce the total wet weight of the pipes by 86.53N/m (37.6%) while meeting the same functional requirements, while keeping the total length of the pipes unchanged. Ultimately, this leads to a reduction in the actual top tension experienced by the pipes at the ends, which is beneficial for reducing the volume of offshore platforms and controlling engineering costs.

4. Thermodynamic Analysis

The thermodynamic performance of the riser is also one of the important parameters that cannot be ignored. The main reason is that for the oil inside the production riser, the viscosity of the fluid is an important indicator for the design of the riser system. If the internal oil is too viscous, it will not only reduce the oil and gas production of the platform, but also lead to blockage inside the riser. The viscosity coefficient of fluids generally decreases with increasing temperature. Therefore, whether the oil transported inside the riser system can reach a normal operating temperature is a key consideration in the design. Compared to traditional steel, HGMs/epoxy resin materials have lower thermal conductivity. This section conducts a thermal steady-state analysis on two different materials of risers under the same thermal load conditions, verifying the advantages of HGMs/epoxy resin material risers in terms of insulation. The thermal conductivity of HGMs composite material is 0.18 W/m·°C, while that of steel is 60.5 W/m·°C. The external wall temperature of the riser is set at 4°C, and the internal heat sources are set at 30°C, 60°C, 90°C, and 120°C respectively.

The average temperature of the internal fluid of steel and composite pipes under different thermal load conditions is shown in Table 3. It can be seen that the internal temperature of composite pipes is generally higher than that of steel pipes. By using HGMs/epoxy resin composite materials to replace part of the steel in traditional metal risers, can not only meet the same mechanical properties, but obtain a better insulation effect. It can improve the fluidity of the fluid, thereby ensuring the normal operation of the riser during the transportation of oil and gas.

Table 3. Temperature gradient table at the same position of different materials riser

Riser Type	Interlayer	Distance from Riser Center	Heat Source Temperature (°C)			
			30°C	60°C	90°C	120°C
Steel Riser	Steel Layer	88 mm	4.0023	4.0050	4.0077	4.0104
		89 mm	4.0019	4.0041	4.0063	4.0085
		90 mm	4.0015	4.0032	4.0050	4.0067
		91 mm	4.0011	4.0024	4.0037	4.0050
		92 mm	4.0007	4.0016	4.0025	4.0033
		93 mm	4.0004	4.0008	4.0012	4.0016
		94 mm	4.0000	4.0000	4.0000	4.0000
Composite Material Layer	Steel Layer	88 mm	5.8939	8.0792	10.264	12.450
		89 mm	5.8939	8.0792	10.264	12.450
		90 mm	5.8939	8.0791	10.264	12.450
		91 mm	5.8939	8.0791	10.264	12.450
		92 mm	5.8938	8.0790	10.264	12.449
	Composite Layer	93 mm	5.7793	7.8323	9.8853	11.938
		94 mm	5.6660	7.5884	9.5107	11.433

5. Summary

This paper focuses on the application of hollow glass microsphere/epoxy resin composite materials in deep-sea oil extraction risers. Addressing the primary challenges that currently restrict deep-sea oil and gas exploitation, the study employs the finite element method to conduct numerical analyses on various riser models. It investigates the static and thermodynamic properties of composite risers, demonstrating the numerous advantages of hollow glass microsphere/epoxy resin composite foam materials over traditional metallic materials. The main conclusions of this study are as follows:

Under identical loading conditions, replacing a portion of the steel cladding with composite material cladding results in maximum equivalent stress levels in the metallic material that are comparable to those before replacement. Meanwhile, the wet weight per unit length of the composite riser is lower than that of traditional steel risers. This indicates that substituting traditional steel with composite materials, while maintaining structural strength requirements, can effectively reduce the load on the upper platform. Consequently, this allows for a reduction in the size of the offshore platform and an increase in the potential depth of oil and gas extraction.

A thermal steady-state analysis was conducted on two types of risers—composite and steel—that fulfill the same functional requirements. The analysis was performed with heat source temperatures set at 30°C, 60°C, 90°C, and 120°C, respectively. The results show that under all four working conditions, the average temperature of the fluid inside the composite riser is higher than that in the steel riser. This suggests that replacing a portion of traditional steel with composite materials helps to maintain higher transportation temperatures for the oil and gas inside the riser, ensuring better fluidity and thereby enhancing the efficiency of oil and gas extraction.

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