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RESEARCH ARTICLE

Novel Bio-inspired Design for the Carcass Layer of Flexible Risers with Increased Strength Under External Pressure

Jaafar Ghanbari[1] **and Ali Baloui**[1]

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Abstract
Flexible risers are crucial pieces of equipment for moving output fluids from wells to platforms during the extraction of oil and gas from deep-sea resources. One of the causes of collapse in these pipes is the high hydrostatic pressure applied to risers in deep water. The innermost layer of a riser, known as the carcass layer, plays a critical role in resistance to external pressure. In this study, we investigated the collapse (nonlinear buckling) of a riser under external pressure, and a novel design based on the structure of a beetle's exoskeleton was used to increase the load capacity of the carcass layer. This type of beetle skeleton is constructed in such a way that it creates strong connections among the various parts of the external skeleton to considerably enhance strength against external pressure while allowing necessary movements. To assess the performance of the design in comparison with the original design, we examined the nonlinear buckling of the new structure under external pressure. Through genetic algorithm optimization, design parameters were obtained, and the maximum strength before collapse was determined. Results show that the critical pressure in the new design substantially increases relative to that in the original design.

Keywords Flexible riser; Carcass layer; Nonlinear buckling; Critical pressure; Bio-inspired design; Finite element method

1 Introduction

The global demand for oil and gas has led to increases in exploration and extraction activities, necessitating the oil and gas industry to venture into challenging environments, including marine environments with harsh conditions, great depth, and unfavorable weather. In this context, marine risers play a pivotal role in offshore oil and gas extraction. A marine riser is a vertical pipe that serves as a crucial link connecting wellhead equipment to a platform and is primarily responsible for transferring various substances, including hydrocarbons, mud, gas injection, and fluids within the well. Marine risers have emerged as important equipment owing to the depletion of easily accessible resources and the industry's shift toward challenging extraction locations. Risers are divided into three main categories: rigid, flexible, and hybrid (Duan et al., 2022). Flexible risers can be broadly classified into two main categories based on their structural design, namely, bonded flexible risers, which are used at short wellhead distances because of their low bending stiffness, and unbonded flexible risers, which are operable at long distances and great depths of the sea because of their bending stiffness and high pressure-bearing capacities. These risers are composed of layers (Bai and Bai, 2019) that slide over each other, as depicted in Figure 1.

Article Highlights

- A flexible riser consists of several layers, each with a specific task.
- The carcass layer bears the external pressure of the riser and supports the flow canal, ensuring that the fluid flows in harsh loading conditions of the sea.
- A new design is presented in this paper which shows improved stiffness and increased collapse pressure.
- The novel design is inspired by the structure of the exoskeleton of a beetle.

✉ Jaafar Ghanbari
ghanbari@qut.ac.ir

1 Mechanical Engineering Department, Qom University of Technology, Qom, Iran

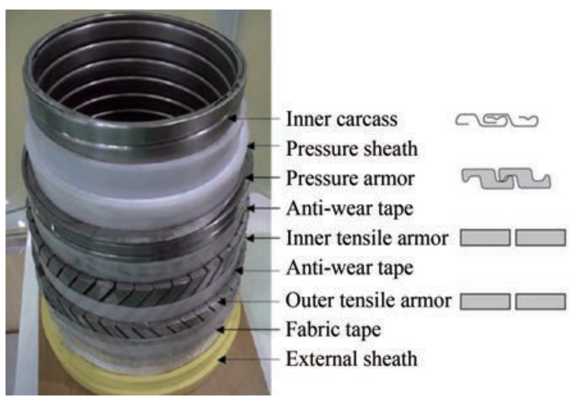

Figure 1 Structure of a typical flexible riser layer (Pinto and Gomes, 2017)

The carcass layer, which is the innermost steel layer of hydrocarbon-carrying pipes, plays a critical role in resistance to circumferential buckling. This layer is specifically engineered to resist external pressure and counteract the effects of trapped gas within pipe rings. The inner pressure sheath, which is composed of polymer material, performs the critical function of isolating liquids within a riser from surrounding rings, ensuring the integrity of the transported liquids by preventing any interaction with steel layers. Moving outward, the steel pressure armor resists radial stress induced by the internal pressure of pipes, acting as a structural support and maintaining the overall integrity of hydrocarbon-carrying pipes. To mitigate friction between metal pipes and enhance their durability, wear-resistant strips are strategically placed, which act as protective barriers that prevent rubbing and minimize wear and tear, consequently preserving the pipes' resistance over time. The steel tensile armor provides tensile resistance and has a dual purpose of supporting risers' weight and efficiently transferring forces from hydrocarbon-carrying pipes to platforms. When used in deep waters, hydrocarbon-carrying pipes must undergo notable modifications. Instead of two armors, four armors are employed. This adjustment enhances a riser's structural integrity, compensating for the increased environmental pressure associated with deeper waters. Lastly, the outer pressure sheath, akin to the inner sheath, is crafted from a polymer material. Positioned on the exterior, it acts as a protective barrier against seawater, protecting hydrocarbon-carrying pipes from external corrosive elements.

In the API RP 17B standard (American Petroleum Institute, 2014), nine failure modes are delineated for unbonded flexible risers, encompassing collapse, burst, tensile failure, pressure failure, excessive bending, torsional failure, fatigue failure, erosion, and corrosion. The standard precisely provides causes of failure and corresponding prevention strategies for each mode, ensuring comprehensive risk mitigation. Expanding on these insights, Simonsen (2014) introduces additional factors influencing collapse apart from those considered in API RP 17B; these factors include the release of gas between rings, collisions, the fall of heavy objects, corrosion, factory defects, and erosion. Drummond et al. (2018) consider the presence of sand and gravel in wellbore fluid a critical factor, especially in gas transmission scenarios; they suggest that these particles can erode, thin the carcass layer, and ultimately lead to collapse. Clevelario et al. (2010) investigate the effect of bending on collapse by testing five different flexible riser structures at a depth of 2 500 m under direct and curved collapse conditions; they develop a numerical model to assess the riser's resistance to collapse under bending. Ha (2016) emphasizes the importance of calculating critical pressure and proposes solutions for reinforcing flexible risers against collapse, including increasing the number of layers and their thickness. Shen and Jukes (2015) examine overly conservative carcass layer designs, highlighting the resultant increase in production, installation, and operation costs. Rosas et al. (2014) explore collapse under hydrostatic pressure and radial force and establish a quadratic relationship between collapse under radial force and collapse under hydrostatic pressure, contributing valuable insights into the interplay of these factors. Finally, Li et al. (2020a) presented an analytical model for predicting wet collapse in the carcass layer with an initial defect and validate it through finite element simulation. In another study (Li et al., 2020b), they simulate finite element collapse under external pressure, considering the impact of the number of riser rings and bending angle on critical pressure.

Dionicio-Bravo et al. (2023) present a finite element study of the carcass layers of flexible risers under external pressure. Ju et al. (2014) explore subsea dynamic riser stress and evaluate the results in accordance with various standards. In a similar study, Webster et al. (2011) conduct a finite element analysis of hybrid offset risers. Hu et al. (2019) survey the response characteristics of flexible risers.

This study comprehensively explores the collapse phenomenon (circumferential buckling) in a carcass layer under external pressure. It examines the nonlinear buckling behavior exhibited by this structure when subjected to external pressure, providing valuable insights into its performance under varying conditions. A notable contribution of the study is the introduction of a novel carcass design, which is based on the external skeleton structure of a specific type of beetle. This innovative approach aims to enhance the resilience of the carcass layer subjected to external pressure collapse. The adoption of bio-inspired design principles offers a fresh perspective on structural challenges encountered in flexible riser systems. Building upon this innovative design, we employ a genetic algorithm to optimize the geometric parameters of the proposed carcass structure. This process is geared toward achieving maximum buckling strength and ensuring that the riser can withstand external pressure effectively. In the final phase of the study, we explore modifications aimed at increasing the flexibility of the riser. These modifications, integrated into the optimal design, contribute to the overall improvement in the riser's flexibility without compromising its structural integrity.

2 Nonlinear buckling analysis

In this section, we explore the nonlinear buckling behavior of the initial carcass layer design subjected to external pressure. Then, we introduce a bio-inspired model and analyze its collapse mode under external pressure. Subsequently, we enhance the model's mechanical properties through optimization methods, presenting a final iteration with increased stiffness against collapse. The collapse criterion is the structure's instability after exposure to external pressure. Initially exhibiting elastic behavior with partial deformation, the structure gradually transitions to plastic deformation, reaching the material's ultimate stress and ultimately becoming unstable, manifesting significant deformations. The critical pressure denotes the equivalent pressure at which instability occurs.

First, we utilize the design examined in the work of Dionicio-Bravo et al. (2023) to assess the performance of the initial design and to verify the simulations. We focus on a two-inch flexible pipe. The pipe's cross-sectional dimensions in millimeters are illustrated in Figure 2.

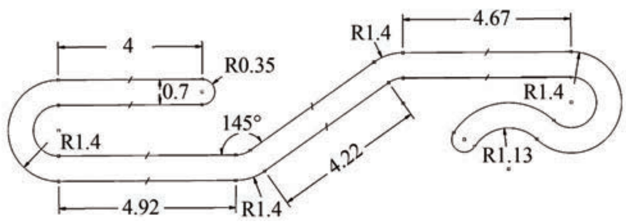

Figure 2 Initial profile design of the carcass layer with its dimensions (units: mm)

This profile undergoes a spiral rotation with an internal radius of 25.4 mm and a pitch of 10.25 mm, producing a carcass ring (as shown in Figure 3). This ring is imported into finite element software, and the desired conditions are incorporated and then axially populated until the specified length for the riser is achieved. Each ring is interconnected to its adjacent counterpart through complete coupling at the contact surface of its corresponding section.

Figure 3 Three-dimensional model of the carcass layer ring

The material of the carcass in the finite element software is defined as steel with a density of 7 850 kg/m^3, an elastic modulus of 207 GPa, and a Poisson's ratio of 0.3. Owing to the large deformation under external pressure, the plastic properties are extracted from the stress-strain diagram of the steel used in the carcass layer in accordance with the research of Souza et al. (2000) (as shown in Figure 4).

In this simulation, a carcass layer with 10 rings is used to prevent the boundary condition from affecting the results. A full-connection constraint is applied between their cross-sections to create a monolithic spiral, and a contact con-

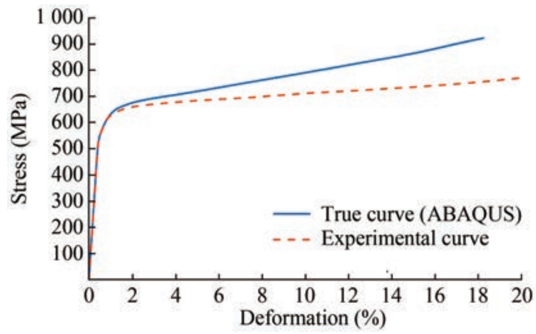

Figure 4 Stress-strain diagram of the steel alloy of the carcass layer from Souza et al. (2000)

straint with a friction coefficient of 0.1 is defined between the inner surfaces of the rings in the entire structure. An explicit dynamic solver is used, and large deformations are considered to account for the nonlinear deformation of the carcass layer.

A pressure of 50 MPa is applied to the outer surface of the rings in a ramped manner from zero at a uniform rate of increase to the final pressure. This high pressure is used in obtaining the nonlinear buckling capacity of the structure. The structure will not withstand this pressure, and in the middle of the solution, it will suffer from nonlinear buckling and large deformations, that is, collapse, because of the critical pressure and applied boundary conditions in Figure 5. The boundary conditions are applied to the edges of the carcass layer in such a way that the carcass is prevented from moving rigidly.

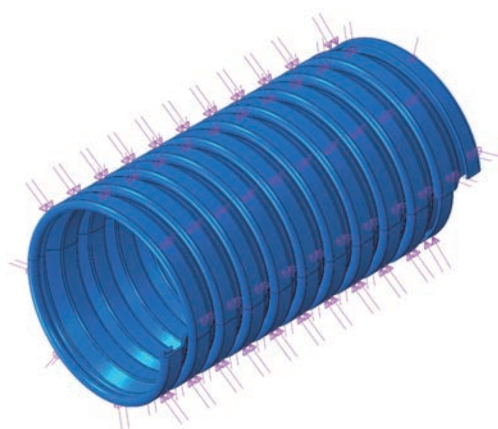

Figure 5 Carcass model with 10 rings, showing the applied external pressure

To obtain the proper mesh size for the simulations, we perform a mesh-convergence study for the model under 25 MPa of pressure. The results of the stress as a function of the element size are shown in Figure 6. An element size of 1 mm corresponding to 44 892 elements of the C3D8R element family for each ring results in an acceptable accuracy and is selected for the remainder of the simulations. Owing to the need to use three-dimensional elements in the bio-inspired model in the collapse simulations, three-dimensional elements are used in this model for the identification of uniform conditions in the solution of both cases, and the effects of element formulation on the analysis result are minimal.

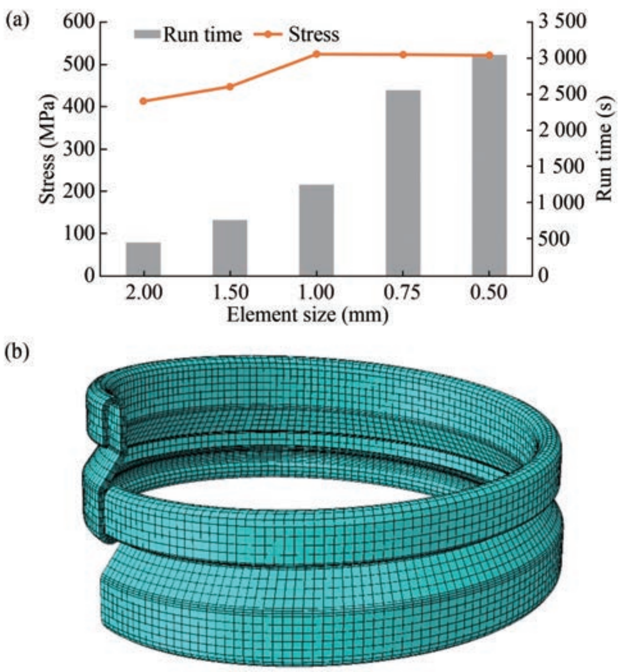

Figure 6 (a) Mesh-convergence results and (b) the mesh of a ring of the carcass

Under critical pressure, instability spreads and causes a decrease in the strength of the structure. The simulation results show that the structure starts to deform considerably at a pressure (P) of 32.15 MPa, which is considered the critical pressure of nonlinear buckling of this structure. Figure 7(a) shows the model shortly before the collapse starts. In Figure 7(b), the model is illustrated before a complete collapse at a pressure of 32.5 MPa. Local deformation corresponding to the first mode buckling of the cylindrical structure occurs and leads to the complete deformation of the carcass and complete collapse at increasing external pressure. Finally, at a pressure of 32.8 MPa, the two internal faces of the pipe collide, and the structure completely collapses. The final deformed view of the structure is shown in Figure 7(c).

Figure 8 shows the displacement diagram versus external pressure in the numerical solution. The diagram is compared with that made by Dionicio-Bravo et al. (2023). Their calculated critical pressure is 30.75 MPa, which shows a difference of 4% compared with the results of the current research.

For the visualization of buckling initiation in both studies, the curves in the figure are magnified. The reference curve exhibits a slightly higher external pressure for increasing radial displacements than the reference curve we obtained, and the buckling onset point occurs at a pressure lower than that in our study. This discrepancy can be attributed to differences in element number or software set-

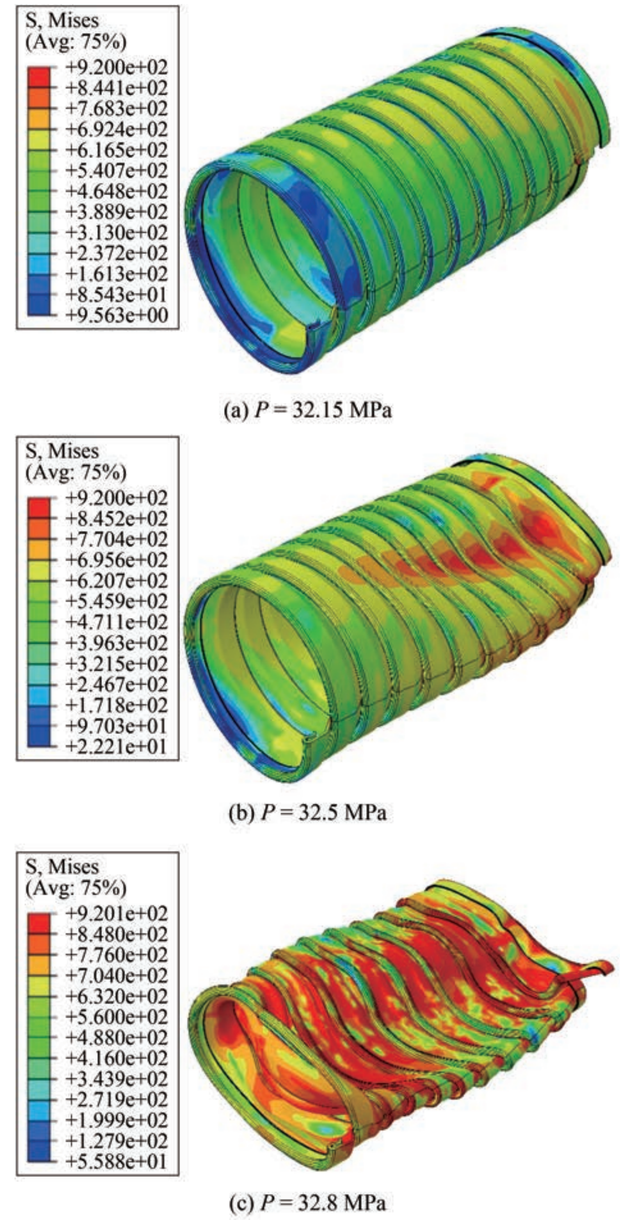

Figure 7 Collapse of the carcass with original design under external pressure

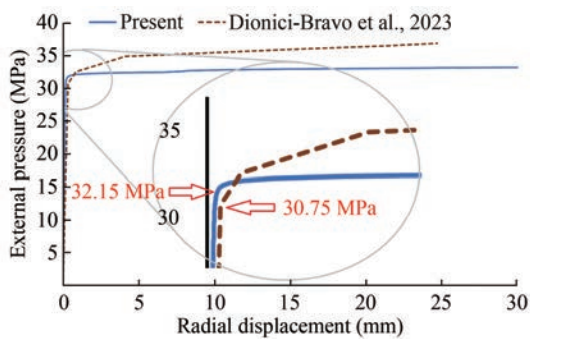

Figure 8 Radial displacement of the carcass vs. external pressure

tings. Nonetheless, given the nonlinearity of the collapse phenomenon and the material model employed, we find the overall results to be in good agreement.

3 Bio-inspired design for the carcass

In designing a carcass layer with a novel approach, a crucial approach is ensuring that the cross-sectional deformation maintains a riser's flexibility while providing adequate resistance to pre-tension exerted from a platform and other external forces, such as bending. Based on nature's cellular structures, a cross-section can be designed to achieve a balance between flexibility and adequate stiffness to withstand pressure and external forces. Nature has produced composites with exceptional mechanical properties, which are evidenced by the intricate tissues in various animals and plants. One striking example is the forewings of the external skeleton (elytra) of an insect known as the infernal iron beetle (*Phloeodes diabolicus*). This desert insect lacks the ability to fly and escape predators and has an elytra that is extremely resistant to impact and crushing and is composed of complex and graded interfaces. This beetle can be found under the bark of hardwood and coniferous trees, pretending to be dead, and due to the rough texture of its elytra, it can mimic a small stone. Apart from feigning death, this beetle has a remarkable ability to withstand crushing blows, piercing predators, and even the weight of vehicles. An article published in Nature (Rivera et al. 2020) has examined the structure of the skeleton of this beetle (as shown in Figure 9). The different parts of the external skeleton are connected through a locking mechanism, which allows the flexibility required for movement while maintaining strength and resistance to external loads.

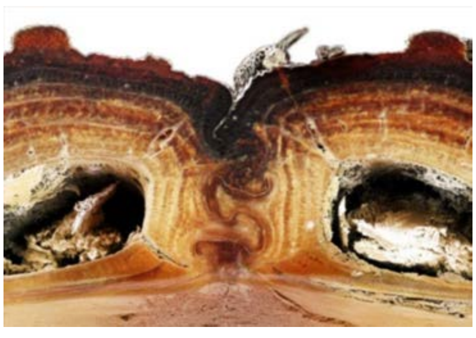

Figure 9 Structure of the elytra of *Phloeodes diabolicus* (Rivera et al., 2020)

Based on the sleek exoskeleton of the beetle, the proposed design not only provides the necessary strength against external pressure but also eliminates the potential for vortex shedding (formation of swirling eddies) because of the smooth inner surface of the riser. This streamlined design minimizes flow-induced vibrations and maintains fluid velocity, rendering it a more favorable option than the original design. The proposed design, similar to the original model, has an internal radius of 25.4 mm and a pitch of 10.25 mm (Figure 10).

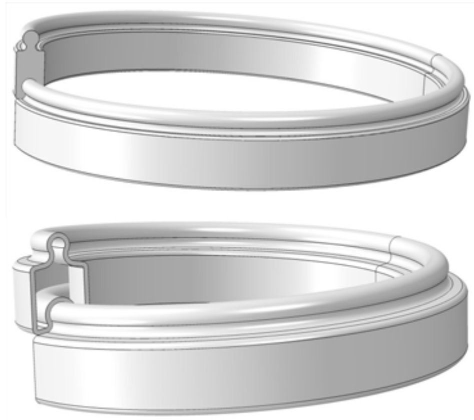

Figure 10 Bio-inspired design of the carcass

The new bio-inspired model, similar to the initial one, comprises 10 rings. The material properties, constraints, loading, and boundary conditions are simulated under conditions identical to those used for the original model. Each ring is discretized using 25 168 elements per ring from the C3D8R family (Figure 11).

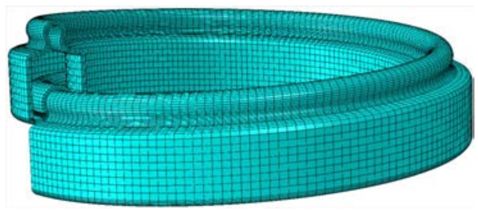

Figure 11 Finite element mesh of the bio-inspired carcass

Subjecting the model to increasing external pressure reveals its structural limitations. Under an external pressure of 20 MPa, the outer web of the section begins to deform. At a pressure of 22 MPa, the model exhibits circumferential deformations along the middle edges of the structure. These deformations intensify with a further increase in pressure, leading to the complete collapse of the structure. Finally, at a pressure of 23.5 MPa, the localized deformation observed at 22 MPa transforms into a general deformation of the entire structure, causing the model to collapse. The deformed configurations of the model at different pressures are shown in Figure 12.

The original S-shaped model's collapse under an external pressure of 32.75 MPa suggests that the bio-inspired model is not a direct replacement and requires further design modifications to withstand high pressure. Optimizing the structure is the first step toward achieving this goal. The model's design parameters (Figure 13) are identified for optimization. Given that a full-factorial variation in the design parameters would necessitate a large number

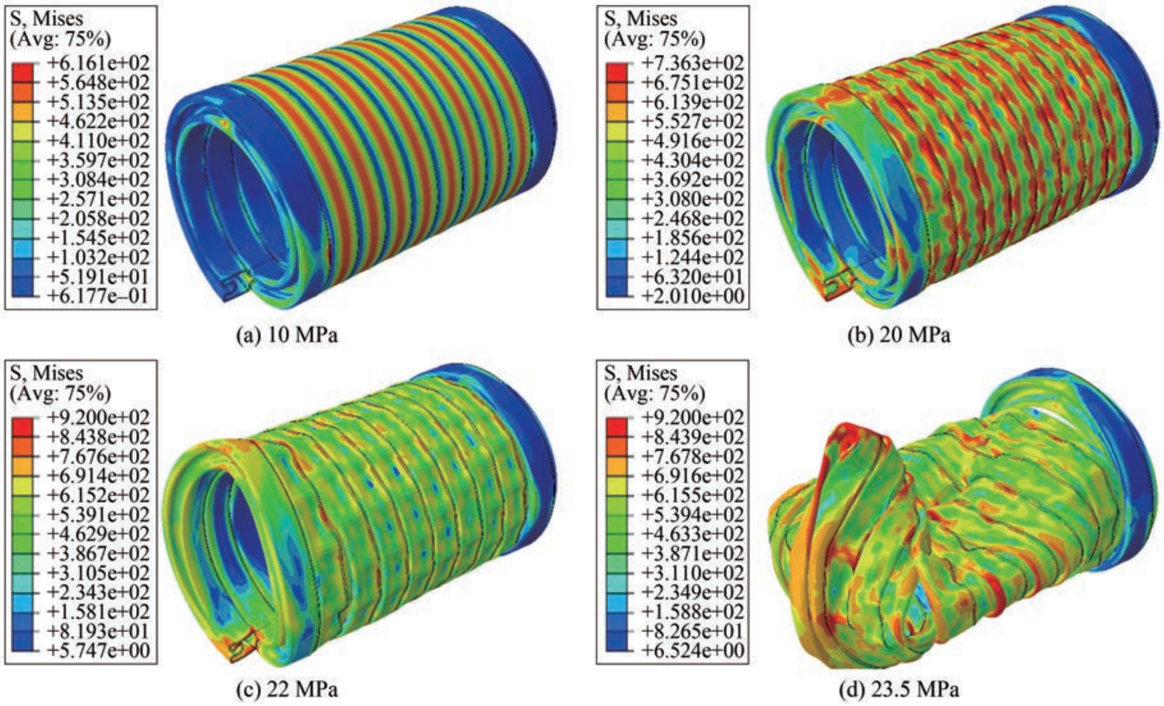

Figure 12 Collapse of the bio-inspired design of the carcass under external pressure

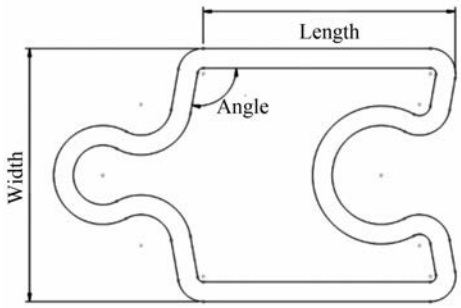

Figure 13 Design parameters of the carcass for optimization using the response surface method

of simulations, the response surface method (RSM) is employed to reduce the computational cost and identify an optimal design. The critical collapse pressure serves as the objective function for the optimization study, and other design parameters, such as the internal radius of the carcass, remain unchanged.

Employing the Box-Behnken method with three variables necessitates 13 experiments for determining an optimized outcome. The range of these factors is established in accordance with manufacturing limitations and the layer's placement within the riser. Utilizing the output obtained through the RSM, we develop suitable models, and the collapse pressure is determined through nonlinear buckling simulations. Table 1 summarizes the conducted experiments and corresponding critical pressure.

The relationship between the objective function and the design variables is given as follows:

Table 1 Design parameters of the optimization studies and the corresponding collapse pressure

Case No.	Angle A (°)	Length L (mm)	Width W (mm)	Critical pressure (MPa)
1	70	6	8	31.56
2	70	12	10	12.56
3	50	6	10	21.35
4	50	12	12	13.25
5	70	6	12	6.25
6	70	18	8	8.53
7	70	18	12	11.19
8	90	6	10	30.35
9	90	18	10	12.00
10	90	12	8	17.77
11	50	12	8	15.68
12	50	18	10	10.23
13	90	12	12	16.58
Optimum	**90**	**6**	**8**	**35.71**

$$P = 0.878W^2 + 0.138L^2 + 0.007A^2 + 0.181LW + 0.007\,5AW - 0.013\,5AL - 20.694W - 5.564L - 0.818A + 184.547$$

where P is the critical collapse pressure, W and L are the width and length of the profile, respectively, and A is the angle (Figure 13). Leveraging the insights gained from RSM optimization, we construct a new model on the basis of the design parameters of the optimal configuration and investigate its collapse behavior under external pressure. Consistent with the previous analysis, a mesh size of 1 mm is employed, resulting in 18 216 elements per ring. As predicted by the RSM, the collapse pressure of the optimized model is 35.71 MPa (as shown in Table 1). Nonlinear buckling simulations reveal that the optimized model initiates collapse at an external pressure of 40 MPa, demonstrating a higher tolerance than that predicted by the RSM. Figure 14 illustrates the collapse behavior of the optimized model.

The optimized model exhibits a significant increase in critical pressure and structural strength. However, the analyzed deformation patterns in this design suggest that further enhancing the collapse strength of the layer is possible by modifying the side webs of the section. Thus, we alter the side webs of the optimal model from straight to curved webs to improve the section's strength. This modification reduces the distance between the side webs and the clamp that locks the sections together, enhancing the robustness of the structure. Figure 15 illustrates the modified model with curved side webs.

Figure 16 depicts the collapse analysis results of the modified model under external pressure. The modified model exhibits enhanced collapse strength, with deformation commencing at a critical pressure of 52.5 MPa.

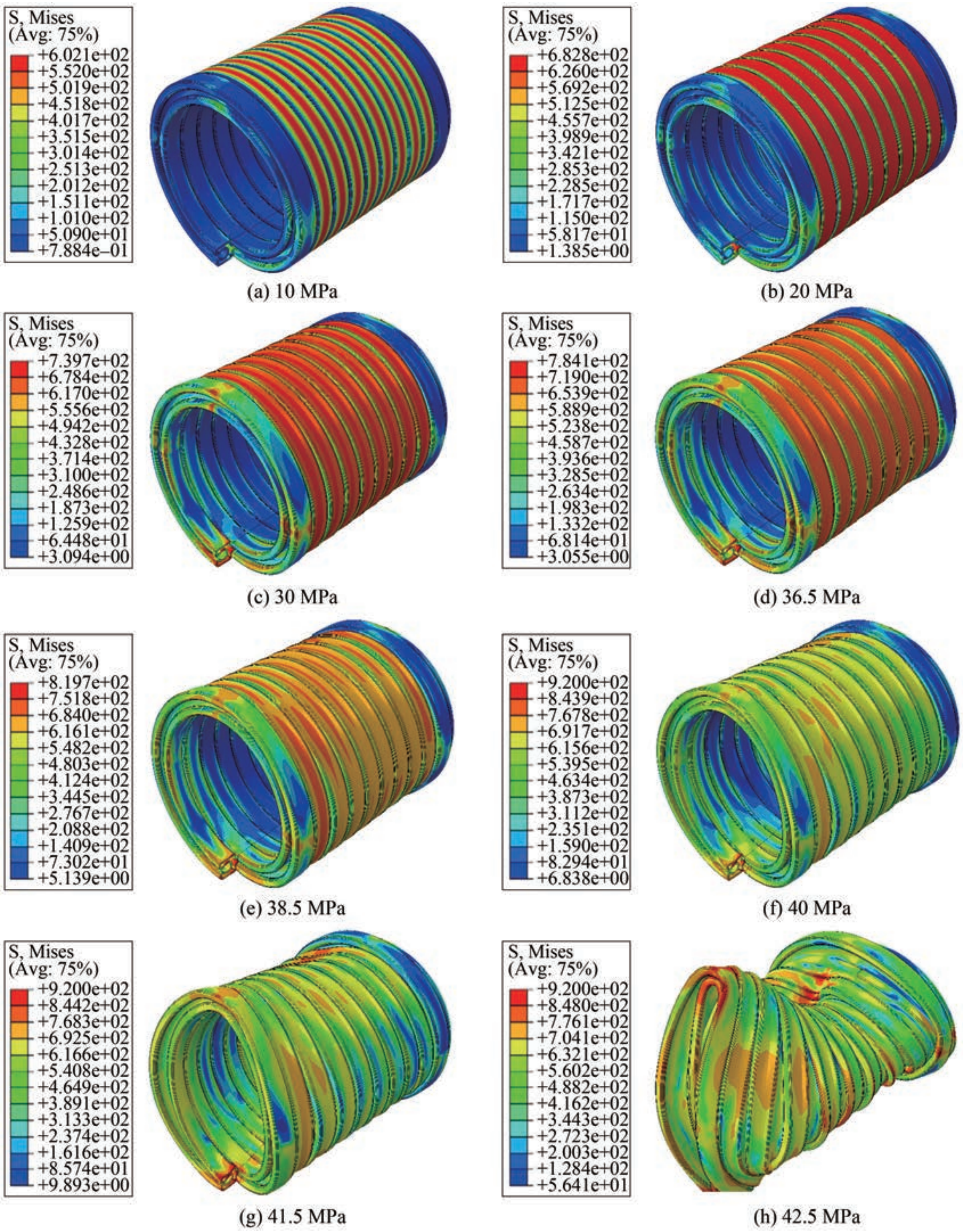

Figure 14 Carcass with optimal design under external pressure

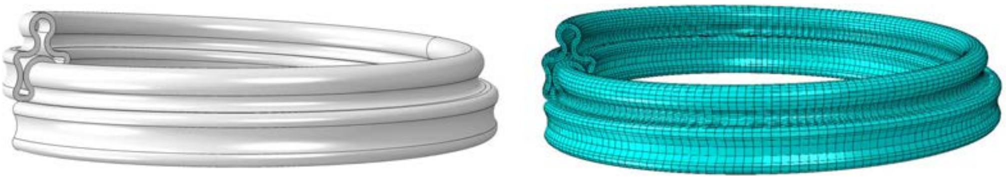

Figure 15 Modified design of the carcass and its mesh

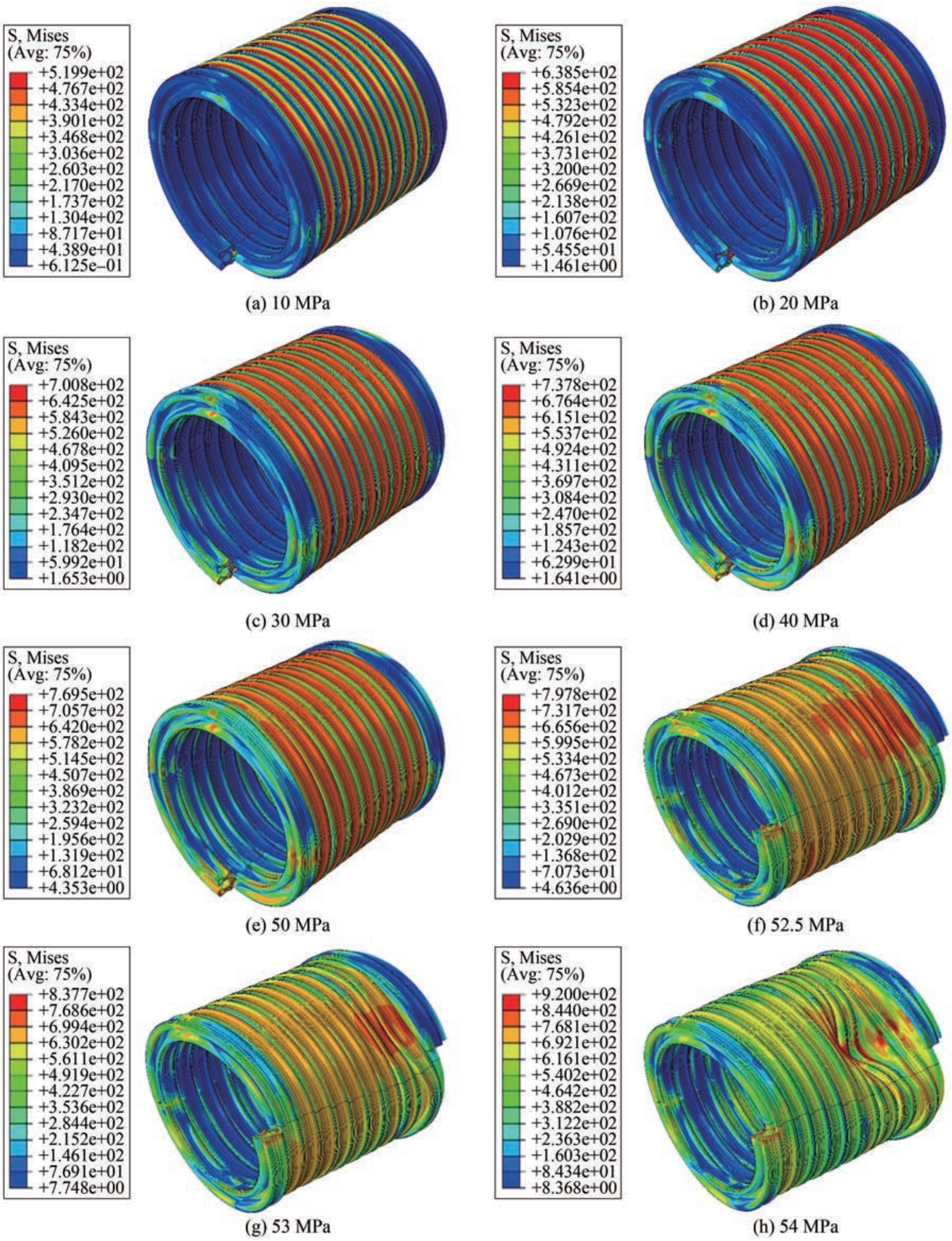

Figure 16 Modified carcass design under external pressure

The modified model with curved webs has considerably higher collapse strength than the model with straight webs. Figure 17 presents a comparative analysis of stress distribution in the rings of the modified bio-inspired model with curved webs under varying external pressure. The original model and results from Dionicio-Bravo et al. (2023) are included for reference. The results demonstrate that the modified model shows exceptional performance in withstanding external pressure, exhibiting markedly lower stress levels for a given pressure than the original model. To further illustrate the model's configuration, we depict important points that impact stress distribution.

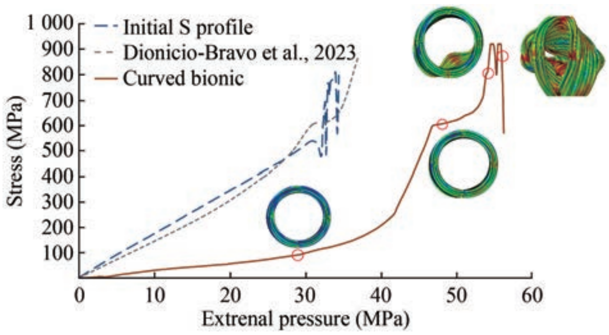

Figure 17 Stress of the carcass during collapse under external pressure for the initial design and new curved bionic design

4 Conclusions

Nonlinear buckling behavior was investigated with a finite element method, and a novel carcass design based on the infernal iron beetle's exoskeleton was proposed. The study's notable contribution lies in its innovative approach, that is, using bio-inspired design principles to enhance the resilience of the carcass layer. RSM optimization further refined the design parameters, maximizing the riser's buckling strength against external pressure. Considering the carcass layer's design, the study emphasizes the importance of maintaining flexibility while resisting external pressure. By emulating the infernal iron beetle's elytra structure, a balance between flexibility and stiffness was achieved, exemplifying nature's mastery in creating composites with exceptional mechanical properties.

The optimized model demonstrated a substantial increase in critical pressure and structural strength, showcasing the effectiveness of the bio-inspired design and optimization process. However, the study identified an opportunity for further improvement by modifying the side webs of the section. The alteration from straight to curved side webs in the optimal model enhanced the robustness of the structure by reducing the distance between the side webs and the clamp. The comparative analysis revealed that the modified model with curved webs outperformed the original model with straight webs in terms of collapse strength. In conclusion, the study demonstrates the efficacy of the bio-inspired design and genetic algorithm optimization in enhancing the collapse resistance of flexible risers. The modification of side webs to curved shapes further improved structural integrity, providing a promising avenue for advancing the design of carcass layers in flexible riser systems.

Despite the beetle-inspired model's exceptional strength, it has some limitations. The closed profile, while offering enhanced rigidity, may pose fabrication challenges compared with the simpler open profile of the original S-type design. Additionally, maintaining consistent section thickness in the new design might lead to a slight increase in weight. Nevertheless, these issues can be effectively addressed through further optimization, which can be performed using advanced lightweight materials and manufacturing techniques, paving the way for the formulation of efficient and robust designs.

Competing interest The authors have no competing interests to declare that are relevant to the content of this article.

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