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Structure Design and Optimization of a New Type of Subsea Pipeline Connector

Xiaoming Hu[1], Liquan Wang[2], Yong Liu[2], Rubo Ge[2], Lei Tan[2], Chuangye Fu[2*] and Zongliang Wei[2]

1. Offshore Oil Engineering Co., Ltd, Tianjin 300000, China
2. Underwater Operation Technology and Equipment laboratory, Harbin Engineering University, Harbin 150001, China

Abstract: The basic configuration of a new type of subsea pipeline connector was proposed based on the press-fitting principle, and a parametric finite element model was created using APDL language in ANSYS. Combining the finite element model and optimization technology, the dimension optimization aiming at obtaining the minimum loading force and the optimum sealing performance was designed by the zero order optimization method. Experiments of the optimized connector were carried out. The results indicate that the optimum structural design significantly improved the indicators of the minimum loading force and sealing performance of the connector.
Keywords: subsea pipeline connector; finite element model; zero order optimization method; structure size optimization
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1 Introduction

A subsea oil pipeline is a piece of conveying equipment for offshore oil and gas exploration; its safety is important to the normal operation of offshore oil development systems. The main reasons for subsea pipeline failure include corrosion, wave flow scouring, mechanical damage or the third party activities, seabed movement, and freezing (Liu, 2011). Once the subsea oil pipeline has leakage, it will affect not only the offshore oil production, but also the users' normal production and life. Therefore, when oil pipeline failure occurs, pipeline restoration work must be implemented immediately to reduce the loss caused by the pipeline leakage.

2 The structure design of a subsea pipeline connector

2.1 Characteristics of press-fitting connection

The press-fitting connection is a new technology for pipe connections. In this technology, the elastic and plastic deformation of the press-fitting connector will occur under an external force from the special loading device, so the gap between the connector and the pipe will be filled due to this deformation, which makes them connect tightly. The ends of the pipe do not need any treatment before this connection, so it can be applied to all kinds of pipes. It is simple and time-saving, no special skills are required, and no harm is done to the surroundings.

2.2 Structure of the subsea pipeline coupling

A pipeline repair connector was used to repair the spills of an 8 inch subsea pipeline of oil and gas; its structure is illustrated in Fig.1. The new connector consists of the middle part-one matrix and the outer part-two extrusion rings; the extrusion rings were moved to the middle part under the external mechanical loading, forcing the two pressure seal rings within the matrix at each end to tightly bite the pipeline surface to form the seal with the plastic deformations and complete the pipeline repairing function. The threaded section inside both ends of the matrix also produces radial contraction, which makes them mesh with the pipeline surface tightly, and prevents the pipeline from being plucked up; the threaded section has eight small open distributed chamfers that are good for radial contraction.

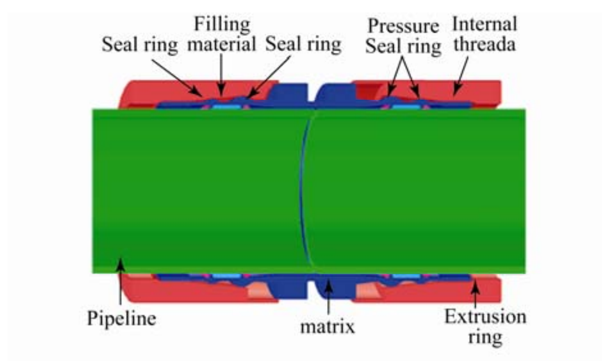

Fig.1 Structure sketch of subsea pipeline coupling

2.3 Connection method of the subsea pipeline coupling

The connector is installed by a specific method with special tools. The specific method is as follows: the outer extrusion ring on the connector is loaded by an external loading machine, causing the connector matrix to produce contraction in the radial direction because of the gap between the outer extrusion ring and matrix, and then the distortion is produced

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***Corresponding author Email:** fu19880725@163.com

in the process of the contact between the ring and pipeline surface, and will be filled into the surface gap for sealing.

3 Structure optimization of the pipeline repairing connector

As for the pipeline connector, the satisfactory sealing performance is the most important area, but in fact, the greater the contact pressure, the greater the plastic deformation of the seal pressure ring (Xu, 2002). It is known from the seal design principle that the seal contact pressure should be greater than the critical contact pressure and have a certain flexibility and rigidity; these two rules are incompatible (Li and Liu, 2007). Therefore, in order to get the best sealing performance and the smallest loading pressure, the ideal structure size must be calculated iteratively by the finite element method combined with the optimization.

3.1 The finite element model of the connector

The finite element model is the premise of acquiring a high precision result and it also can promote the calculation efficiency (Yu and Gao, 2007). In establishing the finite element model of the connector, the following measures should be taken.

The connectors and pipeline are both axisymmetric structures since the boundary conditions are axisymmetric around the centerline, so the 3-D model can be substituted for an axisymmetric model, which greatly improves the calculation efficiency and accuracy (Wang *et al*., 2002). In the finite element model of the connector, the threaded part and some model features are omitted, and the effect of the threaded section sustaining the axial force by meshing with the pipeline is simplified to the small radial displacement caused directly by the load.

Since the friction between the matrix and the extrusion rings does not have a significant effect on the connection performance of the connector, the friction can be ignored in the optimization process. The finite element model of the connectors is shown in Fig.2.

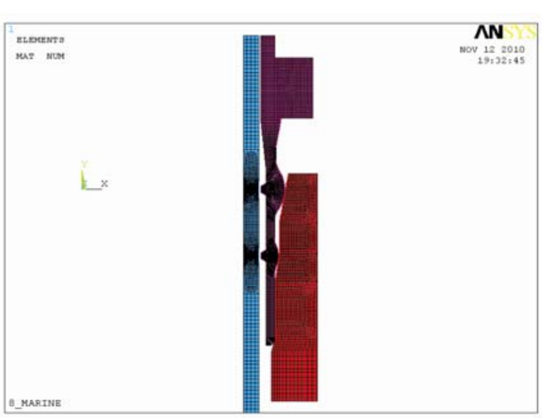


Fig. 2 Finite element model of the connectors

3.2 Multiple objective structure optimization of the connector

This paper focuses on the optimization of the connector structure size. A key size of the connector is chosen as the design variable to be optimized, and the optimal solution is acquired under some design constraints by iterative calculation to make the objective function approximate to the minimum of the design dimension. The zero order optimization can be used to deal with the optimization of a large scale and complex computation model, such as the optimization of the connector structure size (Xiaolan studio, 2004).

3.2.1 Structure size optimization based on the best sealing performance

In this paper, the average contact pressure of the main pressure seal ring contact surface is chosen as the objective function. The objective function values always decrease during the optimization process (Wang *et al*., 2004), while the contact pressure is always expected to increase. So a larger number is chosen to subtract the average contact pressure, and the result is taken as the objective function. In order to ensure that the connectors maintain a good seal in a fluctuating vibration, temperature, and pressure environment, the contact pressure evenly distributed in the contact surface and smaller plastic deformation of pressure seal ring are both important indexes of the design, and these two parameters are taken as constraint variables in the optimization process. Design variables include the basic size of the connector's sealing parts, the interference between the extrusion ring and connector matrix, and the clearance between the connector and pipeline. A total of these eight independent design variables form an 8-D design space. The mathematical model of structure optimization based on the best sealing performance is:

$$\text{Find} \quad X = \{x_1, x_2, \ldots\ldots x_n\}^{\mathrm{T}} \in R^n$$

$$\text{Min} \quad f(X) = 1000\overline{X} \qquad (1)$$

$$\text{s.t.} \quad g_{\mathrm{Min}} \le g_i(x) \le g_{\mathrm{Max}} \quad i = 1, 2, \cdots, 5$$

where, $X = \{x_1, x_2, \cdots, x_n\}^{\mathrm{T}}$, X are optimization design variables, which are respectively eight key connector structure sizes whose distribution is as shown in Fig.3. Objective function, $f(X)$ represents the result where a larger number subtracts the mean contact pressure of the main pressure seal ring. Constraint variables, $g_i(x)$ means variance of the maximal plastic deformation of extrusion rings and contact pressure of the contact surface, and the mean contact pressure of assisting sealing pressure ring interface, respectively.

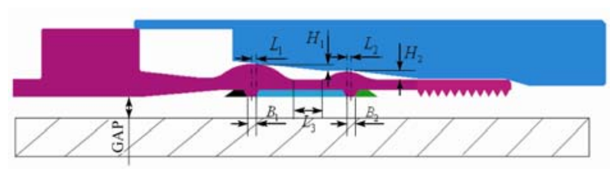


Fig.3 Schemes of design variables

The mean and variance of contact pressure are shown as Eqs.(2) and (3).

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{2}$$

$$S^2 = \frac{1}{n-1}\sum_{i=1}^{n}(X_i - \overline{X})^2 \tag{3}$$

$\overline{X}$ represents the mean contact pressure, S^2 means variance of contact pressure. Average contact pressure can be gained by calculating the mean value of the contact pressure of each contact element and the uniform distribution degree can be quantified by the variance of contact pressure of each contact element. The greater the variance, which shows that the contact pressure distribution is more discrete, the worse the uniformity is. With the combination of the finite element method and optimization techniques, after optimizing with the zero order optimization method, the convergence process of the objective function is shown in Fig.4.

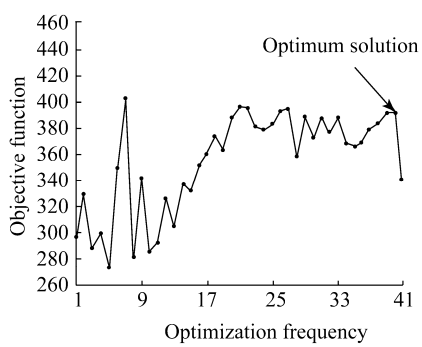
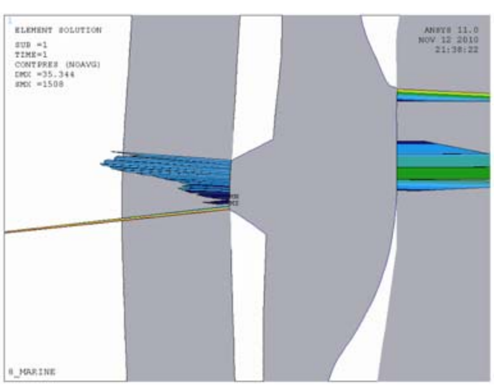
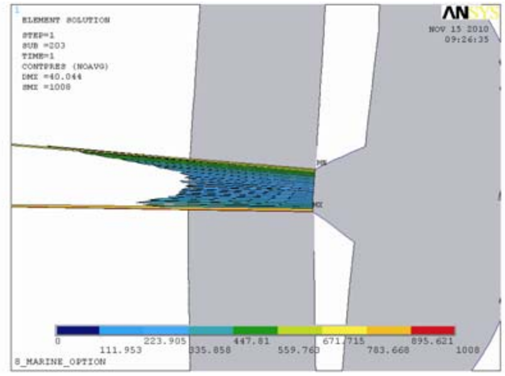


Fig.4 The convergence process of the objective function

It can be seen in Fig.4 that with the increasing number of optimization iteration, optimal solutions appear in the 40th iteration of the optimization process, which means the objective function reaches the minimum value; that is to say, the average contact pressure of the pressure seal ring gains the maximum value under constraints. Fig.5 intuitively shows that the average contact pressure and uniform degree increase significantly after the optimization, and the average contact pressure increases from the initial design of 298.8 to 394 MPa, while variance drops from 39200 to 21806.



(a) Initial design



(b) After optimization

Fig.5 The optimization effect of the main pressure seal ring contact pressure

3.2.2 Optimization design based on the minimum loading pressure

After the structure size optimization based on the best sealing performance, the connector's sealing performance shows obvious improvement. However, the largest loading pressure required is not significantly changed. Similar to the best sealing performance optimization design, the maximum load pressure can be reduced through the optimization of the connector size; the order flow files are written with APDL parameter design language, and optimization analysis is performed by the batch processing function. The design variables, the constraint variables, and the objective function are set according to the general procedure of optimization design.

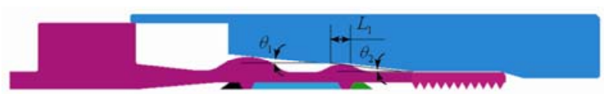


Fig.6 Schematic diagram of design variables

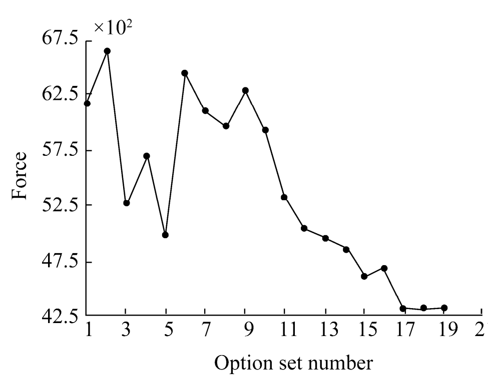


Fig.7 Varying curve of the maximum loading force with the optimization frequency

Three basic sizes are chosen including the extrusion ring angles θ_1, θ_2 and the extrusion tangent offset distance L_1 as the design variables, and the mean contact pressure and variance of the two sealing pressure rings and the maximal plastic deformation as the constraint variables is selected. The maximum loading force is taken as the objective function in the loading process. Fig.7 is the varying curve of the optimization design objective function based on the minimum loading pressure leaving out the friction. With the increase of the optimization number, the maximum loading pressure concussion declines constantly, from the initial 617 260 N to 430 046 N, 30.3% lower. The optimization effect is very obvious. Due to the program convergence in the 19th optimization, the optimization process automatically exits.

4 Experimental confirmation

The experimental prototype has been manufactured according to the optimum structure size. The connector connecting the two parts of the experimental pipeline was loaded directly by the pressure test machine. The loading process is shown in Fig.8. Pipe inner pressure rose slowly by using a handy pressure pump after the connector was installed on the pipeline. The experimental results are shown in table 1. When the pipe inner pressure was increased to 10 MPa, the connector still had no sign of leakage and the pipeline showed no axial displacement, but the pipeline presented a severe bulge at the blind end, leading to leakage at the interface of the pipe and handy pressure pump because of serious deformation, as shown in Fig.8. To this extent, the experiment should be finished. The connector section is shown in Fig.9 (the sealing material is omitted).

Table1 Connector pressure experimental results

Pressure /MPa	Holding time/min	Experimental result	Comment
4.5	30	No leakage in the connector and no pipeline axial displacement	
7.25	30	No leakage in the connector and no pipeline axial displacement	Both pipe ends are free end
10	–	No leakage in the connector and no pipeline axial displacement. Bulge emerged at the pipeline blind end, leakage emerged at the interface	

As shown in Table 1, it is a successful experiment; the connector's compression performance is much higher than the design performance, showing that the optimization process is effective.

Fig.8 Experimental confirmation

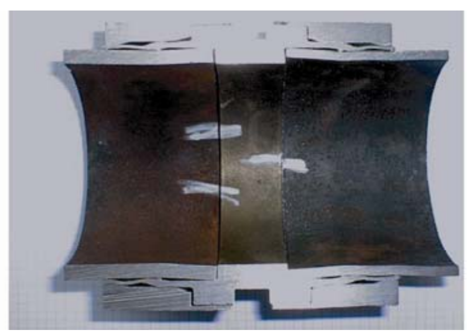


Fig.9 The connector section

5 Conclusions

Optimization design of the new type subsea connector structure was carried out by using finite element and optimization technology. It was proven that the indicators of the seal performance and the maximum loading pressure were improved after the optimization pressure experiment.

1) The seal performance of the connector was clearly improved. The maximum bearing pressure was increased by 40%.

2) The loading experimental results show that the largest loading pressure dropped from 146t down to 108t. In the optimization process the friction between the connector and pipeline along with the common difference of the pipelines were both ignored; the optimization was effective.

The experimental results show that connector structure size optimization is an important means to improve the design efficiency and performance.

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Xiaoming Hu senior engineer, has attended and presided over many scientific research projects and has a broad range of work experiences.

Liquan Wang PhD advisor, and the director of the Underwater Operations Technology and Equipment Lab. He has presided over many scientific research projects and has many papers published in domestic magazine and journal.