Research and Experiment on Repairing Damaged Jacket with Grouting Clamp Parametric Design Method

Bo Zhang
Harbin Engineering University

Zheming Lu (lzmlzm@hrbeu.edu.cn)
Harbin Engineering University

Zhuo Wang
Harbin Engineering University

Hongwen Ma
Harbin Engineering University

Research Article

Keywords: Local defects, Damaged jacket, Grouting clamp, Parametric design method

Posted Date: October 13th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3429788/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.
Research and Experiment on Repairing Damaged Jacket with Grouting Clamp Parametric Design Method

Bo Zhang¹, Zheming Lu², Zhuo Wang¹ and Hongwen Ma¹

Zheming Lu: lzmlzm@hrbeu.edu.cn

1 College of Mechanical and Electrical Engineering, Harbin Engineering University, Harbin 150001 China
2 College of Mechanical and Electrical Engineering, Harbin Engineering University, Harbin 150001 China

Abstract

This article studies the development of local rod defects caused by collisions between offshore platform jackets and ships, and proposes a parameterized design method for grouting clamps. We use clamps to reinforce and repair the defective areas. The principle is to make the axial displacement at the defect section zero, and calculate the structural size of the clamp from the center of the local defect to both sides. A grouting clamp with adjustable length was designed and a bidirectional embedded wedge-shaped tooth block structure was built in to improve mechanical preload. By comparing damage conditions with different defect ratios, the reinforcement and repair effect of grouting clamps on locally damaged jacket was studied. The bearing capacity of the defective jacket members repaired by the clamps increased by up to 80%, indicating that the grouting clamps have strong repair ability.

Keywords Local defects · Damaged jacket · Grouting clamp · Parametric design method

1 Introduction

The ocean plays a very important role in human future development strategies, with the extraction of resources such as wind, oil, and natural gas being an important component of global energy supply [1]. As one of the important resource extraction platforms, offshore platforms are prone to safety accidents due to their complex and difficult working conditions. In the past 40 years, there have been over 6000 offshore engineering accidents [2]. There are countless collisions with ships, and if there are serious defects or damages in the platform structure, it will be difficult to ensure the safety of the offshore platform. Therefore, it is necessary to repair and reinforce it to meet the safety and stability requirements of the platform. Among them, using grouting clamps for repair is a more reliable and convenient solution [3-4].

In 1986, the Elnashai team from Imperial College London in the UK conducted the first experiment on pressure grouting clamps [5]. In 1990, Foo J. et al. from Monash University in Australia conducted grouting clamp reinforcement connection experiments on common offshore platforms and offshore wind turbine jackets [6]. In 2001, the Jin WL team from Zhejiang University in China conducted a study on T-type grouting clamps using the Ottsoen failure criterion [7]. In 2007, Found Ocean company in the UK designed a segmented K-type grouting clamp and injected cement into the gaps after pipeline installation to improve the bearing capacity of the clamp [8-9]. In 2013, Professor Wang Z team from Harbin Engineering University in China designed large K-pipe and straight pipe grouting clamps, which were automatically opened and closed using hydraulic power [10]. In 2014, Professor Shi X team from Ocean University of China proposed a short bolt type grouting clamp and measured its sliding bearing capacity [11]. In 2017, the Jeong-Hwa Lee team from Korea's Goryeo University conducted a load-bearing performance study on grouting clamps subjected to eccentric and concentric loads [12]. In 2018, researchers Johansen A. and Soland G. from Det Norske Veritas discovered the axial bearing capacity of grouting clamps with shear keys under cyclic loading [13]. In 2019, Aragon T. from the University of Notre Dame in the United States conducted a study on the connection performance of grouted sleeve structures under seismic loads. It was found that the grouting strength has a significant impact on the strength of the sleeve connection [14]. In 2021, Chellappan N. from the Indian Institute of Technology in India conducted a bearing capacity study on a 1:8 ratio model of grouting clamps, and found that the bearing capacity of pipelines repaired with grouting clamps under tensile and compressive loads increased by at least 1.6-2 times [15]. In 2022, Professor Peng SM from Zhengzhou University in China studied the properties of polypropylene fiber grouting materials and the mechanical properties of their grouting clamps. He found that grouting materials containing polypropylene fibers made the distribution of bonding stress more uniform [16].

Analyzing the development of grouting clamps at
home and abroad, many reinforcement technologies are based on the reliability and feasibility of maintenance construction. The effect of installing grouting clamps to strengthen local defects in marine jackets is qualitative analysis, so it is necessary to conduct in-depth quantitative assessment of the ultimate load-bearing capacity of grouting clamp reinforcement. Dr. Aritenang W. from the University of London and Professor Foo J. from Monash University in the early 1990s proposed a design formula for prestressed grouting sleeve connections under axial load. In 2007, Det Norske Veritas also proposed a design formula for grouting sleeve connections under two composite loads: torque and axial force, bending moment and shear force. It can be seen that the design of grouting clamps is a single design without standardized parameterization. Therefore, this paper will study the standardization parameterization of grouting clamps. The object of the design is to reduce the strength of local defects in the straight pipe or node of the jacket without instability. When there is a fracture trend, bending or crushing will occur at the defect location as the bending point. This local unstable defect can be regarded as a plastic hinge joint, and the design of the clamp will be centered around its plastic defect location. Therefore, an analysis of the current research status of plastic hinge theory will also be conducted.

In 1965, Norwegian researchers Wen and Janssen first proposed a bilinear element model for early research on plastic hinge theory, as well as the subsequent dual component element model proposed by researchers Clough and Benskna [17]. In 1994, at the ASME Design Automation Conference in the United States, plastic hinge theory was summarized to provide more accurate and effective modeling of structures in impact or collision situations. The concept of plastic hinge model has begun to be widely applied [18]. In 2000, Professor Richard from the National University of Singapore focused on the inelastic stiffness formula of three-dimensional beam column elements, and also emphasized the design impact of geometric defects on the ultimate load of the system [19]. In 2014, researchers from Montuori in Italy and others discussed the results of nonlinear static pushover and dynamic analysis for designing structures, with the aim of designing structures that fail in the overall mode [20]. In 2016, Associate Professor Lin H from China University of Petroleum established a structural failure path search and probability assessment scheme for offshore jackets, introducing the Alternative Load Path Method (ALP Method) [21]. In 2020, Professor Li HW from China Taiyuan University of Technology established an element plastic hinge model, considering the effects of damage and node stiffness, simulating the failure process of plastic hinges and exploring their cumulative damage failure mechanism [22]. In 2022, Professor Li ZN of Jeonbuk National University in South Korea and others proposed a new simulation element to simulate the semi-rigid behavior of plastic hinge connections, and discussed its application in the analysis of steel tube frame structures [23].

This article synthesizes previous research and studies the development and harmfulness of plastic hinge defects in steel structural members of jacket structures. At the same time, a parameterized design method for grouting clamps is summarized and proposed. Based on this method, a bidirectional embedded mechanical grouting clamp is designed, and mechanical bearing experiments are conducted on the clamp to explore its reinforcement effect.

2 Load and Defect Strength Analysis of Jacket Platform

2.1 Establishment of finite element model for jacket platform

Considering that the research object of this study is a defective offshore platform jacket, as shown in Figure 1, ABAQUS/Aqua was used for finite element analysis and solution, using the meter system of units.

![Fig. 1 Schematic diagram of jacket model](image)

The overall size of the adopted jacket is 25×25×40 m, the main structural steel is S355 grade marine steel, with yield strength and tensile strength corresponding to Q345 low alloy steel in China. Its elastic modulus $E = 2.1 \times 10^{11}$ Pa, Poisson's ratio $\nu = 0.3$, yield stress magnitude $384 \times 10^6$ Pa, and density $\rho = 7850$ kg/m$^3$ will be simulated using the B31 beam element type. The structural dimensions are shown in Table 1.

<table>
<thead>
<tr>
<th>Component Name</th>
<th>Leg</th>
<th>Pile</th>
<th>Knighthead (Battered)</th>
<th>Knighthead (Horizontal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>1.4m</td>
<td>1.4 m</td>
<td>0.6m</td>
<td>0.36m</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.07 m</td>
<td>0.1m</td>
<td>0.024 m</td>
<td>0.01m</td>
</tr>
<tr>
<td>Angle</td>
<td>12°</td>
<td>90°</td>
<td>38°</td>
<td>180°</td>
</tr>
</tbody>
</table>

For the boundary conditions of the platform, the treatment of pile soil effect will be treated as a simplified equivalent pile, that is, fixed support will be used at a pile diameter of 6 times below the seabed [24]. Using a static universal analysis step, set the analysis step to 1 second, with a maximum increment step of 100 and a minimum increment step of, and turn on the nonlinear switch.
The environmental conditions are set to a certain offshore sea state in the Bohai Sea, and the working depth of the platform is 28m. The total load of the platform is 1140t. To simplify the calculation, it is simplified as a concentrated force load, which is applied to the reference point of the platform rigid body to transfer to the top of the jacket. The environmental loads on the jacket platform are as follows.

1) Current load. Under general sea conditions, currents can be considered constant. The drag force generated when the ocean current passes through the surface of the jacket structure, and the calculation formula for the structural material load per unit length.

\[ f = \frac{1}{2} \rho C_p D \nu_c^2 \]  

Where: \( \rho \) is the density of seawater, \( C_p \) is the force coefficient, \( D \) is the characteristic width of the structural component, and \( \nu_c \) is the current velocity at the seabed height \( z \).

The sea state data takes the upper layer velocity as 0.72m/s, the middle layer velocity as 0.57m/s, and the bottom layer velocity as 0.

2) Wave loads. Due to the fact that the jacket platform is a rod structure and the ratio of the lateral dimensions to the wavelength of the components is very small (\( D/L < 0.2 \) can be referred to as a small-scale structure), the modified Morison formula can be used, which only includes drag and inertia forces. The following is the formula for the horizontal wave force per unit length.

\[
\begin{align*}
    f_d &= 0.5 C_d \rho A U^2(t) \\
    f_i &= C_M \rho V \frac{dU}{dt} \\
    f_I &= f_d + f_i
\end{align*}
\]  

Where: \( f_d \) is the total horizontal wave force, \( f_d \) is the horizontal drag force, \( f_i \) is the horizontal inertial force, \( A \) is the projected area, \( V \) is the volume of the structure, \( C_d \) is the drag force coefficient, and \( C_M \) is the inertial force coefficient.

Considering extreme sea conditions, the wave height \( H = 5.1m \), wave cycle \( T = 6.2s \), wavelength \( L = 58.1m \), wave velocity \( v = 9.37m/s \) are taken.

3) Wind load. The calculation of the wind load generated by the continuous wind pressure on the structure caused by sea breeze mainly depends on two variables, namely wind pressure \( P \) and structural compression area. The wind speed is 12m/s.

\[ P = 0.5 \rho V^2 \]

Where: \( \rho \) is the offshore density of air, and \( V \) is the sea wind speed.

Wind load calculation formula:

\[ F = C_s C_h SP \]

Where: \( P \) is the wind pressure, \( S \) is the projected area of the wind component, \( C_s \) is the shape coefficient of the wind component, and \( C_h \) is the height coefficient of the wind component.

4) Sea ice load. The sea ice load will mainly act on the jacket in the tidal range area. Based on the sea conditions in the Bohai Sea, the sea ice load of \( 1.828 \times 10^6 N \) will be taken, and the compression formula for sea ice load from the China Shipbuilding Inspection Bureau will be used.

\[ F = K I m D H \sigma_c \]

Where: \( K \) is the contact coefficient, \( I \) is the compression coefficient, \( m \) is the shape coefficient, \( D \) is the width of the extrusion surface, and \( \sigma_c \) is the uniaxial compressive strength of the ice.

Fig. 2 Reduction coefficient of ice pressure on each pile

In the simulation process, due to the shielding effect of the main leg located in the front jacket on the rear row, the ice pressure on the main leg in the rear row was reduced [25]. To simplify the calculation, it is applied as a concentrated force load on the node of the jacket member.

The stress cloud map of the complete jacket platform can be obtained through simulation, with a maximum value of 259.9MPa. As shown in Figure 3, the jacket platform structure did not experience severe plastic strain. At the same time, a displacement map of the complete jacket platform can be obtained, as shown in Figure 4. The maximum displacement value is 0.1727m, which is less than the allowable maximum displacement value of 0.262m.

Fig. 3 Jacket stress cloud chart
2.2 Locally damaged members of the jacket platform

The members of the jacket platform may be subjected to external impacts, such as ship collisions and falling object collisions, as the horizontal deflection at the midpoint of the member is the maximum. Therefore, it is assumed that the member will produce plastic hinges at the midpoint of the damaged member in collision under large displacement loads.

For the jacket platform, three typical locations on its structure are selected for impact analysis, as shown in Figure 5, which are main leg, slant support and flat brace. Assuming that the side board impact of the bow part of a bulk carrier is artificially impacted by external forces, as shown in Figure 6, no energy is absorbed throughout the entire process, the changes and patterns of depressed defects caused by the impact are studied.

During the collision between the ship and the jacket platform, the jacket structure absorbs the kinetic energy carried by the ship through material deformation and displacement. Therefore, the energy generated by the collision can be approximately equivalent to the kinetic energy of the ship, calculated as follows:

$$ E = \frac{1}{2} \alpha m v^2 \quad (6) $$

Where: $\alpha$ is the additional mass coefficient, taken as 1.4 during side impact.

When the initial impact energy consumption meets the conditions, the strain of the structure reaches the limit strain, or the node of the jacket loses its load-bearing capacity, the calculation stops. The characteristics of each working condition are shown in Table 2.

<table>
<thead>
<tr>
<th>position</th>
<th>Ship</th>
<th>velocity</th>
<th>dimensions</th>
<th>strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1500t</td>
<td>1.0m/s</td>
<td>1.4×0.07m</td>
<td>355MPa</td>
</tr>
<tr>
<td>2</td>
<td>1000t</td>
<td>1.0m/s</td>
<td>0.6×0.024m</td>
<td>355MPa</td>
</tr>
<tr>
<td>3</td>
<td>500t</td>
<td>1.0m/s</td>
<td>0.36×0.01m</td>
<td>355MPa</td>
</tr>
</tbody>
</table>
2.3 Residual Strength Analysis of Defective Rods

In order to calculate the residual strength of defective members in the design parameters of grouting clamps, it is convenient to use grouting clamps for repairing and strengthening damaged members, and to compare the ultimate bearing capacity of the jacket after strengthening with grouting clamps. It is necessary to calculate the residual strength of defective rods. The article uses the Ellinas model based reduction coefficient method to analyze the residual strength and bearing capacity of defective bars [26].

\[ P_{res}^* = \phi P_{ud} \]  

(7)

Where: \( P_{ud} \) is the remaining bearing capacity of the damaged member, \( A_d \) is the effective cross sectional area of the damaged member.

During the loading process, because the relationship between residual strength and depression depth can provide a lower limit reference value for the residual strength of damaged steel pipes when the boundary conditions are set to simply supported at both ends, free coupling is used to set the reference point and displacement load is set at the loading point, as shown in Figure 11.

![Condition 1](image1)
(a) Condition 1

![Condition 2](image2)
(b) Condition 2

![Condition 3](image3)
(c) Condition 3

**Fig. 10 Finite Element Model of Damaged Circular Pipe**

To solve its residual strength, the arc length method (Riks method) will be used for axial crushing simulation next. Under the conditions of uncertain displacement and load, the arc length method can effectively track the loading path of the model structure, especially in solving the critical load value of the model structure and the response of the model structure after instability. It is currently one of the most efficient and stable iterative methods in nonlinear analysis. Import the damaged member model after ship collision into another new CAE file to add initial analysis status for axial loading simulation.

Due to the initial damage deformation and residual stress of the damaged circular tube during the simulation process, the defect section on the concave side of the middle section gradually yields during the increase of axial loading displacement, quickly forming a plastic hinge area, and further loading leads to axial collapse, resulting in complete failure.

As mentioned earlier, the development process of plastic hinges is the same. In the elastic stage, the stresses at points on the cross-section are all within the allowable stress values; When in the plastic stage, the stress at the section point on the concave side exceeds the allowable stress, and then the stress at the point on the back of the concave side also exceeds, forming a plastic hinge area. At this point, the maximum axial loading force is reached, which is equivalent to the maximum residual strength of the defective member.

The residual strength results of the members under the above working conditions are shown in Table 3, with both ends hinged.

<table>
<thead>
<tr>
<th>Position</th>
<th>Slenderness ratio</th>
<th>Diameter to thickness ratio</th>
<th>Residual strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>20</td>
<td>25.407x10^5KN</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>25</td>
<td>9.343x10^5KN</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>36</td>
<td>0.913x10^5KN</td>
</tr>
</tbody>
</table>

*Table 2 Residual strength of the rod*

Obviously, diagonal brace and horizontal brace with large diameter thickness ratio are more prone to deformation, and the residual strength decreases with the increase of diameter thickness ratio. And the residual strength calculated by equation (7) is similar to the simulation results, so it is used as the formula for calculating the residual strength at the defect location of the jacket. It is required to meet the necessary conditions for local defect strength reduction without instability. When the damaged steel pipe is 0.4<\( D <1 \), its residual strength is significantly less than 0.3 times the yield strength, which clearly cannot guarantee reliability.

At the same time, in order to simplify the model in subsequent reinforcement bearing capacity analysis experiments, the concave defects under the same working conditions were compared with the circular hole defects to obtain a circular hole defect model with approximate maximum residual strength. The design results were as follows: in working condition 1, the diameter of the circular hole was 0.76m, the defect ratio was about 0.5, in working condition 2, the diameter of the circular hole was 0.18 m, the defect ratio was about 0.3, and in working condition 3, the diameter of the circular hole was 0.28m, and the defect ratio was about 0.8. Working conditions 1-3 are shown in Figure 11, which facilitates the calculation of the length of the hazardous area in the subsequent design process and prepares for the parameterized structural design of the grouting clamp.

![Condition 1](image4)
(a) Condition 1

![Condition 2](image5)
(b) Condition 2
In the figure, their respective maximum residual strength is the maximum value of axial loading force, and their maximum residual bearing capacity is basically the same.

3 Parametric Structural Design of Grouting Clamps

3.1 Main design of grouting clamps

This clamp is designed as a two petal wrapping structure, which is fixed by bolts to achieve clamping of the pipeline, as shown in Figure 15. Then, an expansion high-pressure cement slurry is injected into the area between the damaged jacket and the grouting clamp, which solidifies into a grouting ring to provide expansion stress.

The device structure can be divided into two parts, a bidirectional wedge-shaped tooth block clamping mechanism and a two disc wrapping structure. The bidirectional wedge-shaped tooth block mechanism consists of three wedge-shaped tooth structures distributed in a 120° circular pattern. This structure mainly consists of wedge-shaped blocks, adjustable wedge-shaped tooth blocks, and sliding bases to provide mechanical preload. After installation, use the threaded rods on both sides to push the wedge block, so that the bottom teeth of the wedge block are better embedded into the surface of the rod.

3.2 The main principles of parametric design methods

The main principle of the parameterized design method for grouting clamps is that when a defect occurs in the jacket, the defect position is set as the hinge point. Therefore, the jacket will be bent and broken with the hinge point as the support point, causing the axial displacement of the support point to be zero. The structural size of the clamp will be calculated from the center of the local defect to both sides.

The force direction of the grouting clamp comes from the axial and radial directions, so the effect of radial force can be simplified as bending moment, providing convenience for the analysis process in the following text, the axial force of the unified clamp is $F_z$, and the bending moment is $M_w$.

1) When the load is the axial force $F_z$, the influence length of the defect is solved.

As shown in Figure 16, based on the actual stress situation, the damaged jacket can be considered as a simply supported beam for calculation. In the calculation, it is assumed that the moment at this position is balanced, so the axial pressure is equal. Due to the symmetrical load distribution and geometric structure of the damaged member, only half of it needs to be analyzed [27].
Establish a coordinate system as shown in the figure, with the defect position as the origin, and construct the differential equation of the deflection curve of the beam as follows:

$$EI \frac{d^2w_0}{dx^2} = -\frac{F_x D}{2} 0 \leq x \leq L_0$$  \hspace{1cm} (8)

Where: $w_0$ is the deflection of the damaged pipe at the defect, $L_0$ is half the span length of the defect, $D$ is the outer diameter of the damaged pipe, $E$ is the elastic modulus of the pipe material, and $I$ is the moment of inertia of the pipe section.

According to the symmetry of the submarine pipeline, the slope of $w_0$ at $x=0$ is equal to zero, and the displacement at $x=L_0$ is also equal to zero, so the boundary conditions of the damaged pipeline are:

$$\left. \frac{dw_0}{dx} \right|_{x=0} = 0, \quad w_0\left|_{x=L_0} = 0 \right.$$  \hspace{1cm} (9)

Putting Equation (1) into Equation (2), the defect waveform function formed by the damaged pipeline under the condition of external torque can be obtained as:

$$w_0 = -\frac{F_x D}{4EI} x^2 + \frac{F_x DL_0^2}{4EI}$$  \hspace{1cm} (10)

Therefore, the support height is $w_{lim} = w_0(0) = \frac{F_x DL_0^2}{4EI}$, and its defect half wavelength is $L_0 = \left(4EIw_{lim}/F_xD\right)^{1/2}$. When a defect occurs there, the depth of the defect is considered to be the radius of the damaged pipe, so the influence length of the defect can be calculated.

2) When the load is the bending moment $M_{w1}$, $M_{w2}$, the influence length of the defect is solved.

According to the force analysis in the figure, the following moment conservation equation can be listed:

$$\frac{FL_x}{2} = M_w$$  \hspace{1cm} (11)

Establish the coordinate system as shown in the figure, take the defect position as the origin, and construct the deflection curve differential equation of the beam as:

$$EI \frac{d^2w_0}{dx^2} = -M_w + F_x \quad 0 \leq x \leq L_0$$  \hspace{1cm} (12)

Where: $L_0$ is the length of the damaged pipe.

According to the symmetry of the submarine pipeline, the slope of $w_0$ at $x=0$ is equal to zero, and the displacement and slope at $x=L_0$ are also equal to zero, so the boundary conditions of the damaged pipeline are:

$$\left. \frac{dw_0}{dx} \right|_{x=0} = 0, \quad \left. \frac{dw_0}{dx} \right|_{x=L_0} = 0, \quad w_0\left|_{x=L_0} = 0 \right.$$  \hspace{1cm} (13)

Putting Equation (12) into Equation (13), the defect waveform function formed by the damaged pipeline under the condition of external torque can be obtained as:

$$w_0 = \frac{M_L L_0^2}{2EI} \left(1 - 3x^2 + \frac{2x^3}{L_0^2} \right)$$  \hspace{1cm} (14)

Therefore, the support height is $w_{lim} = w_0(0) = \frac{M_L L_0^2}{6EI}$, and its defect half wavelength is $L_0 = \left(\frac{6EIw_{lim}}{M_L}\right)^{1/2}$. When a defect occurs there, the depth of the defect is considered to be the radius of the damaged pipe, so the influence length of the defect can be calculated.

3) According to the analysis of the above two situations, the overall length of the clamp can be determined by multiplying the calculated influence length by the safety factor. The safety factor selected in this design is 1.5 [28].

3.3 The main steps of the parametric design method

3.3.1 Determination of the type and material of grouting clamps

Firstly, based on the form of the damaged jacket, the types of grouting clamps, such as I type, K type, T type, and X type are selected.

The material of the grouting clamp should be of the same grade as the material of the damaged jacket member that needs to be reinforced, to avoid electrochemical corrosion caused by material grade differences underwater; Choose Portland cement mixed with expansion agent as the grouting material to increase its expansion pressure. If the subsequent verification calculation results do not meet the expected requirements, replace the material type until the expected standards are met.

3.3.2 Preliminary determination of length parameters
of grouting clamps

1) Initially determine the diameter of the clamp end according to the outer diameter of the pipe.

2) The length of the grouting clamp is preliminarily determined according to the design principle. Considering the grouting clamp subjected to bending moment and shear force, the length-diameter ratio of the connecting piece should be designed to be between 1.3 and 1.9.

3) The thickness of the grouting ring is initially determined to be between 30 and 80 mm, and then the inner diameter of the grouting clamp is determined.

4) Determine the wall thickness of the grouting clamp, and then determine the outer diameter of the clamp.

Referring to the relevant standards of GB150-1998 "Steel Pressure Vessel", taking carbon steel material as an example to solve, the calculation expression of wall thickness is derived as:

\[
S = \frac{PD}{2(\sigma)\phi - P}
\]  
(15)

Where: \( S \) is the wall thickness of the grouting clamp, \( P \) is the pressure of the grouting clamp, \( D \) is the inner diameter of the grouting clamp, \( \sigma \) is the allowable pressure of the grouting clamp material, and \( \phi \) is the coefficient of the welded joint.

Fig. 18 Wall thickness change diagram of grouting clamp

As shown in Figure 18 the wall thickness \( S \) of the clamp varies with the inner diameter \( D \) of the clamp and the pressure \( P \). The influence of the pressure is greater, so the calculation accuracy of the pressure is required to be higher in the design.

3.3.3 Slip Check of Grouting Clamps

Install grouting clamps on the damaged jacket, as shown in Figure 19. There is bonding and friction between the grouting ring and the damaged jacket. The combined force of the pre tightening friction force \( f_1 \) generated by the top of both sides of the clamp, the friction force \( f_2 \) generated by the grouting ring, the remaining allowable pressure \( f_3 \) of the damaged offshore jacket members that need to be reinforced at the defective section, and the friction force \( f_4 \) generated by the clamping of the wedge-shaped tooth blocks inside the clamp will bear the load \( F_g \).

blocks inside the clamp will bear the load \( F_g \).

Error! Reference source not found.

Fig.19 Stress analysis of grouting clamp

1) Assuming that the resultant force required to secure the grouting clamp is \( P \), so:

\[
P = N \cdot F_{bo}
\]  
(16)

After locking the welded flange plates of the clamps on both sides with bolts, a preload force \( p_n \) is generated at the end, which can also be expressed as:

\[
P = p_n \cdot d_n
\]  
(17)

Where: \( d_n \) is the diameter of the damaged offshore jacket member, \( N \) is the number of bolts, and \( F_{bo} \) is the bearing capacity of a single bolt.

According to equations (16) and (17), the calculated pre tightening friction force at the end of the clamp is:

\[
f_1 = 2\pi d_n p_n \mu_s = 2\pi P \mu_s = 2\pi N \cdot F_{bo} \mu_s
\]  
(18)

Where: \( p_n \) is the pre tightening force of the metal steel body at the top of the clamp, \( \mu_s \) is the friction coefficient of the metal at the top of the clamp, and \( b \) is the width of the clamp end.

2) After mixing cement slurry and FEA expansion agent, the original empirical formula should be improved according to the effect of the expansion agent on expansion stress, so the new empirical formula is

\[
f_{aw} = 10KC_s f_{cu}^{0.5} + \mu C_p P
\]  
(19)

Where: \( f_{aw} \) is the sliding stress of the grouting clamp, \( K \) is the radial stiffness coefficient of the material, \( C_s \) is the ratio of the length to the diameter of the material, \( C_s \) is the surface condition coefficient, \( f_{cu} \) is the compressive strength of the characteristic grouting, \( \mu \) is the friction coefficient between the grouting material and the steel pipe, \( C_p \) is the expansion pressure enhancement coefficient, and \( P \) is the stress between the cement slurry layer and the defective steel pipe.

The radial stiffness coefficient of the material \( K \) is defined according to the following formula:
\[ K = \left( \frac{D}{t} \right)^{3/4}/m + \left[ \left( \frac{D}{t} \right)_p + \left( \frac{D}{t} \right)_k \right]^{3/4} \]  
(20)

Where: \( m \) is the ratio of the elastic modulus of the damaged jacket to the grouting material, \( D \) is the outer diameter of the material, and \( t \) is the thickness of the material.

The subscripts g, p, k denote the three materials used for the grouting ring, the damaged pipe and the clamp, respectively.

The ratio of length to diameter of a material \( C_i \) is defined according to the following formula:
\[ C_i = \left( \frac{S}{D} \right)^{3/4} + q^{(S/D)} \]  
(21)

Where: \( S/D \) is the ratio of length to diameter, \( n \) is the calibration coefficient, and \( q \) is the calibration coefficient.

The expansion pressure enhancement coefficient \( C_p \) is defined according to the following formula:
\[ C_p = 0.604 \frac{P}{P_{f0}} + 0.61 \]  
(22)

3) The expression for the residual allowable pressure \( f_3 \), at the defect of the steel pipe is:
\[ P_{ud} = \phi \frac{F_k}{\tau} \]  
(23)

4) The expression for the frictional force \( f_4 \) generated by the clamping of wedge-shaped tooth blocks is:
\[ f_4 = 3 \mu_f F_k \]  
(24)

The condition for preventing slippage is \( F_s \leq (f_1 + f_2 + f_3 + f_4) \), the sum of the above three pressures is less than the axial pressure.

3.3.4 Calculation and selection of connecting bolts

When the clamp has a continuous grouting ring, and in working state, the shrinkage of the clamp itself will reduce a part of the bolt load, so the pre-applied stress on the grouting ring will become smaller, which will cause the sliding load. force calculations have a detrimental effect and should be taken into account.

According to the calculation of the force balance condition, the stress between the clamp and the grouting ring \( P_0 \) is:
\[ P_0 = \frac{NF}{2R_0L_s} \]  
(25)

Where: \( N \) is the number of bolts of the clamp, \( F \) is the load of a single bolt, \( R_0 \) is the inner radius of the clamp, and \( L_s \) is the length of the clamp.

According to the equilibrium conditions, the stress between the grouting ring and the surface of the damaged offshore jacket member can be obtained:
\[ \varepsilon_i (P, R_0) = \varepsilon_1 (P, R_0) + \varepsilon_2 (P, R_0) \]  
(26)

Knowing the pressure \( P_0 \), based on the strain boundary and equilibrium conditions, one can formulate the equation for the strain between the cement grouting ring and the damaged jacket:
\[ P_i = \lambda P_{f0} \]  
(27)

Where: \( \lambda \) is the pressure transfer coefficient of the grouting ring.

According to the obtained expansion pressure, the pressure \( P_i \) between the clamp and the cement grouting ring can be calculated by formula (27), and then the total working tension \( F \) of the bolt can be calculated by formula (26), and the effective diameter of the bolt can be calculated by the following formula.
\[ d \geq \frac{4 \times 1.3 F}{n \sigma} \]  
(28)

3.3.5 Strength check of grouting clamps

When it is subjected to axial pressure and bending moment during reinforcement, the strength check method in the axial direction is as follows:
\[ \sigma \leq \frac{N}{A} \pm 0.9 \sqrt{\frac{M_x^2 + M_y^2}{W}} \leq [\sigma] \]  
(29)

Where: \( M_x, M_y \) the bending moments centered on the x-axis and the y-axis, \( \sigma \) is the axial pressure of the clamp, \( N \) is the axial force received by the clamp, \( A \) is the area of the clamp section, and \( W \) is the flexural section modulus of the clamp section. \([\sigma]\) is the allowable stress of the clamp material.

If the clamp is subjected to the combined action of bending moment and torque, and the shear force has a greater effect on it, the check method is:
\[ \tau = \frac{2}{nD} \sqrt{Q_x^2 + Q_y^2 + T^2} \leq [\tau] \]  
(30)

Where: \( Q_x, Q_y \) shear force along the x-axis and y-axis respectively, \( \tau \) is the shear stress of the clamp section, \( T \) is the section torque of the clamp, \( t \) is the thickness of the clamp, \( D \) is the outer diameter of the clamp, \([\tau]\) is the allowable shear force of the material.

Finally, the strength check formula can be used to check the clamp. If its strength is insufficient, it is necessary to modify the size or material parameters of the clamp according to the actual situation until it meets the requirements.

4 Analysis of bearing capacity of grouting clamp reinforcement

4.1 Design example of grouting clamp

After strengthening damaged jacket members with grouting clamps, the main failure mode under axial and transverse loads is the adhesion and sliding failure of the pipe fittings and grouting material. This section will carry out detailed design and calculation of grouting clamp for the defect of slant support, and verify the reinforcement reliability and repair effect through simulation. At the same time, the clamp design and simulation results under two other working conditions with defects will also be provided for
is the initial elastic modulus,
is the plastic strain,
is the bearing capacity analysis.

1) Parameter determination of grouting clamps
The outer diameter of the defective slant support is 600mm, and the diameter of the defective part is 180mm, so the defect ratio is about 0.3. According to the design standard, the specific length is 2273mm. The thickness of the grouting ring is 80mm, and the inner diameter of the clamp is 760mm. Calculate the wall thickness of the clamp (safety factor 2.1) to be approximately 12mm, and the initial outer diameter of the clamp is 784mm.

2) Calculation of slip force of grouting clamps
The slip force of the clamp consists:

\[ f = f_s + f_r + f_t + f_f \]
\[ = 2\pi P\mu_n + A(10KC_c f_{cu} + \mu C_p P) + \phi_s P_d + 3\mu F_t \]  
\[ = 9047786.84 + 45068716.28 + 9343000 + 372600 \]
\[ = 55423403.12N \geq F_t \]

3) Determination of bolts
The initial selection is to use 48 bolts to meet the length requirements, and ensure that the reinforcement and repair effect of the grouting clamp meets the standards, the fullness of the grouting material needs to be greater than 75%. According to equations (26) and (27), the expansion pressure can be calculated, and then the bearing capacity on a single bolt can be calculated using equation (18):

\[ F = \frac{2\pi P L_b}{N} = 5.58 \times 10^6 \text{N} \]

The clamp is made of Q345 steel and the bolt is made of 42CrMo alloy steel with a tensile strength of 800MPa. The allowable stress is obtained by taking a safety factor of 2.1. Furthermore, the minimum effective diameter of the bolt is calculated from equation (28), corresponding to the M18 bolt, with a safety factor of 1.5. Therefore, M27 bolts (GB/T 12618-2019) are used, with an effective area of 459 and an ultimate bearing capacity of 3.62x10^6N, meets the strength requirements, and its pre tightening force refers to the pre tightening force comparison table of high-strength bolts (GB/T 1231-2006). Considering the external load and expansion pressure on the grouting clamp, the maximum pre tightening force of 1.3x10^6N is selected.

4) In the calculation of working condition of defective slant support, the designed grouting clamp is only subjected to axial load, and the radial load is not included temporarily. Later analysis and research will be carried out, and the strength check will be verified by the simulation results.

4.2 Finite element simulation of grouting clamps
1) Geometric and damage plastic models.
   Firstly, the SOLIDWORKS software was used to establish a model of the aforementioned grouting clamp, and then it was imported and assembled and fixed to the defect of the damaged rod. The cross-sectional size of the damaged rod used in the model is the same as the actual size of the jacket rod on the offshore platform. The established geometric modeling of the grouting clamp is shown in Figure 20.

![Fig.20 Reinforced specimen geometric modeling](image) Because both steel pipe members and grouting clamps undergo significant plastic deformation under compression, an elastic-plastic damage model is adopted, and the stress-strain constitutive relationship can be divided into two stages: elastic and plastic. Elastic stage:

\[ \sigma = E_0 \epsilon_t \]

Plastic damage stage:

\[ \sigma = (1 - d_i) E_0 (\epsilon - \epsilon_i) \]

Where: \( E_0 \) is the initial elastic modulus, \( d_i \) is the tensile and compressive damage coefficient, \( \epsilon \) is the elastic strain, \( \epsilon_t \)

Material properties parameters of grouting materials are shown in the table below.

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus (GPa)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grouting material</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Portland cement (P.O42.5) and 10% expansion agent (FEA100)</td>
<td>30</td>
<td>0.2</td>
</tr>
</tbody>
</table>

2) Grid division. In the analysis model, the grid division size for different components, clamps, and grouting materials is 0.02m, 0.01m for flange plates, and 0.05m for damaged members.

3) Unit contact. The clamp, grouting ring, and defective rod components all use a hexahedral solid unit C3D8R. Due to the good bonding performance between the clamp and grouting ring, their contact is set as binding: The grouting ring and the defective rod are in surface contact, with a normal "hard contact" and a tangential friction coefficient of 0.54.

4) Boundary conditions. For the convenience of comparison, its boundary conditions are the same as those in Chapter 2. Reference points are set at the same distance between the two ends, and all node degrees of freedom on the end face are coupled with them. Finally, one end of the reference point is set to
"completely fixed"; Set the displacement in the Z direction on the reference point at the other end.

In order to simplify the model and facilitate calculation, the bolts were omitted. Instead, bolt force was added to the clamp flange plate, and the bolt pre tightening force was equivalent applied to the clamp flange plate. An expansion pressure of 1.55MPa was applied to the outer surface of the grouting ring and the inner surface of the clamp.

4.3 Analysis of finite element simulation results of grouting clamps

Because the reinforcement and repair of grouting clamps largely rely on the chemical bonding force and friction force between the grouting ring and the surface of the damaged pipe fittings, during the axial compression process of the reinforced defective rod with the clamps, the damage will cause the damaged pipe fittings and the grouting ring to slip. At this time, the maximum axial loading force is the maximum sliding bearing capacity of the grouting clamp, as shown in Figure 21, with a maximum sliding bearing capacity of 16782.6KN, The residual strength of the defective rod is about 0.5 times that of it.

The maximum sliding bearing capacity of a steel pipe rod with a defect ratio of 0.5 is 87146.4KN, and the residual strength of the defective rod is about 3.5 times that of it, as shown in Figure 22; The maximum sliding bearing capacity of the steel pipe rod with a defect ratio of 0.8 is 3384.34KN, and the residual strength of the defective rod is about 4.5 times that, as shown in Figure 23.

It can be clearly observed that there are patterns. After the damaged steel pipe members are reinforced and repaired with grouting clamps, the larger the defect ratio, the more obvious the repair effect. That is, the maximum axial bearing capacity of the damaged steel pipe members after reinforcement has been significantly improved.

5 Experimental study on grouting clamp reinforcement

This article follows the principle of mechanical similarity to determine the experimental platform, including geometric similarity, force similarity, and motion similarity. According to the principle of geometric similarity, the grouting clamps and experimental pipe fittings used in engineering applications were proportionally reduced. The experimental objects were four types of steel pipes, namely defect free, defect diameter 27mm, defect diameter 45mm, and defect diameter 72mm. The outer diameter was 89mm, the inner diameter was 84mm, and the length was 350mm. The defect ratios were 0.3, 0.5, and 0.8, respectively, as shown in Figure 24 (a). The grouting clamp prototype used in the experiment has an inner diameter of 159mm, an outer diameter of 178mm, and an adjustable maximum length of 380mm, as shown in Figure 24 (b).
According to the principle of force similarity, the range of axial force applied in the experiment is set to 1-5t, and the range of radial force applied in the experiment is set to 1-3t. In order to prevent errors, the measured microstrain is used to represent extremely small deformation by reading the values multiple times and taking the average as the final experimental data. The unit symbol is $\mu\varepsilon$.

Based on the principle of motion similarity, considering the axial and radial forces on the grouting clamp, a screw jack is used to simulate the axial force applied to the steel pipe, and a vehicle jack is used to simulate the radial force on the steel pipe and clamp. Therefore, the schematic diagram of the experimental device constructed in this article is shown in Figure 25.

The loading tools for this experiment are screw jack and vehicle jack with a range of 10T, AFT-CM-32 static resistance strain gauge, 120-3AA uniaxial tension and compression strain gauge, Delta DVP28SV PLC, etc. When applying force to the steel pipe and clamp, the current signal of the pressure sensor is sent to the PLC through the matching BSQ-001 transmitter. The PLC communicates with the upper computer, and finally reads and saves the collected data on the computer.

The type of experiment this time is a comparative experiment, and the actual device is shown in Figure 26. By comparing the bearing capacity of the pipe fittings before and after reinforcement with grouting clamps, corresponding conclusions can be drawn. This experiment reflects the bearing capacity of the pipe fittings from the side according to the measured strain value at the outer wall of the steel pipe fittings. Under the same load, the larger the value of the strain gauge at the same position, the greater the defect influence, and the smaller the bearing capacity.

The location of strain gauge on defect free pipe fittings is shown in Figure 27 (a), and the location of strain gauge on defect pipe fittings is shown in Figure 27 (b).

To facilitate the comparison of the reinforcement of the clamps under axial force, the mean strain values of No. 4 and No. 5 in the pipe fittings without defects, containing 27mm circular hole defects, and after the reinforcement of the clamps were taken for linear fitting, as shown in Figure 28. Under the axial pressure, the average value of the strain gauge at the central defect of the defective pipe is significantly increased, and the bearing capacity is also decreased. The average value of the strain at the defect is reduced by about 50% by the reinforcement effect of the clamp, and the slope of the curve after reinforcement, that is, the defect sensitivity, is reduced.
Similarly, as shown in Figure 30, the average strain of the 72mm diameter defective steel pipe decreased by about 80% after reinforcement. The results show that when the locally defective steel pipe is subjected to axial pressure, its strain value significantly increases, indicating that the defect will seriously reduce the bearing capacity of the steel pipe fittings; After installing the grouting clamp on the damaged pipe fitting, the strain value decreases by approximately 50%~80%, and the rate of strain increase decreases, indicating that the reinforcement effect of the clamp is strong.

4 Conclusion

1) We studied the impact of locally damaged members on the collision between the jacket platform and the ship, and obtained more realistic deformation characteristics and residual strength of the defective members.

2) A parameterized design method for grouting clamps was proposed, based on the plastic hinge theory. The design steps of this method were introduced, and numerical examples and simulation analysis were conducted.

3) Designed an adjustable length grouting clamp with built-in bidirectional embedded wedge-shaped tooth block clamping structure to improve mechanical preload.

4) Axial compression experiments were conducted on ideal steel pipes and defective steel pipes before and after reinforcement with grouting clamps. The experimental results showed that the bearing capacity of the reinforced steel pipes increased by 50% to 80%, indicating that the repair ability of grouting clamps is strong.

Acknowledgements This paper was funded by NNSFC (Contract name: Research on ultimate bearing capacity and parametric design for the grouted clamps strengthening the partially damaged structure of jacket pipes). (Grant No: 51879063).

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Replication of results The necessary information for replication of the results is present in the manuscript.

References


WANG P X. Research on vertical and lateral thermal buckling of subsea pipelines with defects[D]. Dalian University of Technology, 2019: 36-50.

Gong S F. Research on collision damage and reliability and fatigue life assessment of offshore platform structures [D]. Zhejiang University, 2003: 29-42.


XU Lin. Parametric design and bearing capacity analysis of jacket grouting clamp [D]. Harbin Engineering University, 2020: 45-52.