Mechanics Experiments and Analysis of Grouting Clamp Reinforcement to Local Defects on the Ocean Jacket

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Abstract. This paper makes a study on the technology of grouted clamp which strengthens and consolidates the impaired pipe, in order to solve the problem of insufficient strength of the local damaged structure of the offshore platform. By building mechanics experimental platform of grouted clamp for reinforcement pipeline, we made an experiment of the uniform axial compression on the pipeline and which installed the grouted clamp, getting the experimental data of axial stress before and after the installation of grouted clamp. We use the buckling theory of the pipeline under uniform external pressure to compress the internal stress formula which shows the reinforcement effects of the grouted clamp. And use the finite element analysis software to analyse the contact stress of the steel body and flexible body. It can be obtained from mechanical properties experiments and theoretical analysis of the clamp that straight tube after grouting clamp installed, the axial stress value of straight tube center under the same positive pressure decreases significantly, and the difference of both shows increasing trend. The technology can be used in daily inspection, maintenance and repair of ocean jacket, so the cost is low, and have reliability and security.

1. Introduction
Offshore oil and gas resource development has attracted the attention of the whole world because of the increasing depletion of land oil and gas resources. Exploit advanced marine petroleum equipment is an important symbol of the effective development of offshore oil and gas resources [1]. Offshore oil and gas resource development are based on the offshore platform structure. The structure of jacket platform is large and complex, and the sea breeze ocean wave’s currents sea ice always has impact on it [2]. The offshore jacket platform will appear in different forms of damage which work in the harsh marine environment for a long term, the main damage types including dent, corrosion foundation erosion and sea ice [3]. I.E Tebbett analyzed the causes of damage to the more than 100 damaged offshore platforms in the world, finding that the damage caused by crack and corrosion have a large proportion[4], and the proportion increased from 30% to 40% within five years from the date of statistics[5]. Therefore, the maintenance and reinforcement of the offshore platform play an important role in ensuring the safe operation of the offshore platform. According to the main form of structural damage to offshore platform, the main ways of maintenance and reinforcement in engineering include platform welding, clamp, grouting filling technology[6][7]. Many engineering experiences show that the reinforcement of grouted
clamp is important to increase the strength of offshore platform which has mature technology, high tolerance and the relatively short clamp size. According to statistics, there are about 1000 sets of grouted clamp have been used abroad [8]. The United States, China, Norway, the United Kingdom, Holland, Japan and Singapore and other countries have a study on the maintenance and reinforcement technology of damaged structure of an offshore platform and make some progress in nearly 30 years [9]. Domestic and foreign scholars have carried out some theoretical analysis on the use of grouting method to repair the offshore platform, but most of the theoretical studies are aimed at grouted sleeve and casing, such as the influence of key shape on the ultimate bond strength[10], and the influence of temperature on the bearing capacity of grouted sleeve[11]. By applying an axial load to the sleeve and measuring the relative displacement between the steel tube and the sleeve to find the mechanic’s performance of grouted casing connection section[12][13]. The research of influence of compressive strength of cement paste on ultimate bearing capacity of grouting sleeve connection mainly is obtained from experiment, theoretical analysis is also less [14]. Chinese scholars summarized the design method of grouted clamp on the aspects of clamp material, screw quantity and clamp slipping prevention for short bolt type expansion type self-stress grouted clamp [15]. However, the research on grouted clamp repair local defects of ocean jacket still have problems that is the reinforcement and strengthening mechanism of grouted clamp. In this paper, we firstly do the mechanical performance simulation test of the reinforcement of granted clamp and secondly give the theory analysis of the strengthening mechanism of grouted clamp.

2. The mechanical experiment methods of pipe reinforced by grouted clamp

2.1. Stress characteristics of the connection section of the grouted clamp

The complexity of the marine environment and the impact of strong wind, waves, internal waves, storm surge and other extreme environmental factors cause the position of the local damage structure random. The damage may occur above the water or a few meters underwater. The connect section of using grouted clamp to repair the damaged structure bears the complicated loads. This load is divided into two aspects, on one hand, including self-weight of the connect section of grouted clamp and the loads of jacket joints, on the other hand, including the pressure of water, wave load, debris impact and other additional load. The working condition of the grouted clamp on the jacket as shown in Figure 1. It can be seen from Figure 1 that the gravity load of the vertical clamp is the largest. Therefore, the vertical clamp is selected as the experimental object.

![Figure 1. Schematic diagram of underwater grouted clamp](image)

2.2. The composition of the mechanical experiment system of grouted clamp

The experimental system of grouted clamp is mainly composed of pressure testing machine, pipe, grouted clamp model, strain gauge and strain measuring instrument as shown in Figure 2.
1 - Press 2 - Pipe fitting 3 – Grouted clamp 4 - Strain gauge 5 - Strain measuring instrument

Figure 2 The composition of the mechanical experiment system of grouted clamp

There are two kinds of the grouted clamp prototype. One is straight pipe with 108mm diameter. The other is K-joint with 133mm diameter. The prototype of the grouted clamp used to imitate the two kinds of offshore jacket is shown in Figure 3 (a), (b). The strain gauge is attached to the middle of the pipe. At the same time as the accuracy of the experiment, four strain gauges paste evenly along the ring in the middle position of the pipeline. Four strain gauges distributed into figure ten. Strain gauge is adhered as shown in Figure 3 (c), (d).

Figure 3 Grouted clamp prototype of experiment

The press of 200 tons was selected to experiment and get the stress value from the strain measuring instrument, as shown in figure 4 (a), (b).

Figure 4 the press and strain measuring instrument used in the experiments

2.3. Mechanical experiment methods and steps of grouted clamp
The mechanical property test method of the grouted clamp is to apply pressure to the pipeline which with clamp and without clamp. Then contrast the ultimate load before and after installing the clamp to verify the effect of reinforcement and maintenance of the pipeline by the clamp.

The first procedure is to place the clamp in the pressure test machine, then start the pressure test machine to make it firmly clamp the clamp. The stress in the rod is fed back by the strain gauge which is attached to the pipe, and we get the stress data from strain measuring instrument. Then record the data for subsequence analysis.

3. The results of the experiments

Four strain gages were numbered in accordance with the order in the pressing process and recorded the strain by strain gauges. And then the average value was calculated. We can calculate the stress value according to the stress-strain formula that \( \sigma \) is equal to \( E \) multiplied by \( \varepsilon_0 \). The material of pipeline is cold rolled steel sheet, so the young's modulus of cold rolled steel is 2.05E11 MPa according to mechanical manual. When the pressure reached 47MPa, the material will yield. The recorded data as shown in Table 1.

| Exerting force (ton) | Strain No.1 \( \varepsilon_1 \) | Strain No.2 \( \varepsilon_2 \) | Strain No.3 \( \varepsilon_3 \) | Strain No.4 \( \varepsilon_4 \) | Average strain \( \varepsilon_0 \) | Stress \( \sigma \) MPa |
|----------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 10                   | -495            | -258            | -356            | -254            | -341            | 69.85           |
| 15                   | -666            | -424            | -515            | -431            | -509            | 104.34          |
| 24                   | -971            | -740            | -792            | -765            | -817            | 167.48          |
| 27                   | -1076           | -856            | -891            | -892            | -929            | 190.39          |
| 30                   | -1169           | -950            | -980            | -1004           | -1026           | 210.27          |
| 33                   | -1267           | -1061           | -1069           | -1122           | -1130           | 231.59          |
| 36                   | -1362           | -1179           | -1158           | -1249           | -1237           | 253.58          |
| 39                   | -1446           | -1299           | -1248           | -1384           | -1344           | 275.57          |
| 42                   | -1522           | -1414           | -1363           | -1538           | -1459           | 299.14          |
| 45                   | -1574           | -1636           | -1512           | -1780           | -1626           | 333.22          |

As can be seen from the table, the stress of pipeline with clamp is much smaller than the pipeline without clamp at the same stress before the material yield, and the difference increase gradually.
4. The mechanical analysis of reinforcement effect of grouted clamp

The data in Tab.3 was drawn in order to clear the effect of reinforcement and maintenance of the pipeline by the clamp, which is shown in Figure 5.

![Figure 5](image)

**Figure 5** The contrast of stress before and after installing clamp

As can be seen from Figure 5, the axial stress of the pipeline with clamp decreased significantly under the same positive stress, which illustrated well the effect of reinforcement and maintenance of the pipeline by the clamp.

Offshore platform jacket not only bears the external pressure, but also bears the axial compression. The buckling critical value of the pipeline under uniform axial compression can be solved by the Karman-Donnel buckling equations. Karman-Donnel large deflection balance equation is [17]:

\[
DV^4 w - \frac{1}{R} \frac{\partial^2 \varphi}{\partial x^2} = \Lambda(w, \varphi)
\]  

(1)

Where:

\[
\Lambda(g, f) = \frac{\partial^2 g}{\partial x^2} \frac{\partial^2 f}{\partial y^2} - 2 \frac{\partial^2 g}{\partial x \partial y} \frac{\partial^2 f}{\partial x \partial y} + \frac{\partial^2 g}{\partial y^2} \frac{\partial^2 f}{\partial x^2}
\]  

(2)

The plane forces of the pipe which produced from uniform axial compression is assumed by the theory of non-moment. Arboez need to consider the following boundary conditions [18].

\[
w(0, y) = w(L, y) = w_y(0, y) = w_y(L, y) = 0
\]

(3)

The Karman-Donnel equation can be simplified as:

\[
DV^8 w + \frac{Et}{R^2} \frac{\partial^4 w}{\partial x^4} + \frac{N}{2\pi R} \nabla^2 \left( \frac{\partial^2 w}{\partial x^2} \right) = 0
\]

(4)

In simply supported condition, the displacement function is \(w(x)\)

\[
w(x) = \sum_{m=1}^{\infty} A_m \sin \frac{m\pi x}{L}
\]

(5)

Where: \(m\) is axial half wave number during buckling.

From equation (4) and equation (5).

\[
\sigma_\tau = \frac{N}{2\pi R t} = \frac{DA^2}{tR^2} + \frac{E}{\lambda^2}
\]

(6)
Where: \[ D = \frac{Et^3}{12(1 - \mu^2)}, \quad \lambda = \frac{m\pi R}{L}. \]

Taking a derivative with respect to \( \lambda \), make it equal to 0. The critical load is obtained:

\[
\sigma_{cr} = \frac{Et}{R\sqrt{3(1 - \mu^2)}} \quad (7)
\]

Where: \( t \) is pipe thickness, mm; \( R \) is the radius of the pipe, mm; \( \mu \) is poisson’s ratio; \( E \) is elastic modulus, MPa.

In order to show the relationship between the critical bucking pressure under uniform axial compression and the diameter thickness ratio clearly, we can get the equation from (7).

\[
\sigma_{cr} = \frac{2E}{\sqrt{3(1 - \mu^2)}(D/t)} \quad (8)
\]

Put elastic modulus and Poisson’s ratio into equation (8), getting the equation as follow.

\[
\sigma_{cr} = \frac{249354}{D/t} \quad (9)
\]

According to formula (9), the critical buckling pressure under uniform axial compression of the pipeline is inversely proportional to the diameter thickness ratio.

The pipeline installed grouted clamp is equivalent to three homogeneous layer with composite layer equivalent theory and the formula of pipeline installed grouted clamp was derived by the solving equation of pipeline under uniform axial compression as follows:

\[
\sigma_{cr} = \frac{2}{\sqrt{3D_0}} \sum \frac{Et}{\sqrt{1 - \mu^2}} \quad (10)
\]

Where: \( D_0 \) is the average diameter, mm.

After installing the clamp, the buckling critical pressure of the tune changes under the influence of uniform axial compression. In order to show how it changes clearly, the results was shown as Table 3.

| Table3. Critical pressure before and after installing clamp |
|-------------|-----------------|-----------------|-----------------|-----------------|
| \( \frac{D_0}{t} \) | Without clamp | With clamp | Difference | |
| 20 | 1246.70 | 17975.00 | 5507.30 | |
| 25 | 9974.16 | 15805.00 | 5830.84 | |
| 33 | 7480.62 | 13635.00 | 6154.38 | |
| 40 | 6233.85 | 12550.00 | 6316.15 | |
| 50 | 4987.08 | 11465.00 | 6477.92 | |
| 67 | 3740.31 | 10380.00 | 6639.69 | |
| 100 | 2493.54 | 9295.00 | 6801.46 | |
| 200 | 1246.77 | 8210.00 | 6963.23 | |

The buckling critical pressure can be calculated according to formula 9 and 10. As can be seen from the figure, the critical buckling pressure of pipe after installing clamps in comparison with the pipe before installing clamp significantly increased. The critical pressure of pipe increases under uniform axial compression which indicates that the ability to resist external damage has increased. Thus the grouted clamp not only play a role in repair but also play a role in strengthening. When a pressure makes the pipeline damage, it cannot make the pipeline which is installed grouted clamp damage. This is consistent with the experimental data. It also can be observed in the figure, the greater the diameter to
thickness ratio, the greater the critical pressure difference will be. With the increasing of diameter to thickness ratio, the critical pressure difference gradually into a horizontal range.

5. Conclusion
By analyzing experimental and theoretical analysis of mechanical properties of the reinforced grouted clamp prototype pipeline, it can be installed directly after the grouting card hoop, the same is in the axial pressure pipe center stress value decreased significantly, and the difference between them becomes bigger, which can help consolidate pipes. Additionally, the application of the finite element method is used to illustrate the reliability and feasibility of the grouted clamp as a repair method of damaged jacket. The grouted clamp technology can solve the problem of water under the platform of local damaged insufficient structure strength, and greatly reduce the costs of oil maintenance and daily maintenance, and will ensure the reliability and safety of the whole offshore platform.

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