Mechanical test and buckling analysis of X-type grouted clamps for the offshore platform structures

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Abstract. Grouting clamps, especially X-type ones, as typical jacket nodes, have been widely used in underwater engineering for repairing marine damaged jackets as a kind of reinforcement technology. This article is devoted to studying the X-type grouting clamp and conducted the relevant experiments to achieve the purpose of strengthening the strength of the jacket. At first, X-type grouting clamps were designed and processed. An experimental system was fabricated to carry out the experiment to test the bearing capacity which loads axial pressure on the X-type grouting clamp. Secondly, the stress and strain data are obtained experimentally. From the analysis of the experimental results, the X-shaped tube can be derived. The value of stress and displacement after reinforcement are reduced, as compared to earlier reinforcements, which indicates that the bearing capacity of the jacket is enhanced. Finally, the buckling analysis of the bearing capacity of the X-type grouting clamp is carried out by the finite element method, and the ultimate load of the grouting joint is obtained. It is proved that the X-type grouting clamp has the bearing capacity of a pipe joint.

1. Introduction

The whole world has caught the attention of development of marine oil and gas resources due to the depletion of land and oil resources [1-2]. The marine oil and gas resources depend on the structure of the offshore platform. The offshore platform is bulky, complex and very costly. The marine environment is distinct from the land structure such as sea currents, ice, breeze, and waves [3]. The long-term service of the jacket of offshore platform results in different types of damage forms in the harsh marine environment [4]. Due to the severe environment of the ocean and the damage of the jacket and other factors, the accidents of offshore platform frequently occur [5], which causes economic losses and adverse effects to the society. The maintenance and strengthening of an offshore platform play an essential role in ensuring the safe operation of the offshore platform. According to the different types of defects, different maintenance methods need to be used for maintenance and reinforcement. Samindi et al. summed up the marine maintenance and reinforcement technology [6]. In this paper, the grouted clamp is discussed, which is a mature high-tolerance simple and effective reinforcement technology [7].

Grouted clamp repair damaged jacket research began in 1980s, straight pipe and K type joint grouted clamp has been applied [8], but the use of grouted clamp in marine engineering is still few in China. The
The grouted clamp involves only straight, \( T \)- and \( K \)-type pipes, the way of locking has the hydraulic telescopic type, the long and short bolt type, for other types (such as L/X/Y, etc.) grouted clamp structure is not found in the literature. Some scholars have used the grouted clamp to repair the offshore platform for some theoretical analysis, but most of the academic studies are focused on grouted sleeves casing, for example, the effect of shear bond shape on ultimate bond strength in grouted casing [9], the effect of temperature on the bearing capacity of the grouted sleeve [10], the force mechanism of grouted casing connection section, the relative displacement between the steel tube and the sleeve is measured by the axial load test [11-12]. The effect of cement compressive strength on the ultimate bearing capacity of the grouted sleeve is mainly obtained by experiment [13], and the theoretical results are also scarce.

In the light of the above findings, this study analyses the mechanical properties of X-type grouted clamp. Experimental results are compared to the results of the finite element buckling analysis of X-type to verify the reinforcement effect of grouted clamp on the offshore platform structure.

2. The experimental method of X-type grouted clamp

2.1. X-type grouted clamp device
To verify the reinforcement effect of different types of pipe joints, the X-type pipe was fabricated. Figure 1. is the state of the X-type pipe before and after the installation of the clamp. The diameter of X-type pipe joint is 50mm, the diameter of X-type grouted clamp is 76mm, and the wall thickness is 5mm. The X-type grouted clamp was filled with cement slurry of density, 1.85g/cm^3, until the density of the outlet and inlet. Figure 1 (a), (b) and (c) shows X-type pipe before and after the installation of the clamp, and the grouting process of X-type grouted clamp, respectively. In the grouting process, there was no leakage of the cement slurry, which proved that the sealing effect of the structure was sound. The number of bolts and arranged location were reasonable. After grouting, the mechanical experiment was carried out.

![Figure 1. X-type pipe clamp.](image)

2.2. Mechanical experimental system
The experimental mechanical system of the grouted clamp is mainly composed of the press, X-type pipe, grouted clamp device, strain gauge and so on, as shown in figure 2.

![Experimental setup](image)
Figure 2. The composition of X-type pipe mechanics experimental system.

The yield limit is determined by the finite element simulation. The critical load corresponding to the yield limit of the X-type pipe is 2t, and that of X-type grouted clamp is 8t. The load should be controlled below the critical level to avoid the device damage. Given applied load range, the WDW3100 micro control electronic universal testing machine with the limit loading pressure of 10t was used. The computer software controlled the rise and fall of the moving beam, recorded and saved the experimental data in the real time scale, which where visualized on the LED display.

2.3. The mechanical experiment of the grouted clamp

Before the beginning of the mechanical experiment, the strain gauges were pasted. The X-shaped pipe joint has a diameter of 50 mm, the grouting clamp 76 mm, and the wall thickness is 5 mm. The height is 350mm, and the width is 400mm with an angle of 90°. The four branches of the root end of the X-type pipe were posted by the three pieces of biaxial strain gauge at 45° interval, two biaxial strain gauges were attached to the branch pipe with the distance of 80mm, and the biaxial strain gauge could measure the axial and circumferential strains. Position and number of strain gauges are shown in figure 3(a). Due to the lack of space for pasting strain gauges, their number was limited. To measure easily, the lead wire on the strain gauge was welded to the crocodile clip, and the latter was clamped in the position to be measured. Since no strain gauges could be pasted on the pipe outside surface, biaxial strain gauges were pasted on the surface of the X-type grouted clamp at the position shown in figure 3(b).

![Figure 3. Installation of position number of strain gauges.](image)

To obtain a strain of the strain gauges accurately, it is necessary to compensate the strain gauge in parallel, in the strain gauge measuring circuit, as shown in figure 4.

![Figure 4. Strain gauge compensation circuit wiring.](image)

Because the size of X-type pipe end face was larger than that of the pressed chuck, the rectangular steel plates were placed above and under the X-type pipe, as shown in figure 3 on the left. In the software operation interface set, the initial applied load of 0.25t was raised with the interval of 0.25t until the load
level of 1.5t was reached. The particular force and strain data were recorded and listed in table 1. The X-type pipe device was removed, and the X-type grouted clamp device was installed in the press using the same method, as shown in figure 5. An initial load of 0.25t was applied and raised stepwise until the load of 2T was attained. Specific force and strain data were recorded and listed in table 2.

3. Results and Discussion

3.1. Experimental results
For brevity sake, the data in tables 1 and 2 are reduced to the values of the X-type pipe and the X-type grouted clamp on the same side, respectively.

Table 1. Experimental data on loads and strains in the X-type pipe axial compression test.

| Load, t | Measured strain ($\varepsilon = \Delta L/L$) |
|---------|------------------------------------------|
|         | a1, a2, a3, a4, a5, c1, c2, c3, c4, c5 | |
| axis    | cycle | axis | cycle | axis | cycle | axis | cycle | axis | cycle | axis | cycle | axis | cycle | axis | cycle | axis | cycle | axis | cycle |
| 0.25    | -19   | 2    | -41   | 11   | -24  | 12   | -26  | -28  | -1   | -12  | 15   | -7   | 30   | 21   | -21  | 12   | -18  |
| 0.50    | -20   | 4    | -54   | 38   | -36  | 23   | -42  | -19  | -3   | -15  | 20   | -31  | 41   | 48   | -24  | 14   | -19  |
| 0.75    | -22   | 10   | -69   | 41   | -37  | 25   | -58  | -3   | -5   | -25  | 35   | -56  | 60   | 72   | -25  | 15   | -20  |
| 1.00    | -26   | 17   | -77   | 45   | -56  | 36   | -67  | 17   | 2    | -34  | 37   | -87  | 82   | 81   | -31  | 21   | -25  |
| 1.25    | -37   | 21   | -94   | 54   | -66  | 45   | -88  | 14   | 12   | -37  | 52   | -96  | 100  | 84   | -33  | 25   | -27  |
| 1.50    | -42   | 22   | -107  | 71   | -73  | 67   | -108 | 16   | 20   | -42  | 62   | -100 | 102  | 92   | -36  | 30   | -37  |

Table 2. Experimental data on loads and strains in the X-type grouted clamp axial compression test.

| Load, t | Measured strain ($\varepsilon = \Delta L/L$) |
|---------|------------------------------------------|
|         | A1, A2, A3, A4, A5, C1, C2, C3, C4, C5 | |
| axis    | cycle | axis | cycle | axis | cycle | axis | cycle | axis | cycle | axis | cycle | axis | cycle | axis | cycle | axis | cycle | axis | cycle |
| 0.25    | -7    | 1    | -2    | 14   | -1    | 6    | 2    | 3    | -3    | 6    | -5    | 7    | -15   | 11   | -1    | 0    |
| 0.50    | -9    | 3    | -4    | 29   | -2    | 11   | 4    | 8    | -5    | 10   | -12   | 10   | -19   | 13   | -3    | 0    |
| 0.75    | -15   | 7    | -7    | 30   | -2    | 12   | 10   | 10   | -10   | 15   | -13   | 12   | -20   | 16   | -4    | 0    |
| 1.00    | -23   | 11   | -11   | 31   | -5    | 12   | 13   | 10   | -14   | 17   | -13   | 12   | -21   | 17   | -7    | 0    |
| 1.25    | -25   | 11   | -15   | 38   | -6    | 13   | 14   | 17   | -17   | 22   | -18   | 13   | -25   | 17   | -8    | 1    |
| 1.50    | -38   | 12   | -15   | 39   | -10   | 16   | 17   | 21   | -19   | 25   | -25   | 15   | -26   | 18   | -8    | 1    |
| 1.75    | -43   | 14   | -16   | 39   | -11   | 21   | 19   | 23   | -20   | 28   | -29   | 23   | -31   | 19   | -9    | 2    |
| 2.00    | -45   | 15   | -19   | 42   | -13   | 22   | 19   | 23   | -21   | 36   | -32   | 29   | -35   | 23   | -10   | 3    |

3.2. Analysis and discussion of experimental results
The analysis of data in tables 1 and 2 reveals that in the same position of comparative strain, the strain values decreases after reinforcement of X-type pipe, because the direction of the applied force is perpendicular to the cross-section of the pipe. Thus, each branch pipe is loaded by the axial force combined with the additional moment. But some data are significantly affected by tensile stress. When the tensile stress becomes compressive, the compressive strain is observed. The displacement after reinforcement is reduced considerably, indicating the improved bearing capacity of the reinforced X-type grouted clamp.

4. Study on bearing capacity of X-type grouted clamp

4.1. X-type grouted clamping device
Grouted clamp structure is composed of two semi-circular clamps, as shown in figure 5. It is welded with the corresponding connecting plates on the edge of the grooved clamp structure, these are reinforced with ribs, and the two clamps are locked by bolts to achieve closure effectively. Due to the annular space formed between the grouted clamp and the steel, it is necessary to weld a thick annular shape at the end of the two ends of the grouted clamp. The annular diameter is the diameter of the pipe, the outer diameter of the ring is the diameter of the clamp, the circular inner side is provided with a sealing groove, the upper and lower surfaces of the grouted clamp are designed with a slurry outlet and a slurry inlet, respectively. The grout is injected into the annular gap formed by the clamp and the damaged pipe through the grouting port until the density of the outlet and inlet is the same, the filling is stopped. If the repair of the underwater damaged pipe is to be done, it is necessary to fill gas into the room formed by the clamp, draining the sea water, and then grout the work.

4.2 Buckling analysis of X-type grouted clamp

In the stable equilibrium state, according to the principle of potential energy, the equilibrium equation of static structural calculation is expressed as [14-15]:

\[
\begin{bmatrix} K_s \end{bmatrix} + \left[ \begin{bmatrix} K_G \end{bmatrix} \right] \{U\} = \{P\}
\]

(1)

where \( K_s \) is elastic stiffness matrix of structures; \( K_G \) is geometric stiffness matrix of structures; \( \{U\} \) is nodal displacement vector; \( \{P\} \) is nodal load vector.

When the structure reaches the equilibrium state, the two-order variation of the potential energy of the structural system is equal to zero. Thus, we get the following formula:

\[
\begin{bmatrix} K_s \end{bmatrix} + \left[ \begin{bmatrix} K_G \end{bmatrix} \right] \{\delta U\} = 0
\]

(2)

Eventually, this yields:

\[
\begin{bmatrix} K_s \end{bmatrix} + \lambda \begin{bmatrix} K_G \end{bmatrix} = 0
\]

(3)

Assuming a set of external loads \( \{P^0\} \), the geometric stiffness matrix of the structure is \( K_G^0 \). When the structure is unstable, considering load is \( \lambda \{P^0\} \), so that \( \begin{bmatrix} K_s \end{bmatrix} = \lambda \begin{bmatrix} K_G \end{bmatrix} \), and formula (3) can be reduced to the following form:

\[
\begin{bmatrix} K_s \end{bmatrix} + \lambda \begin{bmatrix} K_G^0 \end{bmatrix} = 0
\]

(4)

Formula (4) can be converted into the following eigenvalue equation:

\[
\begin{bmatrix} K_s \end{bmatrix} + \lambda \begin{bmatrix} K_G \end{bmatrix} \{\phi\} = 0
\]

(5)
where $\lambda_i$ is $i$-order eigenvalue; $\{\phi_i\}$ is the characteristic vector corresponding to $i$, that is the corresponding structural deformation shape, which is also an unstable mode.

To verify the correctness of the experimental results, that is the bearing capacity of the grouted clamp, the buckling analysis of inner tube finite element under axial compression before and after reinforcement is carried out. The critical load and stability of the X-type grouted clamp under a specific load is studied. Linear buckling analysis is based on the Eigenvalue as the object of study that is the buckling load factor, ten mode load factor is obtained before and after the reinforcement, to obtain the limit load of the grouted clamp. When the load reaches a critical value, the structure will jump to the equilibrium state of the event.

X-type pipe and installation of grouted clamp X-type pipe are subjected to the pressure of 1MPa, for which the ten-order models are shown in figures 6 and figure 7, respectively. These figures are deformation nephograms for X-type pipe before and after installing the grouted clamp. Further, we compare the deformation before and after reinforcement as shown in figure 6 (grouted clamp is hidden). The tenth-order buckling load factor is shown in table 3. The buckling load is the product of the external force 1MPa applied to the buckling analysis corresponding to the buckling load factor.

![Figure 6. Deformation nephogram of X-type pipe before reinforcement.](image)

![Figure 7. Deformation nephogram of X-type pipe after reinforcement.](image)

Among these, the X-tube parameters are consistent with the previous ones. That is, the material is Q235-a, the constraint is applied to the bottom surface, the pressure load is applied to the top, and the node is the fusion treatment. Elastic modulus is $E=2.05 \times 10^{11}$ Pa.

| Pipe  | 1 order | 2 order | 3 order | 4 order | 5 order | 6 order | 7 order | 8 order | 9 order | 10 order |
|-------|---------|---------|---------|---------|---------|---------|---------|---------|---------|----------|
| Clamp | 674.84  | 1787.7  | 1873.7  | 2039.8  | 2238.8  | 3315.8  | 3403.4  | 3649.4  | 3734.4  | 3853.7   |

It can be seen in figures 5 and 6 that the grouted clamp can strengthen the reinforcement effect of the inner tube, especially near the node, and reduce the stress concentration. By order of the modal load factor, it can be found that the buckling pressure after reinforcement is higher than the reinforcement before with the increasing order. It is pointed out that the deformation of the damaged inner pipe would cause the contact between the cement ring and the inner pipe in the clamp, and the mechanical strength of the inner tube will be improved by this strengthening mechanism.

5. Conclusions
In this paper, the design of X-type grouted clamp and experimental research are carried out by taking the X-type grouted clamp in the form of a typical jacket node as an example. The theoretical and finite element simulation analyses of the X-tube joint and X-type grouted clamp were performed by the axial pressure test, buckling analysis theory, and buckling deformation assessment before and after the X-tube reinforcement. The finite element simulation results are verified by the axial pressure load tests, which proved that the X-type grouted clamp strengthen the jacket. This also solves the problem of insufficient strength of the damaged jacket and improves the bearing capacity of the pipe joint. Therefore, the analysed X-type grouted clamp has important engineering applications.

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