The research about ultimate load of CFRP repaired pipes under long-term seawater immersion and bending moment

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Abstract. Corrosion is a common failure form for subsea pipes. Corroded pipes are increasingly repaired by the composite material because of the low cost and the simple and quick process. However, the repair will be affected by factors such as long time bending moment and seawater immersion. To study the law of the effect, the bending moment and seawater immersion factors are considered in this paper. For the experiment of CFRP repaired pipes, 14 groups of CFRP-pipe specimens were designed, and 30% bending moment was applied, the seawater concentration 5 times more than that recommended by ASTM D1141-98 (2013) was adopted to accelerate the experiment. The pipe specimens were immersed in seawater for different time period (200 hours, 400 hours, 600 hours and 800 hours). The experimental result showed that the ultimate bending load capacity of the repaired pipe decreases with the increasing of time. To study the reasons for the decrease of the ultimate load of the repaired pipes, CFRP-steel plate and CFRP durability tests were set up, 5 groups of CFRP and 5 groups of CFRP-steel plate specimens were designed. It was found that the decrease of the interfacial bonding strength of CFRP repaired pipe and decrease of the CFRP strength resulted in the decline of ultimate load of repaired pipe.

1. Introduction

With the development of offshore and deep-water oil and gas resources in world, the construction for subsea pipes known as the “lifeline” of offshore oil and gas fields is increasing. As an important part of offshore oil and gas field development, it plays a key role in the development, production and transportation of oil and gas. However, due to the harsh marine environment, subsea pipes are easy to be damaged. Corrosion is a common failure form for subsea pipes. Therefore, effective anti-corrosion measures must be taken for subsea pipes. Three technologies are commonly used for repair of subsea pipes: welding repair, fixture repair and composite material repair technology [1]. Composite material repair technology has been widely applied in the maintenance and repair of the oil and gas pipes because of its low cost, relatively simple process and short time consumption [2,3]. However, with the increase of service time, the repair effect will be affected by factors such as long time bending moment and seawater immersion, so the performance of the composite repair will degrade. If the degradation is great, it may even cause the failure of the repaired pipe, resulting in serious environmental pollution and huge economic losses. Therefore, it is of great significance to study the effect of bending moment, seawater immersion on pipes repaired by composites.

Fiber composite repair technology was initially used to reinforce bridge concrete structures. In the 1970s, the technology of repairing pressure pipes and vessels with fiber composite materials emerged in foreign countries. At present, a great deal of research has been done on composite material repair
technology and the degradation of composite material. Borrie [4] studied the durability of steel structures strengthened with CFRP laminates and sheets under seawater environment with increasing temperature. The results showed that even in short-term exposure, protecting and maintaining the bonding interface of the repaired structure were essential to ensure the strength and elasticity of the reinforced steel. Kabir [5] studied the durability of CFRP structural members under long-term low temperature environment by means of experiments and finite element analysis. The results showed that the strength and stiffness of CFRP structural members would be reduced in 12 months under low temperature environment. Almosawe [6] studied the bond behavior between CFRP laminates and steel members under impact load. The results showed that there is a significant bonding strength enhancement under impact load, while high load rate has little effect on the effective bonding length. Nguyen [7] studied the bonding properties of CFRP-steel interface at different temperatures. It was proposed that the bonding failure time was the result of the triple action of temperature, time and load. Compared with the specimens subjected to constant temperature, 47% of the specimens subjected to cyclic temperature have been failed at the same load level. Peck [8] studied the fiberglass wound repair pipeline and studied the mechanical properties of the repaired pipeline by internal pressure test and simple four-point bending test, and verified by finite element analysis results. Abarilla M A [9] immersed the carbon fiber epoxy resin matrix composites at different temperatures, the results showed that the strength and elastic modulus of the composite decreased after immersing for a long time, and the degree of degradation for strength is great, but the elastic modulus is relatively small. Ramirez [10] studied the mechanical properties of fiberglass and carbon fiber composites after different immersion time in seawater. It was found that the properties of carbon fibers were better, and the strength of both fiberglass composites and carbon fiberglass composites decreased after immersion in seawater, among them, the strength of glass fiber decreases more obvious. Based on a theoretical method and the finite element method (FEM) with different crack lengths, Zhang [11] studied the stress distributions of adhesive in a cracked steel plate repaired with CFRP. The results showed that the maximum shear stress and peel stress in the adhesive were obtained from products of stress ratios and stresses for the case of a through-wall crack, and the adhesive failure or the maximum load can be simply predicted by using quadratic stress criteria. Kafodya [12] studied the durability of carbon fiber reinforced polymer (CFRP) plates in water and seawater under 30% and 50% ultimate bending strain. The results showed that the shear strength of carbon fiber composites decreases significantly when immersed in two kinds of media, and the effect of immersion on the tensile strength and modulus of carbon fiber composites is small. Chan [13] studied the mechanical properties of steel pipes repaired by fiber reinforced polymer composites under bending load by experimental method and finite element method. The result showed that use CFRP as repairing material, the bending stiffness of corroded pipes and the ability to bear bending load can be improved.

The durability of CFRP repaired pipe under long-term bending moment and seawater immersion is considered in this paper. For the experiment of CFRP repaired pipes, 14 groups of CFRP-pipe specimens were designed, 30% bending moment was applied to the specimens. By setting the used seawater concentration 5 times more than that recommended by ASTM D1141-98 [14] to accelerate the experiment, the pipe specimens were immersed in seawater for different time period (200 hours, 400 hours, 600 hours and 800 hours). Then the 5 groups of CFRP-steel plate and 5 groups of CFRP durability tests were set up to further explore the reasons for the decrease of ultimate load of repaired pipe.

2. Ultimate bending load of CFRP repaired pipe

2.1. Experimental condition
The CFRP cloth is made of 3K-200g high strength two-way 0/90 braided carbon fiber cloth, and the API 5L X60 seamless pipe is selected as the base material. The material parameters are shown in tables 1 and 2.
Table 1. Material parameters of CFRP cloth.

| Material parameter | CFRP cloth |
|--------------------|------------|
| Thickness/mm       | 0.22       |
| Density /g/cm³     | 1.8        |
| Elastic modulus/GPa| 240        |
| Tensile strength/MPa| 1700      |
| Poisson’s ratio    | 0.3        |
| Elongation         | 2.07%      |

Table 2. Material parameters of the API 5L X60 seamless pipe.

| Material parameter       | Pipe     |
|--------------------------|----------|
| External diameter/mm     | 21.3     |
| Thickness/mm             | 1.6      |
| Yield strength/MPa       | 355      |
| Tensile strength/MPa     | 600      |
| Poisson's ratio          | 0.3      |
| Elastic modulus/GPa      | 210      |
| Length of pipe/mm        | 300      |
| Corrosion length/mm      | 10       |
| Corrosion depth/mm       | 1.5      |
| Corrosion angle/°         | 15       |

The adopted adhesive was Araldite 2015, as shown in figure 1. The elastic modulus of the adhesive is 2 GPa, the tensile strength is 22.3 MPa and the ultimate elongation is 1.85%. Double bond DB406 metal corrosion resistant filler is used as repair filler, as shown in figure 2. The elastic modulus of the filler is 5.5 GPa, Poisson's ratio is 0.4 and the shear strength is 15 MPa.

Two groups of experiments were set up in this paper. The experimental schemes are shown in tables 3 and 4.

In the first group, CFRP repaired pipes were subjected to seawater immersion and bending moment for a long time before the test to measure the ultimate load. The long-term bending the pipes were first subjected to 30% ultimate bending moment, which is equal to the ultimate bending moment of the original undamaged pipe. Then put into the 5 times seawater concentration at 17°C. The seawater immersion of the pre-loaded pipe specimens lasted for different time period (200 hours, 400 hours, 600 hours and 800 hours). To study the effect of a single factor on the repairing effect, another group of experiment was set up, the pipe specimens were only subjected to 30% ultimate bending moment.
The effects of bending moment and seawater immersing time on the ultimate load of the CFRP repaired pipe was studied by three-point bending experiment.

### Table 3. Experimental scheme with seawater immersion and bending moment.

| Type               | Bending moment | Time/hours | Seawater concentration | Temperature /℃ |
|--------------------|----------------|------------|------------------------|-----------------|
| CFRP repaired pipe | 0%             | 0          | 5 times ASTM standard  | 17              |
|                    |                |            | 200                    |                 |
|                    |                |            | 400                    |                 |
|                    |                |            | 600                    |                 |
|                    |                |            | 800                    |                 |
|                    | 30%            | 0          | 200                    |                 |
|                    |                |            | 400                    |                 |
|                    |                |            | 600                    |                 |
|                    |                |            | 800                    |                 |

### Table 4. Experimental scheme with bending moment.

| Type               | Bending moment | Time/h |
|--------------------|----------------|--------|
| CFRP repaired pipe | 30%            | 0      |
|                    |                | 200    |
|                    |                | 400    |
|                    |                | 600    |
|                    |                | 800    |

14 groups of CFRP-pipe specimens were designed. According to the standard ASME PCC-2-2011 [15], the thickness and length of CFRP repair winding were calculated as 0.6mm and 50mm respectively. The Araldite 2015 structural adhesive was used for bonding between the pipe and the CFRP cloth and between the layers of the CFRP cloth during winding, as shown in figure 3. The two ends of the pipe specimens are roughly polished by a grinder to prevent slippage during loading.

![Figure 3. CFRP repaired pipe specimens.](image)

The bending device of CFRP-pipes are shown in figure 4. By applying a certain torque to the nut, the bending moment was applied to the CFRP pipes, and the vertical bending distance of the pipe is measured at the bottom center of the repair region. The pre-loaded specimens were placed in the seawater, as shown in figure 5. The three-point bending test device for studying the ultimate bending load of the CFRP pipes is shown in figure 6. The span for installation of the pipe specimens is 210 mm, the load is controlled by the displacement control mode, and the load speed is 0.5mm/min.
2.2. Experimental result

The shape diagram of the corroded pipes and CFRP repaired pipes before and after deformation is shown in figure 7. Through the experiment, it was found that the deformation of the pipes mainly developed from circular to flat section. For the CFRP repaired pipe, under the continuous loading, partial interface slipping occurred between the carbon fiber cloth and the pipe.

To avoid the error caused by the experiment, each group of experiments were tested twice and then the average value was obtained. For example, when the CFRP repaired pipes were subjected to no immersion and bending moment, the ultimate loads are 6.8 KN and 6.9 KN, and the average load was 6.85 KN. The load-displacement curves of corroded pipe and CFRP repaired pipe is shown in figure 8. With the increase of load, the displacement increases rapidly and reaches the peak after a short hardening effect, and then the load drops with the increase of deformation. The whole curve has obvious characteristics of early elasticity, mid-term plastic strengthening and post-softening. The ultimate load of CFRP repaired pipe with no immersion and bending moment is 6.85 KN, and the ultimate load of corroded pipe is 5.35 KN, the experimental results showed that the pipe repaired with CFRP can improve the ultimate bending capacity.

The load-displacement relationship of CFRP repaired pipe under different conditions are shown in figure 9. With the increase of time, the ultimate load of CFRP repaired pipes under different conditions decrease gradually. For example, the ultimate loads are 6.7 KN, 6.4 KN, 6.2 KN and 5.9 KN under seawater immersion and bending moment for 200, 400, 600 and 800 hours, separately. When the time is 800 hours, the ultimate loads decrease by 15% compared to the repaired pipe with no immersion and bending moment.
Figure 8. Load-displacement relationships of the corroded pipe and the repaired pipe.

Figure 9. Relationship of load-displacement under different conditions. (a) Relationship of load-displacement under different immersion time, (b) Relationship of load-displacement under different bending moment time and (c) Relationship of load-displacement under different immersion and moment time.

The relationships between the ultimate load and time under different conditions are shown in figure
10. With the increase of time, the ultimate loads of CFRP repaired pipes decrease linearly. When the time was 800 hours, the decline of the ultimate load was the most serious. It was found that the effect of bending moment on the ultimate load of pipe was less than that of the seawater immersion, it decreases about 15% when both of the bending moment and the seawater immersion time acted. Compare to only consider bending moment or seawater immersion, the ultimate loads decrease seriously.

![Figure 10](image)

**Figure 10.** Relationship between time and load under different conditions.

From the above results, it can be found that ultimate load decreased gradually with time under different conditions. Through the experiment, it is found that the interface between the carbon fiber cloth layer and the pipe slipped partially under bending moments, which was considered to be one of reasons for the decrease of the ultimate load of the CFRP repaired pipe. Another reason was assumed that the mechanical properties of CFRP decreased with time under different conditions. To explain the reasons for the decrease of ultimate load of the CFRP repaired pipes, the durability of CFRP-steel plate and CFRP were studied in the followings.

3. **Durability of CFRP strength and CFRP-steel plate interfacial bonding strength**

3.1. **Experimental condition**

![Figure 11](image)

**Figure 11.** Sizes of CFRP plate. (a) CFRP plate and (b) CFRP for bonding with steel plate.

Two different sizes of CFRP plates were selected for the experiment. One group was used for CFRP durability test, and the other group was used for CFRP-steel plate interface strength test. Since the
cutting edge of the fixture of universal testing machine is easy to destroy the surface of carbon fibers. Therefore, the strengthen sheet is pasted on the specimen to prevent the early failure of CFRP plate. The size of the test specimen is shown in figure 11, tensile strength and elastic modulus of CFRP material are 1700 MPa and 235 GPa. The material of steel plate is Q235, its material parameters are shown in table 5.

Table 5. Material parameters of steel plate.

| Material parameter | Steel plate |
|--------------------|-------------|
| Length/mm          | 250         |
| Thickness/mm       | 5           |
| Width/mm           | 30          |
| Yield strength/MPa | 258         |
| Tensile strength/MPa | 414         |
| Elastic modulus/GPa | 198         |

The adopted adhesive between CFRP and steel is also Araldite 2015. For the experiment of CFRP and CFRP-steel plate, 5 groups of CFRP-steel plate and 5 groups of CFRP were set up in this paper, as shown in table 6. The CFRP plates and CFRP-steel plates were put into the 5 times seawater concentration at 17°C for different time (200 hours, 400 hours, 600 hours and 800 hours).

Table 6. Experimental scheme.

| Type         | Time/hours | Seawater concentration   | Temperature/°C |
|--------------|------------|--------------------------|----------------|
| CFRP         | 0          | 5 times ASTM standard    | 17             |
| CFRP-steel   | 200        |                          |                |
|              | 400        |                          |                |
|              | 600        |                          |                |
|              | 800        |                          |                |

Figure 12. CFRP-steel plate specimens. (a) CFRP-steel plate from top view and (b) CFRP-steel plate from front view.

According to the experimental scheme, CFRP and CFRP-steel plate specimens are designed. The
bonding length and width of CFRP-steel plate are 100 mm and 15 mm, as shown in figure 12. To obtain good bonding performance, before bonding CFRP and steel, the surface of steel plate was polished, and the surface of steel plate and CFRP was cleaned with acetone. The container for seawater is shown in figure 13, the test load device of CFRP and CFRP-steel plate is shown in figure 14.

3.2. Experimental result
When the CFRP sheet tensile test is carried out, the CFRP sheet will occasionally emit the splitting sound in the linear stage. As the load increases, the sound becomes more and more obvious. The tensile fracture of the CFRP sheet is shown in figure 15. The process of CFRP tension includes a long linear stage and a very short yield stage. When the yield stage is reached, the fiber breaks. The sound is dense when the fiber test piece is completely broken, and the break is accompanied by a lot of fiber spatter, while emitting a strong burnt smell.

The experimental results of CFRP sheets are shown in figure 16. The ultimate loads are 38.3 KN, 36.1 KN, 32.7 KN and 29.3 KN under seawater immersion at 200, 400, 600 and 800 hours. With the increase of immersion time, the ultimate load decreases gradually. When the immersion time is longer, it decreases more quickly. The relationship between ultimate load and time is shown in figure 17.

![Figure 13 The container for seawater.](image1)

![Figure 14. Test device of CFRP and CFRP-steel.](image2)

![Figure 15 Fracture of CFRP specimens.](image3)

![Figure 16. Relationship of load-displacement under different immersion time.](image4)

![Figure 17. Relationship between ultimate load and time.](image5)
For the CFRP-steel plate experiment, with the increase of load, the adhesive layer at the load end gradually destroys, and then the peeling of CFRP plate gradually spreads to the free end. When the peeling of CFRP plate approaches the free end or the peeling of CFRP layer occurs, the load drops rapidly and then the specimen fails. The failure modes of CFRP-steel plate under different immersion time are shown in figure 18. When there is no seawater immersion, the interfacial failure may happens from steel-adhesive, adhesive-CFRP or the fracture of CFRP (shown in figure 18(a)). When the seawater immersion time is 800 hours, it can be seen that the interface of CFRP and steel plate has been seriously eroded by seawater, resulting the debonding strength of CFRP-steel decreases greatly.

Figure 18. Failure modes of CFRP-steel plate. (a) No immersion and (b) Immersion for 800 hours.

As the load increases, the interface between CFRP plate and steel slips and gradually peels off. The load-displacement curve is basically linear before the specimen fails, and the load suddenly decreases when failure occurs. The load-displacement curves under different seawater immersion time is shown in figure 19. The ultimate loads are 6.5 KN, 5.4 KN, 4.9 KN and 3.5 KN under seawater immersion at
200, 400, 600 and 800 hours. With the increase of immersion time, the ultimate load decreases gradually. When the immersion time is 800 hours, the ultimate load decreases by 60% compared to the CFRP-steel plates with no seawater immersion, according to the analysis, it can be seen that the bonding interface is seriously eroded by seawater, and the interface is easily damaged.

The average bonding strength of CFRP and steel plate can be calculated by the ultimate load, and the relationship between time and average bonding strength is shown in figure 20. It can be found that the average bonding strength decreases with the increase of time.

From the above results, it can be found that the strength of CFRP and the bonding strength of CFRP-steel decreased as the immersion time increases, which leads to the decrease of ultimate load of repaired pipe.

4. Conclusion
In this paper, the durability of long-term bending moment and seawater immersion on CFRP repaired pipes were considered. The ultimate load of CFRP repaired pipe under different seawater immersion time and bending moments were tested by three-point bending test. Then the CFRP-steel plate and CFRP durability tests were set up to study the reasons for the decrease of ultimate load of repaired pipe. The following conclusions are obtained:

- With the increase of time, the ultimate load of repaired pipe decreases under long-term bending moment and seawater immersion. The effect of bending moment on the ultimate load of repaired pipe is less than that of immersion time. When both of bending moment and immersion time act, the ultimate load decreases seriously.
- The strength of CFRP and the bonding strength of CFRP-steel decreases with the increase of immersion time, as the immersion time increases, the speed of decline increases, when the immersion time is 800 hours, the decrease is the largest.
- Through the durability test of CFRP and CFRP-steel plate, it can be proved that the interfacial bonding strength of CFRP repaired pipe and CFRP ultimate strength decrease under long-term immersion, which lead to the decrease of ultimate load of the repaired pipe.

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