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Failure Analysis of Damaged Prestressed Concrete Cylinder Pipes Strengthened with Prestressed Carbon Fiber-Reinforced Polymers

Hao Hu,[1, 2] Kejie Zhai,[3, 4,*] Bin Li,[3, 4] Niannian Wang,[3, 4] Binghan Xue,[3, 4] Mingrui Du[3, 4] and Xupei Yao[3, 4]

Abstract

Prestressed concrete cylinder pipes (PCCPs) are widely used in large-scale water conservancy projects. Due to factors such as materials, design, construction, and operation, the prestressed steel wires in PCCP may break, resulting in damage to PCCP. Hence, an innovative approach for repairing damaged PCCPs with prestressed carbon fiber reinforced polymers (CFRPs) was proposed. A hydraulic pressure experiment was performed on a full-scale PCCP, and the damage maps in damaged section and repaired section were compared, which revealed that the prestressed CFRPs had an obvious repair effect. Then, a finite element model was established for a damaged PCCP repaired with prestressed CFRPs. Afterwards, a simplified analytical model was proposed. The results of the experiment, finite element (FE) simulation and analytical model were in good agreement. Finally, the effects of broken wires number, and the value of CFRP prestress on the PCCP performance were analysed. The results showed that these three factors substantially influenced the PCCP bearing capacity. When broken wires number was less than or equal to 30, the damaged PCCP could be repaired with 4 layers of CFRP with 20% prestressed.

Keywords: Prestressed concrete cylinder pipe (PCCP); Prestressed carbon fiber reinforced polymer (CFRP); Analytical model; Prototype test; Failure study.

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1. Introduction

Prestressed concrete cylinder pipe (PCCP) was invented in 1893 by a French engineer named Aimee Bonna and has been in use for more than 100 years.[1,2] PCCP has many good performance metrics, such as a high pressure bearing capacity, good impermeability, strong adaptability to foundations, excellent seismic performance, and low cost.[3-5]

Underground pipelines have a harsh service environment.[6-8] Due to the influence of corrosion, hydrogen embrittlement and other factors, the prestressed steel wire in PCCP is prone to break, which greatly reduces the pipe bearing capacity. This reduction could lead to a pipe explosion accident, which would substantially affect production and potentially result in loss of life.[9-11] Accordingly, strengthening methods have been developed for damaged PCCP. The Great Man-Made River Authority (GMRA) developed an external prestressed repair approach that was successfully applied in practical projects; hence, it was proposed that this repair approach can be used as a final solution for damaged PCCP.[12,13] Rahman *et al*.[14] proposed that in addition to replacing the damaged pipe with a new pipe, the most widely used method for PCCP repair is the use of a steel cylinder liner, which can update a pipeline economically and quickly. They discussed the advantages of steel cylinder liners from the aspects of manufacturing, design, installation and corrosion protection. Moreover, they provided descriptions and comparisons of other repair techniques. To better understand the long-term performance of a PCCP with a steel liner, Faber *et al*.[15] conducted failure tests on two sections of a steel-lined PCCP, wherein they detailed the test procedures, PCCP failure

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[1] *Yellow River Conservancy Technical Institute, Kaifeng, 475000, China*

[2] *North China University of Water Resources andW Electric Power, Zhengzhou, 450001, China*

[3] *School of Water Conservancy and Transportation, Zhengzhou University, Zhengzhou, 450001, China*

[4] *Yellow River Laboratory (Henan), Zhengzhou, 450001, China*

**E-mail:* kejiezhai@zzu.edu.cn (K. Zhai)

modes, and wire performance, mainly focusing on external loading capacity tests. Their results showed that the steel liner substantially improved the external loading capacity of the pipeline. Yuan *et al*.[16-18] designed the polystyrene and the content of multi-walled carbon nanotubes composites with random structures and segregated structures, and they also investigated the mechanical behavior of concretes where river or sea pebbles replace traditional gravel as coarse aggregate. Zhai and Moore used the finite element method to obtain the performance improvement of the repaired pressure pipes and the stress equation of the repair material. Their research results can be used to formulate the pressure pipeline repair standard.[19-21]

Carbon fiber-reinforced polymers (CFRPs) have been gradually applied as reinforcements in civil engineering, such as in buildings and bridges.[22-25] Many studies have investigated the use of CFRPs as steel pipe reinforcements.[26] Moreover, CFRPs have been used as liners to reinforce damaged PCCP. Deschamps *et al*.[27] summarized the main points of the external repair method and the CFRP liner repair method. The advantages and disadvantages of the two methods were discussed, and an automatic method of CFRP liner repair was introduced. Zarghamee *et al*.[28] proposed a design framework for CFRP liners in concrete pressure pipelines. This design method considers undegraded, degraded and severely damaged pipes, in which the bonding quality between the CFRP and the pipe has important impact on the bearing capacity. Through a detailed nonlinear finite element (FE) analysis, the mechanical performance of the pipe was determined. Bologna *et al*.[29] introduced multiple PCCP repair strategies, including PCCP replacement, external prestressed tensioning, steel cylinder liners and CFRP liners, based on an actual repair project, wherein they clarified the advantages of the CFRP liner repair approach and formulated corresponding repair procedures. In a pipeline repair project, Chwiedosiuk *et al*.[30] considered the pipeline replacement, steel cylinder liners and CFRP liners. After careful evaluation, the CFRP liner repair approach was selected. They also introduced some difficulties that were overcome during the construction process, including a large amount of water intrusion caused by heavy rain. As the service life of a CFRP liner increases, various defects gradually appear in the CFRP system. Lytvyn *et al*.[31] highlighted the importance of checking CFRP liner repairs and described the defects observed. In addition, the shortcomings of the related standard were discussed. To meet the current requirements of water tightness and strength, Engindeniz *et al*.[32] carried out CFRP liner repairs on many PCCPs with inner diameters ranging from 60 inches to 66 inches; these repairs were performed within a period of 30 days. Afterwards, they discussed the challenges faced by such a wide range of CFRP liner repairs and expounded upon the procedures that could be used to ensure that the construction quality will not be affected when multiple construction teams are working at the same time. To increase the working pressure from 100 psi to 150 psi, Engindeniz *et al*.[33] evaluated open channel replacement and several trenchless repair methods and ultimately selected the CFRP liner repair approach; they also analysed the feasibility of construction. Gipsov *et al*.[34] studied the use of CFRP liners to repair a damaged PCCP (diameter of 96 inch) and compared the design and details with other currently used methods, wherein they primarily analysed the causes of leakage and the details of CFRP materials and installation. They reviewed the past and current repair methods, thereby increasing the awareness of the latest technology.

The above repair techniques can effectively strengthen and repair pipelines. Considering that the use of CFRP liners requires the water supply needs to be stopped and is not suitable for pipelines with small-diameter, Zhai *et al*.[35-37] proposed an approach where the exterior of a damaged PCCP is wrapped with CFRP for repair and strengthening and conducted related tests and finite element simulation studies. They found that the CFRP wrapping approach can substantially improve the mechanical performance of a PCCP. The failure of a prestressed wire will cause a loss of stress in the pipe, and CFRP liner and CFRP wrapping repair approaches cannot compensate for this phenomenon. Therefore, a repair approach where the exterior of a damaged PCCP is wrapped with prestressed CFRPs was proposed in this study. Through a prototype test, the repair effect of the prestressed CFRPs on a PCCP with broken wires was verified. In addition, a model of the damaged PCCP repaired by prestressed CFRP was established using the FE method. Afterwards, a simplified analytical model was proposed. Moreover, the results from the tests, FE simulations and analytical model were compared. Finally, the influences of broken wires numbers, and CFRP prestress values were analyzed.

2. Prototype test

2.1 Parameters of the PCCP

An PCCP with an inner diameter of 1.4 m and a length of 6 m is selected for this test. The design depth of the cover soil is 3 m, the thickness of the concrete core is 0.11 m. The thickness of the steel cylinder, the diameter of the prestressed steel wire, and the diameter of the steel cylinder, is 1.5 mm, 6 mm, and 1503 mm, respectively. The compressive strength of the concrete core is 40 MPa, the tensile strength of the prestressed wire is 1530 MPa. The tensile strength and the elastic modulus of the CFRP is 3400 MPa and 240 GPa, respectively.

2.2 Test scheme

After the pipe was hoisted to the water pressure machine (Fig. 1(a)), two 600-mm-long sections of the pipe were selected for wire breaking (Fig. 1(b)). Then, one section was kept in a broken wire state (Fig. 2(a)), whereas the other section was repaired with prestressed CFRPs using custom-built equipment (Fig. 2(b)). Four layers of 500-mm-wide prestressed CFRP were used for the repair process. After completing the repair process, strain gauges were bonded on the CFRP in section 2 and on the mortar coating, concrete, and steel wires in the middle section. A DH-3816N data acquisition system was used to record the strain data, as shown in Fig. 2(c). Finally, the hydrostatic pressure was applied to the pipe in stages. The applied pressure was held constant for approximately 5 min in each stage, after which the pressure was incremented by 0.1 MPa; this process was repeated until the PCCP was damaged severely, at which time the test was stopped.

3. 3D FE model

3.1 Model state description

The geometric parameters are the same as those of the pipe used in the test. The concrete and mortar are modelled with C3D8R solid elements. S4R shell elements are used to simulate the cylinder and CFRP. Since only the linear stress along wire length is considered, the prestressed wire is simulated using T3D2 truss elements.[38-40]

The prestress of the steel wire and CFRP are applied using a thermal gradient method. The relationship between the prestress value and the physical parameters of the steel wire and CFRP is shown in Eq. (1).

$$\Delta t = \frac{F}{\alpha EA} \tag{1}$$

where Δt is the applied temperature gradient, F is the force, E is the elastic modulus, α is the thermal expansion coefficient, and A is the cross-sectional area.

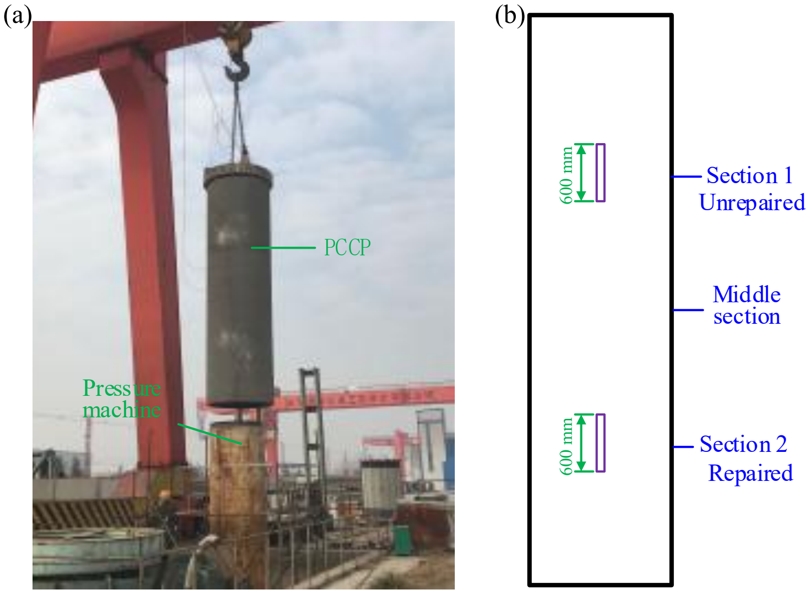

Fig. 1: (a) Hoisting of the PCCP, (b) Diagram of the distinct sections in the PCCP.

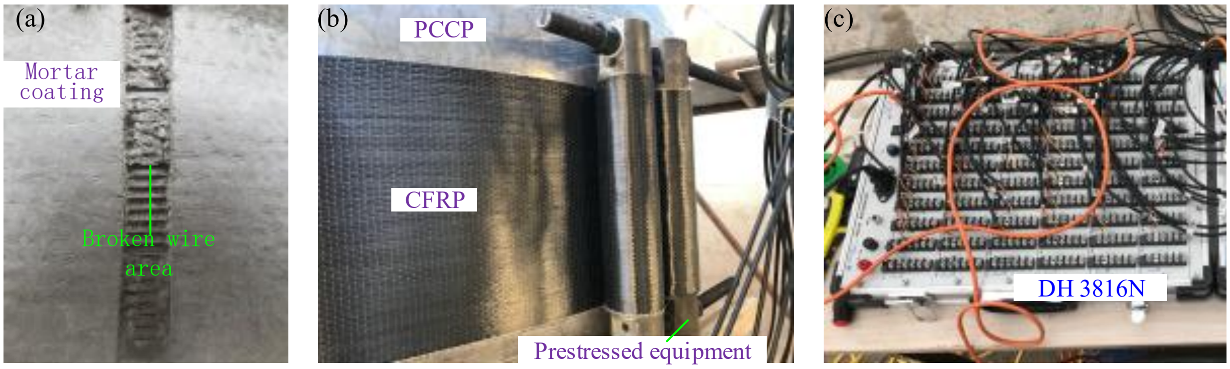

Fig. 2: Photographs of the (a) broken wire area, (b) prestress application, and (c) DH-3816N data acquisition system.

The relationship of concrete and cylinder is “embed”, and also the relationship of wire and mortar. A “TIE” constraint is used to bind the mortar and concrete core. Due to the prestressing effect of the CFRP, there is almost no relative sliding between the CFRP and mortar when bearing internal pressure. Therefore, the CFRP and mortar are bound by a “TIE” constraint. The boundaries at both ends of the pipeline are only allowed to be displaced in the radial direction, whereas the other directions are fully constrained.[41,42]

3.2 Material constitutive relation

In the model, the material parameters are the same as experiment. For concrete and mortar, the concrete damaged plasticity (CDP) model is adopted to simulate their behaviour. The stress-strain relationship of the steel cylinder is assumed to be ideal elastic-plastic, as shown in Fig. 3. In Fig. 3, ε_y, σ_y, E_y and f_y are the strain, stress, elastic modulus and yield strength of the steel cylinder, respectively.

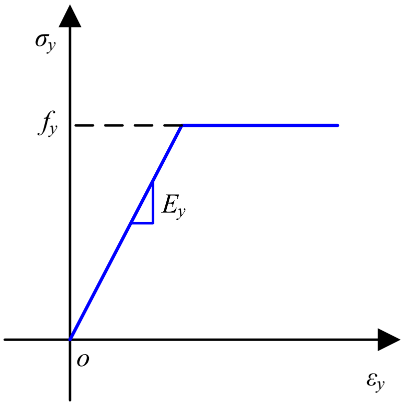

Fig. 3: Constitutive model of the steel cylinder.

The CFRP is simulated as an ideal elastic-brittle material. According to the American standard, *Design of Prestressed Concrete Cylinder Pipe* (AWWAC304),[30] the elastic-plastic constitutive relation of the prestressed wire is expressed as follows in Eq. (2):

$$\begin{cases} f_s = \varepsilon_s E_s & \varepsilon_s \le f_{sg} / E_s \\ f_s = f_{su}\left[1-(1-0.6133\varepsilon_s E_s / f_{su})^{2.25}\right] & \varepsilon_s > f_{sg} / E_s \end{cases} \tag{2}$$

where ε_s, E_s and f_s are the strain, elastic modulus and stress of the prestrssed wire, respectively; f_{su} is the tensile strength of the wire; and f_{sg} is the tensile control stress of the wire.

4. Analytical model

4.1 Material stress-strain relationship

The stress-strain relationships of the prestressed wire and the cylinder are the same as those used in the simulation model. The constitutive relationship of concrete and mortar is simplified as a line,[43] as shown in Figs. 4 and 5.

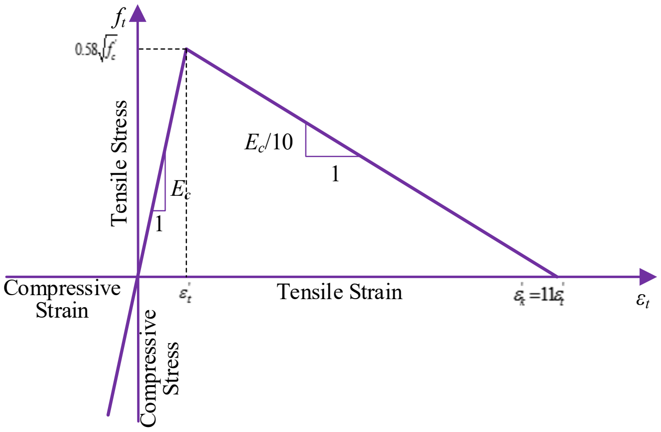

Fig. 4: Constitutive model of concrete.

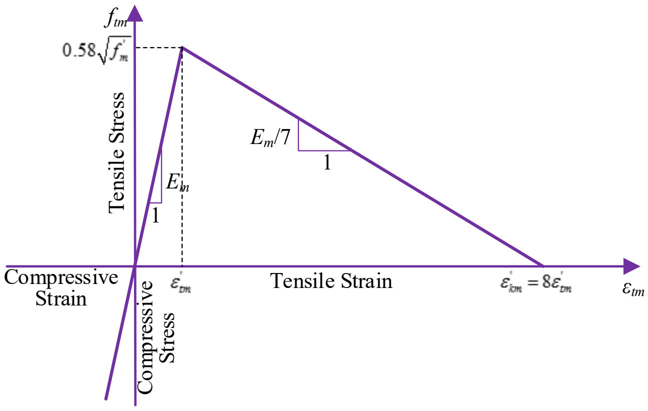

Fig. 5: Constitutive model of mortar.

E_c, E_m, ε_t, and ε_{tm} are the concrete elastic modulus, mortar elastic modulus, concrete strain, and mortar strain, respectively; f_t and f_{tm} are the tensile strength values of the concrete and mortar, respectively; and f_c' and f_m' are the compressive strength values of the concrete and mortar, respectively. The elastic moduli of concrete and mortar can be expressed as $E_c = 0.074\gamma_c^{1.51}(f_c')^{0.3}$ and $E_m = 0.074\gamma_m^{1.51}(f_m')^{0.3}$, respectively, where γ_c =2323 kg/m^3 and γ_m= 2242 kg/m^3.

4.2 Stress-strain calculation and simplified model

The concrete is compressed because of steel wires wrapped, resulting in a compressive strain, and the steel cylinder also generates stress accordingly. The value of stress/strain in the material are called the initial stress/initial strain, respectively.

Depending on the balance of forces in Eqs. (3) and (4):

$$f_{ic} = A_s f_{sg} \div (A_c + n_i A_s + n_i' A_y) \tag{3}$$

$$\varepsilon_{ic} = f_{ic} / E_c \tag{4}$$

The steel cylinder is embedded in the concrete, and the two deform together. Therefore, the initial strain of the steel cylinder can be expressed as follows: $\varepsilon_{iy} = \varepsilon_{ic}$.

The initial stress in the cylinder can be expressed as Eq. (5):

$$f_{iy} = E_y \varepsilon_{iy} \tag{5}$$

After the concrete is compressed, the stress in the prestressed wire using Eq. (6):

$$f_{is} = -f_{sg} + n_i f_{ic} \tag{6}$$

Moreover, the initial stress in the wire in Eq. (7):

$$\varepsilon_{is} = f_{is} / E_s \tag{7}$$

where f_{ic}, f_{iy}, and f_{is} are the initial stresses in the concrete, cylinder, and prestressed wire, respectively; ε_{ic}, ε_{iy}, and ε_{is} are the initial strains of the concrete, cylinder, and prestrssed wire, respectively; A_s, A_c, and A_y are the cross-sectional areas of the wires, concrete and cylinder, respectively; n_i is the prestressed wire-to-concrete elastic modulus ratio; and $n_i^{'}$ is the cylinder-to-concrete elastic modulus ratio.

The two-dimensional schematic diagram of the PCCP under internal water pressure is shown in Fig. 6. Due to the symmetry, half of the structure is used for the analysis. In Fig. 6, P is the hydrostatic pressure and F_m, F_s, F_c and F_y are the forces of the mortar, prestressed wires, concrete and cylinder, respectively.

The balance of forces can be obtained as follows:

$$2 \times (F_m + F_s + F_y + F_c) = \int_0^{\pi} (P \times b \times r \cdot d\theta) \cdot \sin\theta \tag{8}$$

where r is the inner radius of the PCCP and b is 1000 mm.

In the test, the pipe has not reached its working internal pressure. Assuming that the material deformation in this process is the same and is still in the elastic state, the stress in each material can be obtained as follows:

$$F_c = \int_{\varepsilon_{ci}}^{\varepsilon} E_c A_c d\varepsilon \tag{9}$$

$$F_y = \int_{\varepsilon_{yi}}^{\varepsilon} E_y A_y d\varepsilon \tag{10}$$

$$F_m = \int_0^{\varepsilon - \varepsilon_{ci}} E_m A_m d\varepsilon \tag{11}$$

$$F_s = \int_{\varepsilon_{si}}^{\varepsilon_{si} + \varepsilon - \varepsilon_{ci}} E_s A_s d\varepsilon \tag{12}$$

The following relationship between material strain and internal water pressure can be obtained by combining Eqs. (9)-(12) with Eq. (8).

5. Results and discussion

5.1 Comparison of the results from the test, analytical model and simulation

Fig. 7 shows a comparison of the results from the test, analytical model and finite element (FE) simulation, wherein the material strain in the middle section is plotted against the change in internal water pressure. The three results are in good agreement, indicating that the analytical model and the FE simulation produce reliable results.

Fig. 8 shows a comparison of the CFRP strain between the FE simulation and test. In the initial stage of the test, the strains increased linearly, which is consistent with the response in the simulation. When the pressure in the test was 0.8 MPa, the CFRP strain changed abruptly due to crack formation. However, the sudden change in CFRP strain occurred at 0.9 MPa in the simulation; this slight difference occurred because the constitutive parameters in the simulation model were not the same as those in the experiment. In general, the FE results matched very well with the test data, which shows the reliability of the FE simulation.

5.2 Parameter study

Considering that the broken wire number, and the value of CFRP prestress have an important effect on the PCCP's bearing capacity, the calculation and analysis of different cases were carried out based on the FE model. The effects of the broken wires number, and the value of CFRP prestress on the mechanical properties of the PCCP were studied.

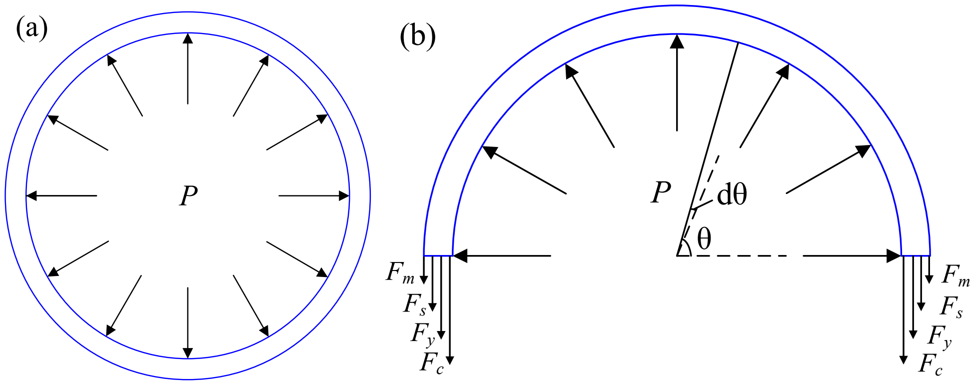

Fig. 6: Schematic diagram of force under internal pressure: (a) whole structure and (b) half structure.

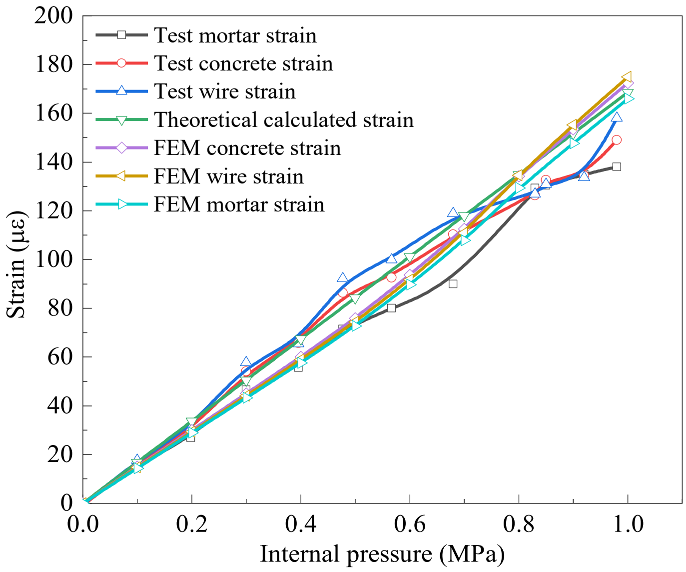

Fig. 7: Comparison of the results from the test, FE simulation and analytical model.

For a PCCP with different numbers of broken wires that is repaired by 4 layers of CFRP with 20% prestress, the variation law of cylinder and concrete strain with respect to the hydrostatic pressure is shown in Fig. 9. When the number of broken wires was less than 30, the material strain increased linearly with increasing hydrostatic pressure, and the pipeline can operate normally. When the 35 broken wires and the hydrostatic pressure exceeded 0.9 MPa, the material strain, especially that in the concrete, increased dramatically. Then, the pipe began to fail; however, the pipeline could still bear the hydrostatic pressure of 1.0 MPa. When there were 40 broken wires and the internal pressure was 1.0 MPa, the concrete reached its visible crack strain, so the pipeline was considered to have failed.

When PCCP with different numbers of broken wires and repaired by 4 layers of CFRP with 20% prestress, damage maps of the concrete core are shown in Fig. 10. When broken wire number was less than 30, there was almost no damage to the concrete. When the 35 broken wires, the concrete was slightly damaged. When broken wire number was greater than 40, the concrete was seriously damaged, which is consistent with the results of the concrete strain analysis. Fig. 11 shows the stress maps of the steel cylinder with different broken wire numbers.

Under different numbers of broken wires, the wire and CFRP stress are shown in Fig. 12. Similar to the strain changes in the concrete and cylinder, the stress in the CFRP and wire increased linearly as the pressure when less than 35 broken wires. If the broken wire number continued to increase, the stress in both increased sharply at 0.9 MPa. When 40 wires were broken, the stresses in the steel wire and CFRP increased greatly but were still far less than the ultimate tensile strength of these materials.

Figs. 13 and 14 show the stress contours of the prestressed wire and CFRP under hydrostatic pressure of 1.0 MPa for different broken wire numbers. The stresses increased as the number of broken wires. When broken wire the number reached 40, the stress increased significantly, which is consistent with the analysis in Fig. 12.

Under the condition of 35 broken wires and 4 layers of CFRP with different prestress values, the variation law of the concrete and cylinder strain is shown in Fig. 15. The strain increased with increasing internal pressure. As the prestress value increased, the strain decreased. When the prestress was 25%, the material strain increased linearly, and no damage

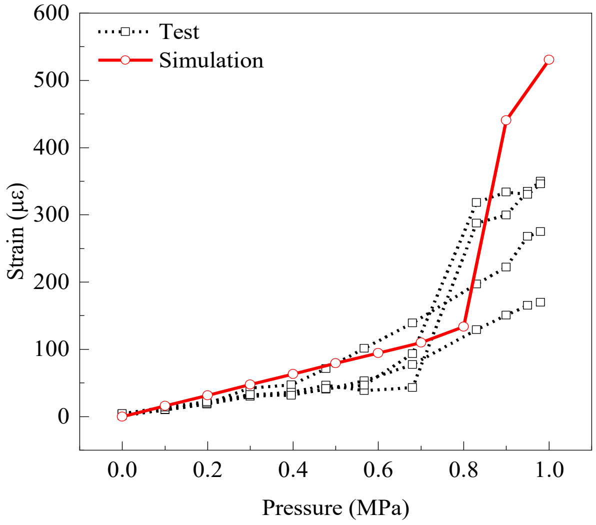

Fig. 8: Comparison of CFRP strain between the simulation and test.

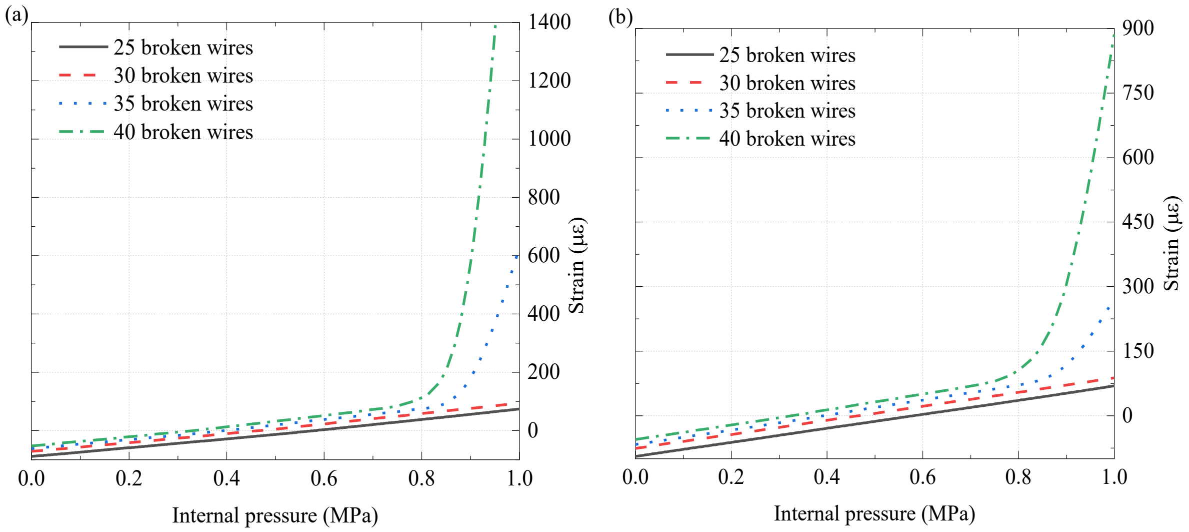

Fig. 9: Material strain with different numbers of broken wires: (a) concrete, and (b) cylinder.

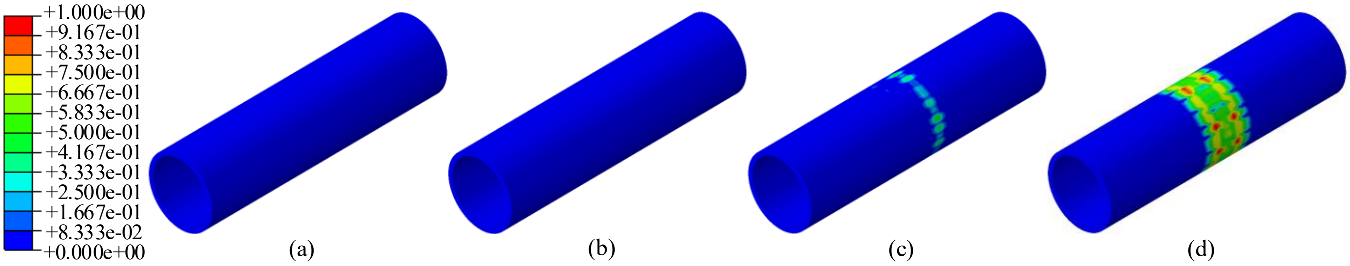

Fig. 10: Concrete damage with different numbers of broken wires: (a) 25, (b) 30, (c) 35, and (d) 40.

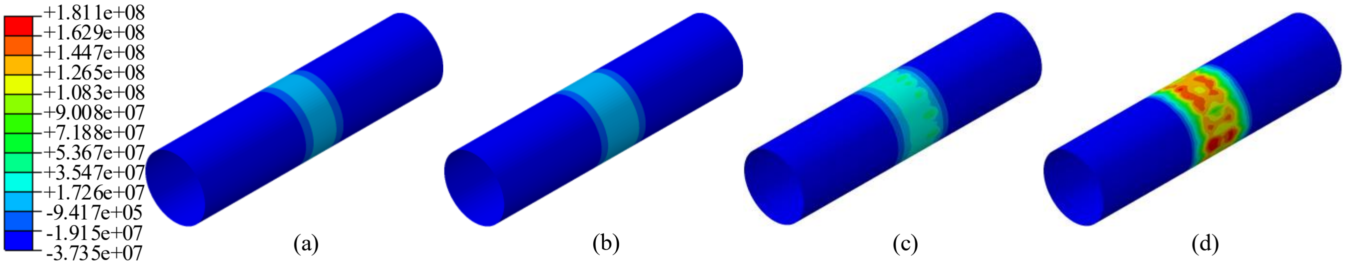

Fig. 11: Cylinder stress maps with different amounts of broken wires: (a) 25, (b) 30, (c) 35, and (d) 40.

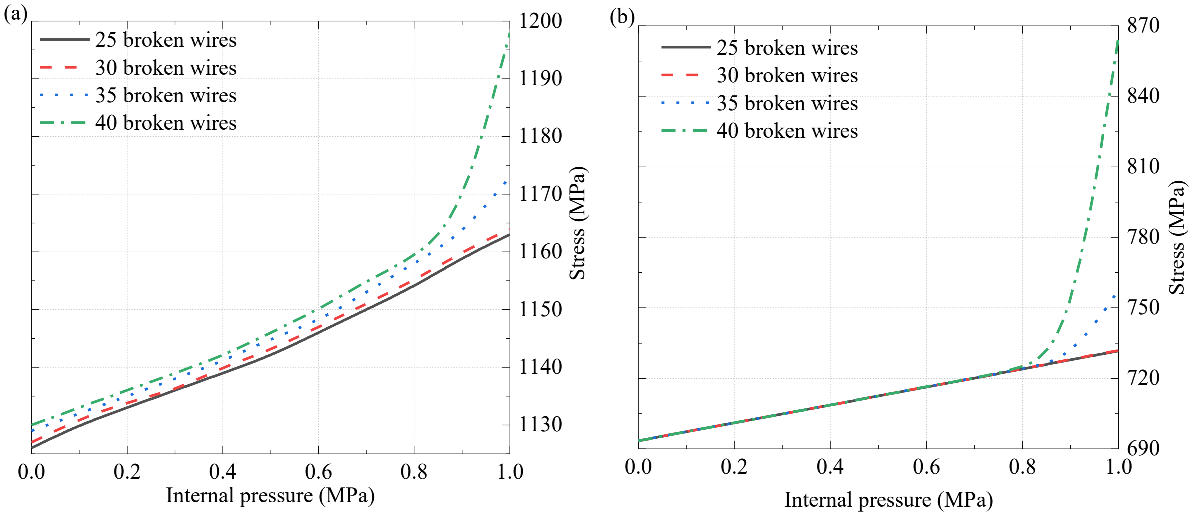

Fig. 12: Stress with different numbers of broken wires: (a) wire, and (b) CFRP.

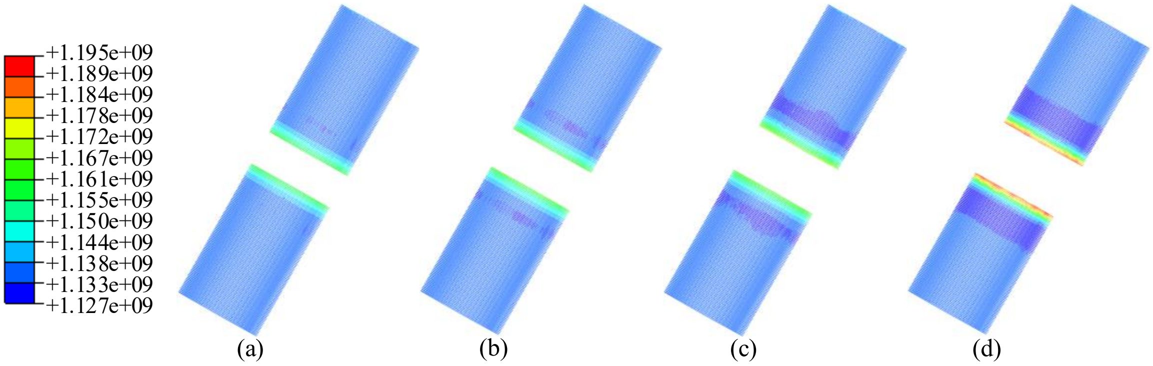

Fig. 13: Stress maps of the wires with different numbers of broken wires: (a) 25, (b) 30, (c) 35, and (d) 40.

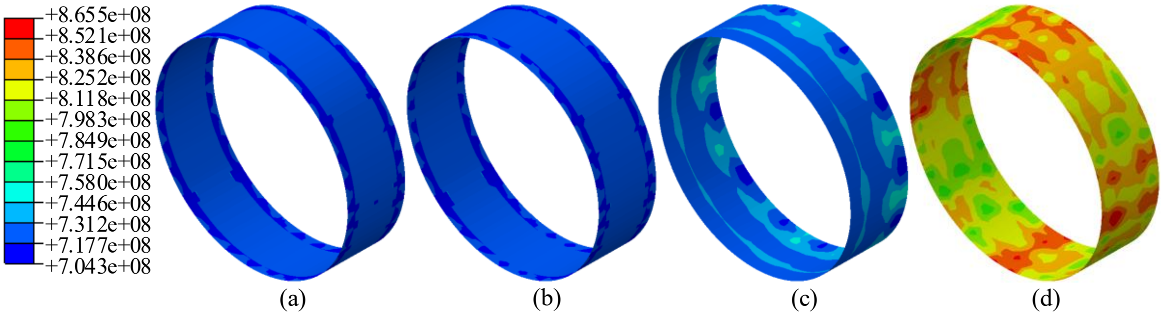

Fig. 14: Stress maps of the CFRP with different numbers of broken wires: (a) 25, (b) 30, (c) 35, and (d) 40.

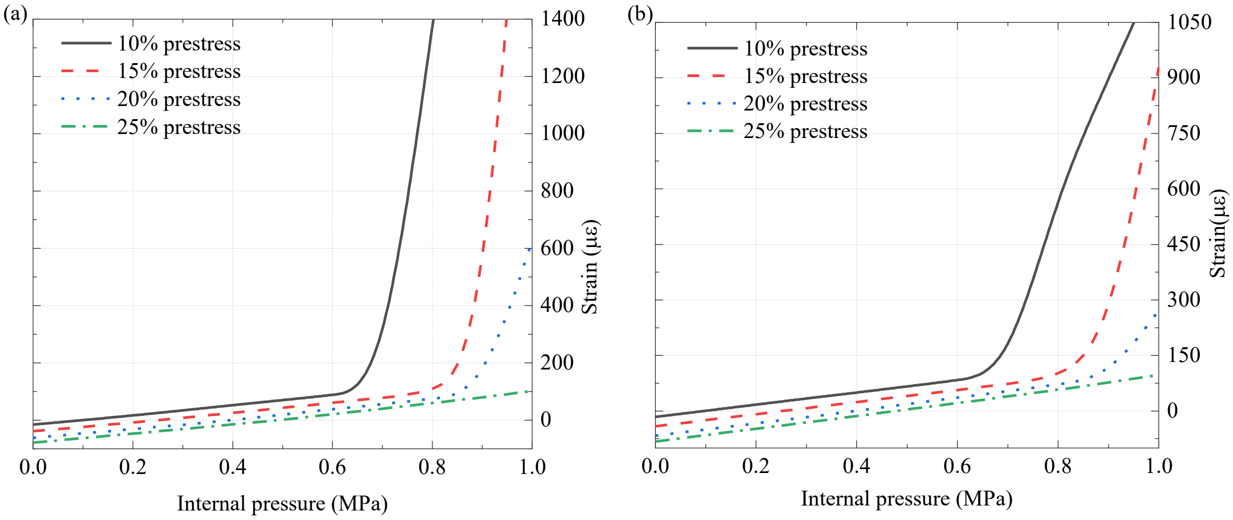

Fig. 15: Strain under different CFRP prestresses: (a) concrete, and (b) cylinder.

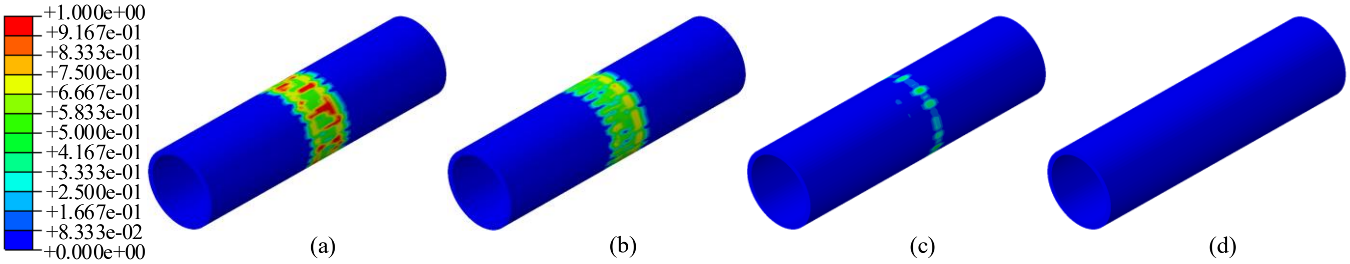

Fig. 16: Concrete damage under different CFRP prestresses: (a) 10%, (b) 15%, (c) 20%, and (d) 25%.

occurred in the material. The strain suddenly changed at 1.0 MPa, 0.9 MPa and 0.7 MPa when the CFRP prestress was reduced to 20%, 15% and 10%, respectively. When the prestress was less than 15%, the concrete had a large strain, which is considered to be damaged.

Fig. 16 shows the damage maps of the concrete with different CFRP prestresses under the pressure of 1.0 MPa. With the increase in prestress, the concrete damage decreased gradually. When the prestress increased to 25%, no damage happened at the concrete and the PCCP can operate normally, which shows that the 4-layer CFRP with a prestress of 25% can successfully rehabilitate a pipe with 35 broken wires. Fig. 17 shows the stress maps of the cylinder with different CFRP prestresses under the pressure of 1.0 MPa. As the prestress increased, the stress in the cylinder decreased.

Under the condition of 35 broken wires and 4 layers of CFRP with different prestress values, the wire and CFRP stress is shown in Fig. 18. Similar to the concrete and cylinder strains, the wire stress increased linearly with respect to the hydrostatic pressure when the CFRP prestress was 25%. As the prestress value decreased, the possibility of PCCP explosion increased. The same is true for the change in CFRP stress. The CFRP stress changed suddenly at 0.7 MPa, 0.9 MPa and 1.0 MPa when the prestress was 10%, 15% and 20%, respectively.

The stress maps of the steel wire when different CFRP prestresses are shown in Fig. 19. With increasing prestress, the stress in the wire gradually decreased, and the possibility of pipe explosion decreased. Fig. 20 shows the CFRP stress maps. It can be seen that with the increase in the prestress, the CFRP stress increased significantly; however, the stress level was still far below the ultimate tensile strength of the material.

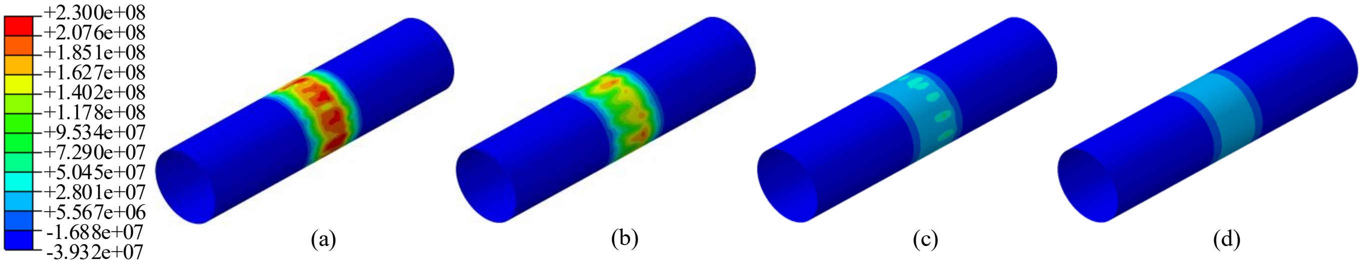

Fig. 17: Cylinder stress under different CFRP prestresses: (a) 10%, (b) 15%, (c) 20%, and (d) 25%.

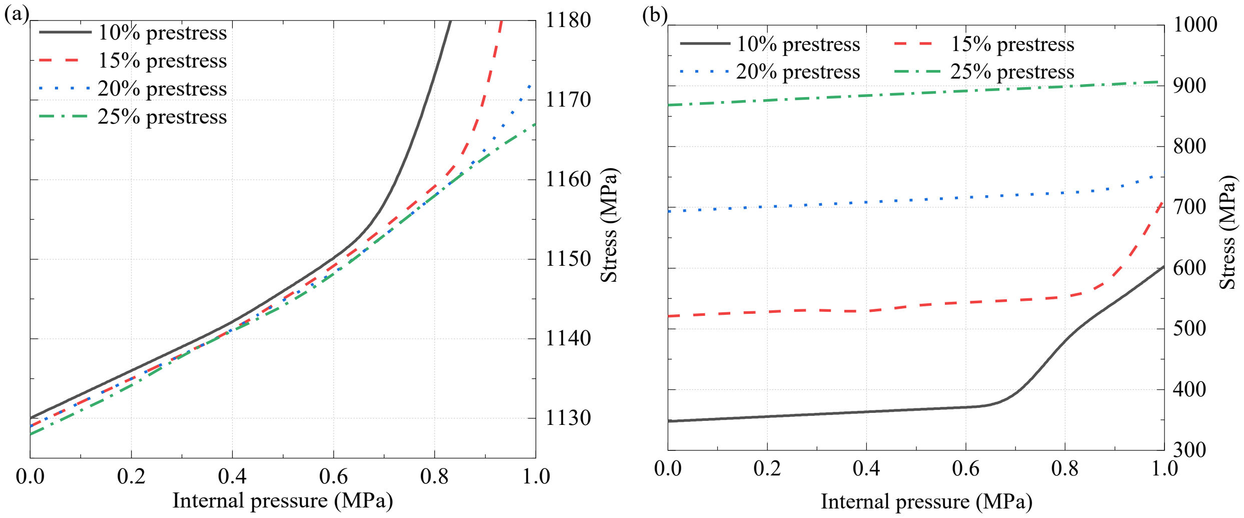

Fig. 18: Material stress under different CFRP prestresses: (a) wire, and (b) CFRP.

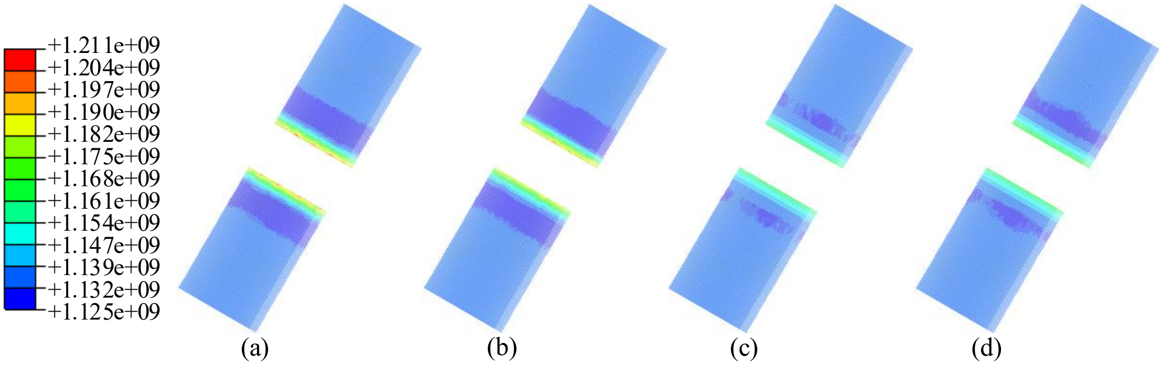

Fig. 19: Wire stress under different CFRP prestresses: (a) 10%, (b) 15%, (c) 20%, and (d) 25%.

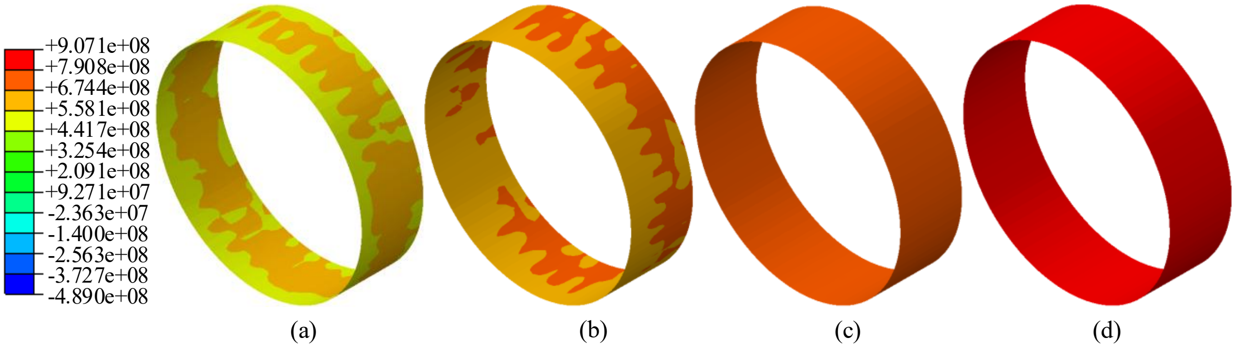

Fig. 20: CFRP stress under different CFRP prestresses: (a) 10%, (b) 15%, (c) 20%, and (d) 25%.

6. Conclusion

A method for strengthening damaged PCCPs with prestressed CFRPs was proposed. Afterwards, an internal hydraulic test was conducted on a PCCP, and a comparative study and analysis were carried out between the unrepaired section and the repaired section, which verified the repair effect of the proposed approach. Then, a 3D FE model was established, and a simplified analytical model was proposed. Based on the 3D FE model, some cases were analysed. The conclusions are as follows:

(1) Prestressed CFRP had a significant effect on improving the bearing capacity of PCCP.

(2) When the hydrostatic pressure was smaller than the working pressure, the PCCP can be simplified to a 2D planar mechanical problem, and the strain in each material was consistent at this time.

(3) The results of the experiment, 3D FE simulation and analytical model were in good agreement, indicating that the FE simulation and analytical model produced reliable results.

(4) The broken wire numbers and the values of CFRP prestress both had a great impact on the performance of PCCP. The PCCPs with fewer than 30 broken wires can be repaired by 4 layers of CFRP with 20% prestress.

This study can provide a reference of engineering practices for PCCP strengthen that are not suitable for internal CFRP liner bonding or where water supply interruption is not allowed. There are some limitations in this study, such as the impact of soil around the pipeline is not considered, and the cost, labor, and long-term durability of prestressed CFRP reinforcement are not discussed, which will be carried out in the subsequent research.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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