Research Article

Bond-Slip Behavior between Plastic Bellow and Concrete

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Despite the widespread use of plastic bellows in prestressed channels, their poor bonding with concrete and mortar results in “layering,” which limits their application in practical engineering. In this study, the bonding property between plastic bellows and concrete or grout material was investigated using a single-end compression test on plastic bellow concrete. The slip failure mode, ultimate load, and slip of plastic bellows were obtained. Furthermore, the analysis of the bond-slip properties of plastic bellows indicated that the bond strength decreased with increasing bond length. Moreover, the increase in the loading force was greater than the increase in the contact area. Based on the test data, a bond-slip constitutive relationship model was established, which accurately reflects the bond-slip process. The expressions of bond and slip were derived along with different bond positions of plastic bellow concrete specimens. Finally, a three-dimensional finite element model of a plastic bellow concrete specimen was established. The numerical simulation curve was compared with the experimental and fitting curves. The results indicated that the bond strength of the plastic bellow concrete specimen decreased with increasing bond length. The influence of bond strength on the contact area was comprehensively analyzed. This study effectively combines experimental research, theoretical analysis, and numerical simulation to analyze the bond performance between plastic bellows and concrete or grout material.

1. Introduction

Research and field investigations have reported that the pore-forming process and quality of posttensioned prestressed concrete box girder significantly impact the bearing capacity and durability of its prestressed system [1]. Among the posttensioned prestressing techniques, prestressed hole forming is a leading technique [2]. The continuous progress of materials, machinery, and other technologies has resulted in the development of posttensioned pore-forming materials from the earliest rubber extractive pipe to metal bellows, which have then evolved to plastic bellows [3]. In comparison with metal bellows, plastic bellows exhibit a lower friction coefficient, adequate sealing performance, and electrochemical corrosion resistance. At present, they are widely used in several projects with high durability requirements, including highway bridges [4, 5] and other structures [6–8].

However, plastic bellows exhibit certain disadvantages in practical engineering applications, such as high unit price, poor ductility, and low density [9]. Typically, plastic bellows have a low elastic modulus and strength, making them easier to bend than metal bellows [10]. This reduces the bonding ability between bellows and concrete or grout, resulting in stratification [11]. During construction, large transverse tensile stress may occur if the prestressed beam deviates in the length direction, resulting in sectional cracks and safety risks.

To address these issues, we investigated the bond between plastic bellows and concrete or grout material. At present, the bonding mechanism between plastic bellows and concrete or grout material is similar to that between
2. Test Materials and Methods

2.1. Materials. C50 concrete was used. The material properties of concrete were determined using a concrete cube compression test. The concrete cube with a nominal side length of 150 mm comprises materials obtained using common mixing and curing techniques [25, 26]. The elastic modulus of concrete is measured according to the standard “Test methods of cement and concrete in highway engineering” (JTGE30-2005 [27]). Table 1 summarizes the concrete material test results.

According to the requirements of TB/T 3192-2008 [28], the ratio of the grout is cement: water: admixture = 1 : 0.35 : 0.09. Herein, ordinary Portland cement with strength grade of 52.5 MPa is used. The compressive strength test of a sample was performed according to GB/T 17671-1999 [29]. The experimental test results (Table 1) satisfy the strength requirements of greater than or equal to 50 MPa.

The specification of plastic bellows is $\varphi 90$, with an elastic modulus of 800 MPa, the tensile yield stress of 17 MPa, the density of 900 kg/m$^3$, and Poisson’s ratio of 0.35. The tensile stress and elongation at break of plastic bellows were measured according to the GB/T 8804.1-2003 standard [30]; the results are presented in Table 1.

2.2. Cement-Filled Concrete with Different Interface Material Specimens. The concrete was mixed evenly in the mixer, poured into the test mold, and vibrated to obtain uniform and dense concrete in the test mold. After completing the concrete vibration, the specimen was grouted. A total of 5 specimens were placed in a standard curing room for 28 days before being used for testing.

2.3. Test Process. The operational methods and parameters of the test were obtained based on the relevant standards and specifications of the industry [22–26]. Figures 1 and 2 depict the specimen parameters.

The test was conducted to measure the displacements of the free end ($S_1$) and loading end ($S_2$) surfaces of grout, and the relative slip was calculated as the difference between them.

As depicted in Figure 3, the test machine adopts a 2000 kN universal pressure machine, which is in line with the requirements of the “Standard for test method of concrete structures” [31]. The specimen was preloaded with a loading force of 20 kN before the test. The force was loaded step by step, and the change in the displacement gauge value was observed for 1 min at each 100 kN. The loading was continued until the specimen was destroyed or the displacement gauge reading increased abruptly.

3. Analysis of Test Results

3.1. Typical Bond Stress-Slip Curves. We considered the load-slip curve of plastic bellow concrete with an inner diameter of 90 mm and an adhesive length of 135 mm. To reduce the error, the average slip (Figure 4) of two ends was used to analyze the bond-slip behavior during the entire loading process. The bonding force can be calculated as indicated in equation (1) [32]. The interface between the plastic bellows and concrete or grout is considered to be a non-corrugated smooth cylinder, and the bonding stress is assumed to be evenly distributed along with the interface.
where $\tau$ denotes the average bonding stress between bellows and concrete or grout, $d$ indicates the diameter of plastic bellows, $P$ represents the loading force at the loading end, and $l$ denotes the bond length. The forced end slip was obtained by the press machine directly, and the free end slip was given by the displacement meter. The slip was defined as the difference between the forced end slip and the free end slip.

The stress process of plastic bellow concrete structure can be divided into six stages. In this first stage (0A), owing to the elastic compression of concrete and grout and expansion and stretching of bellows, grout material produces a micro-slip. The chemical bond between the plastic bellows and surrounding concrete and grout is instrumental in this process. The slip of the free end of the grout material can be neglected. In the second stage (AB), as the load increases, the slip of the free end increases rapidly when the chemical cementation force penetrates the free end. Friction and mechanical bite force between the plastic bellows and external concrete and internal grout play a major role at this stage. Additionally, the amount of slip increases rapidly. In the third stage (BC), the grout material in the plastic corrugated pipe is deformed or crushed by the loading end, resulting in a transverse deformation. The force is transferred to the plastic bellows, which are subjected to the expansion pressure of the grout material. Owing to the tensile properties of the plastic bellow material, the bellows stretch outward along the diameter direction. The continuous expansion and deformation of plastic bellows affect the concrete in contact with it, applying pressure to the internal concrete. In the fourth stage (CD), an apparent turning point is observed at this stage in the $\tau - S$ curve. Cracks begin to appear in the specimen (Figure 5), which gradually increase and extend until they run through the entire specimen, and the load attains the limit value. The load increases rapidly owing to the effect of bellows, and the slip deformation is relatively small before the load attains the ultimate value.

In the fifth stage (DE), when the external load attains the peak value, the load begins to decline rapidly. Simultaneously, the displacement of the free end develops rapidly until the load becomes stable. At this stage, the crack of the specimen is apparent, and the specimen is damaged. In the last stage (EF), the load remains stable and the displacement at the free end of the grout continues to increase.

3.2. Effects of Bond Length and Contact Area on Bonding Properties. There are a total of 5 specimens tested in the laboratory, and the test results are shown in Tables 2 and 3 and Figure 6.

Figure 6(a) depicts the bond-slip curves of plastic bellow concrete specimens with different bond lengths, namely 90, 135, and 180 mm. As indicated in the figure, the bond stress decreases with the increase in bond lengths, which can be attributed to the bond stress exhibiting ripples on the surface of plastic bellows and the bond and slip not changing linearly. Thus, the bond length of plastic bellows significantly influences the bond strength.

Equation (1) indicates that under the same loading force $P$, the bond stress $\tau$ is inversely proportional to the inner diameter $d$ of the bellows and bond length $l$ between the bellows and concrete or grout material. In other words, the
bond stress is inversely proportional to the surface area of the hollow cylinder. As depicted in Figure 6(b), the contact area is regulated by controlling the inner diameter and bond length. According to the test data, the loading force \( P \) required for plastic bellow specimen to produce the same amount of slip increases with the increase in the contact area. This slip is inversely proportional to the bond stress \( \tau \) calculated using equation (1) and the contact area. When the loading force \( P \) is maintained constant, the larger the contact area, the smaller the bond stress \( \tau \). Therefore, with the increase in the contact area, the increase in the loading force is greater than that of the contact area.

4. FEM Simulation

4.1. Model Establishment. Based on the bond-slip curve and constitutive relationship of plastic bellow concrete obtained in the single-end compression test, the bond performance of plastic bellow concrete was analyzed using the ANSYS FE software. We used the SOLID65 element [33], wherein concrete adopts an isotropic nonlinear elastic constitutive relationship. In this case, the cracking or crushing of concrete is not considered. Grout material also used the SOLID65 unit, whereas the shell element SHELL181 [34] was selected for calculation in the established parametric FE model of plastic bellows. The plastic bellows used for concrete in this study are made of high-density polyethylene (HDPE) [35]. For plastic bellows, the main input parameters are as follows: elastic modulus is \( E_c = 800 \text{ MPa} \), Poisson’s ratio is \( \nu = 0.3 \), density is \( 9500 \text{ kN/m}^3 \), and thermal expansion coefficient is \( 5-10/\text{°C} \). Spring unit COMBIN39 [36] was used to simulate the bonding between plastic bellows and concrete or grout material. COMBIN39
has axial deformation and torsional deformation ability [37].

In the ANSYS FE simulation analysis, the spring element is used to analyze and simulate the bond stress on the interface between plastic bellows and concrete or grout material; the stiffness coefficients are $K_1$ and $K_2$. In the FE model, the spring element is placed on a contact surface where adhesive slip may occur. In the ANSYS FE simulation, the plastic bellows and concrete or grout material may result in bond-slip failure. Therefore, the normal deformation is substantially lesser than the tangential deformation. To simplify the calculation, the normal spring can be considered as a spring with a particularly large stiffness coefficient. Additionally, the normal spring is assumed to bear only pressure, regardless of shear force and other factors. The tangential stiffness coefficient is nonlinear, and the stiffness of tangential spring is defined by bond-slip constitutive relationships obtained from the single-end compression test.

The bond-slip between plastic bellows and concrete or grout material is simulated using the spring COMBIN39 element. Springs have no length. The performance of the simulated spring is determined based on the spring force-deformation ($F$–$D$) curve [38].

The $F$–$D$ curve is obtained from the bond-slip constitutive relationship curve of the plastic bellow concrete structure. The specific solution can be summarized as follows:

1. The corresponding relationship between the bond stress and slip of each spring at different positions can be obtained based on the bond-slip constitutive model of plastic bellow concrete structure. As the variable monitoring of bond stress and slip quantity with changing positions was not performed during the test, the bond-slip relationship in the free end was adopted.
2. The $F$–$D$ curve of the spring unit at different positions can be evaluated considering the theoretically derived relationship of the bond stress changing with the bond length. The $F$–$D$ value indicates the corresponding bond stress multiplied by the area occupied by the corresponding contact surface of the spring.

### Table 2: Peak values of bond stress and the corresponding slips of different bond lengths.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Bellow diameter $R$ (mm)</th>
<th>Bond length $l$ (mm)</th>
<th>$\tau_{\mu}$ (MPa)</th>
<th>$S$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D90-L90</td>
<td>90</td>
<td>90</td>
<td>5.16</td>
<td>1.70</td>
</tr>
<tr>
<td>D90-L135</td>
<td>90</td>
<td>135</td>
<td>4.18</td>
<td>1.55</td>
</tr>
<tr>
<td>D90-L180</td>
<td>90</td>
<td>180</td>
<td>3.72</td>
<td>1.40</td>
</tr>
</tbody>
</table>

### Table 3: Peak values of bond stress and the corresponding slippage of different contact areas.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Bellow diameter $R$ (mm)</th>
<th>Bond length $l$ (mm)</th>
<th>Contact area $S$ (mm$^2$)</th>
<th>$\tau_{\mu}$ (MPa)</th>
<th>$S$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D80-L120</td>
<td>80</td>
<td>120</td>
<td>30159.29</td>
<td>3.94</td>
<td>1.30</td>
</tr>
<tr>
<td>D90-L135</td>
<td>90</td>
<td>135</td>
<td>38170.35</td>
<td>4.18</td>
<td>1.55</td>
</tr>
<tr>
<td>D110-L165</td>
<td>110</td>
<td>165</td>
<td>57019.90</td>
<td>4.56</td>
<td>1.35</td>
</tr>
</tbody>
</table>

![Figure 6: Bond-slip curves considering different (a) bond lengths and (b) contact areas.](attachment:image.png)
Figure 7(a) depicts the established FE solid diagram and mesh division. Figure 7(b) illustrates the contact interface simulated by the COMBIN39 nonlinear spring unit.

4.2. FEM Simulation Results. Considering different influence parameters, we selected five representative specimens for the FE simulation analysis. Figure 8 illustrates the slip cloud diagrams of the loading and free ends of the model.

Figure 9 depicts the bond-slip test results, constitutive model curves derived in this study, and the simulation results. As indicated in the figure, the derived constitutive model curve is more similar and consistent with the experimental curve than the simulation results. In Figure 9(b), the fitting curve of the plastic bellow concrete structure with an inner diameter of 90 mm and bond length of 135 mm is more consistent with the test data curve. This is because we used the specimen model (90 mm inner diameter and 135 mm bond length) to deduce the bond-slip constitutive model; the coincidence degree of the model reached more than 90%. The curve relations in Figure 9 indicate that the coincidence degree of the entire rising section of the fitting curve with the test data is substantially greater than that observed in the falling section of the curve.

The curves of the FE simulation model (Figure 9) differ from the experimental results to a certain extent. As observed in the displacement cloud diagram of the loading end (Figure 8(a)), the displacement is primarily caused by the stressed grout material and its surrounding concrete. Additionally, its deformation expands circularly outward along the loading end of the grout material, which is different from the deformation observed in the actual test. Although the grout material at the loading end and surrounding concrete are affected to a certain extent during the test, the surrounding concrete structure produces a small displacement. Furthermore, certain plastic bellow concrete structures exhibit small cracks on the outer surface before the test loading, which also results in a few errors.

4.3. Analysis of Bond-Slip Performance

4.3.1. Influence of Different Pore-Forming Materials on Bond-Slip Performance. Owing to the limited number of tests, only three types of pore-forming materials with pore diameters of 90 mm were analyzed. FE analysis was performed on the plastic bells with the inner diameter specified in the existing specification of the ANSYS FE software. Additionally, the bond between the metal bellows with identical pore diameters and the rubber extractive pipe was analyzed. As depicted in Figure 10, the comparison of the peak bonding stress indicates that the bond between plastic bellows and concrete or grout material is slightly worse than that between metal bellows and concrete or grout material under identical diameter conditions; however, the bond is greater than that observed in the case of a rubber extractive pipe. Overall, the bond stresses of the three materials tend to increase with the increase in diameter.

4.3.2. Influence of the Main Factors on the Bond-Slip Strength of Plastic Bellow Concrete Specimen

(1) Influence of Bond Length. The ANSYS FE software was used to analyze the influence of bond length on the bond performance of plastic bellows in contact with concrete or grout material. Under the same parameters of concrete strength, grout material strength, and inner diameter of plastic bellows, the plastic bellow concrete model with different bond lengths was used to calculate and analyze the bond performance, which compensates for the problem of limited variables in the test. The inner diameter of the plastic bellow is 90 mm, and the bond length ranges from 30 to 270 mm. Figure 11 depicts the ANSYS FE calculation.

Figure 11(a) indicates that the bond performance of the specimen decreases with the increase in the bond length. The bonding stress is significantly affected by the bond length when it is smaller than the inner diameter. Conversely, the bonding stress gradually decreases owing to the influence of the bond length when it is larger than the inner diameter; however, the stress continues to decrease with the increase in the bond length. This is the result of the nonlinear distribution of bond stress with respect to the surface of plastic bellows. In railway prestressed concrete bridge engineering, the length of each section of a prestressed tunnel is generally 24, 32, or 40 m, and the bond length of pore-forming material with concrete and grout material is substantially greater than its inner diameter. Therefore, in practical engineering applications, the bond stress does not differ significantly despite the change in the bond length.

(2) Influence of Contact Area. Similarly, considering that the plastic bellows are hollow smooth cylinders, the bonding stress was determined to be inversely proportional to the surface area of the hollow cylinders. As depicted in Figure 10(b), the bond stress of the plastic bellow concrete structure is significantly affected by the contact area. However, the bond stress does not change regularly with the contact area. Based on the ANSYS FE analysis, we determined that when the inner diameter of plastic bellows is maintained constant, the bonding stress decreases with the increase in the contact area by changing the bond length between plastic bellows and concrete or grout material. In other words, the bonding stress decreases with the increase in the bond length. When the inner diameter and bond length of plastic bellows change, the bonding stress increases with the increase in the contact area. This implies that when the inner diameter and bond length of plastic bellows increase, the bonding stress between plastic bellows and concrete or grout material increases. However, the figure indicates that when the contact area \( A < 3000 \text{mm}^2 \), no apparent linear relationship exists between the bond stress and contact area. Even when \( 3000 \text{mm}^2 \leq A < 8000 \text{mm}^2 \), no apparent linear relationship is observed between the bonding stress and contact area as the contact area increases. However, the bond stress fluctuates with the change in the contact area, and the fluctuation range is approximately 1.5 MPa.
Figure 7: Finite element (FE) models: (a) FE mesh diagram and (b) the distribution of spring units.

Figure 8: Slip clouds of the (a) loading and (b) free ends of the model.

Figure 9: Continued.
Figure 9: Comparison of simulation results and test results. (a) D90-L90. (b) D90-L135. (c) D90-L180. (d) D80-L120. (e) D110-L165.

Figure 10: Relationship between the peak bond stress and pore-forming materials.
4.4. Fitting Curves and Analytical Solution

(1) OB Segment: OA stage is extremely short, and the critical points of micro-slip and slip stages are not particularly apparent. Therefore, when analyzing the bond-slip curve, the micro-slip and slip stages can be combined into a single stage, which is referred to as the initial ascending segment of the curve. At this stage, the exponential distribution is more consistent with the experimental data than that observed at the straight line. Software-based statistical regression was performed on the test data, wherein the correlation coefficient reached 0.999. Its mathematical expression can be written as follows:

\[
\tau(x) = A_1 e^{-A_2 S} + A_3 \quad (0 \leq S < S_1).
\]  

(2) BC Segment: this indicates the fluctuating unstable stage of the curve. The mathematical expression can be obtained based on the statistical regression of the test data with a correlation coefficient of 0.9, expressed as follows:

\[
\tau = B_1 S^2 + B_2 S + B_3 \quad (S_1 \leq S < S_2).
\]  

(3) CD Segment: this segment represents the upward phase of the curve. Owing to the lack of experimental data, this stage was simplified to linear processing. Statistical regression was performed on each specimen at this stage to obtain the mathematical expression as follows:

\[
\tau = C_1 S + C_2 \quad (S_2 \leq S < S_3).
\]  

(4) DE Segment: this indicates the descending stage of the curve, which is close to the quadratic parabola. Statistical regression was performed for each specimen, and the correlation coefficient was greater than 0.98. The corresponding mathematical expression can be represented as follows:

\[
\tau = D_1 (S - S_3)^2 + D_2 (S_3 \leq S < S_4).
\]  

(5) EF Segment: this stage represents the horizontal residual segment of the curve. As the residual strength is independent of slip, this stage can be simplified into a straight line. The corresponding mathematical expression can be obtained as follows:

\[
\tau = \tau_4 (S \geq S_4).
\]

The fitting formulas of the aforementioned five segments indicate the bond-slip constitutive relationship fitted in this study. Figure 12 illustrates the fitting results of each specimen and the comparison of experimental results. As indicated in the figure, the fitting relationship affects all specimens adequately.

Analytical Solutions of Local Bond Stress, Slip, and Normal Stress along Bond Length. The differential element is taken from the plastic bellow concrete structure to conduct an overall force analysis of the structure, as shown in Figure 13.

Balance of forces yields the following:

\[
A_c d\sigma_c + A_g d\sigma_g = 0,
\]  

(7)

\[
\frac{\pi d_g^2}{4} d\sigma_g = \pi d_g \tau dx,
\]  

(8)

where \( \tau \) is the bond stress, \( \sigma_c \) is the concrete stress, \( A_c \) is the concrete area, \( A_g \) is the grout area, \( \sigma_g \) is the grout stress, and \( d_g \) is the grout or bellow diameter.

The formula for slip \( S \) and position \( x \) is given as follows:

\[
S(x) = S_g(x) - S_c(x).
\]  

(9)

Differentiating equation (9) yields the following:

\[
\frac{dS}{dx} = \frac{dS_g}{dx} - \frac{dS_c}{dx} = \varepsilon_g(x) - \varepsilon_c(x).
\]  

(10)
Figure 12: Comparison of experimental and fitting results of different specimens. (a) D90-L90. (b) D90-L135. (c) D90-L180. (d) D80-L120. (e) D110-L165.
We assume that plastic bellows, concrete, and grout obey Hooke’s law:
\[ \sigma = E \varepsilon, \]  
(11)
where \( E \) is the elastic modulus and \( \varepsilon \) is the strain.

According to equations (7)–(11):
\[ \frac{d^2 S}{dx^2} - \frac{4}{\varepsilon_g A_g} \left( 1 + \frac{E_g A_g}{E_c A_c} \right) \tau(x) = 0. \]  
(12)

Let \( Q = (4/E_g d_g) (1 + (E_g A_g/E_c A_c)) \), and then, the formula can be simplified to
\[ \frac{d^2 S}{dx^2} - Q \tau(x) = 0. \]  
(13)

From equation (13), we can see the relationship between the bond stress and slip. However, in practical applications, nonlinear deformation of concrete, grout material, and bellows and uneven deformation should also be considered, which is not the ideal state of existence hypothesis. However, the deduction and simplification of the theory still reflect the trend that the bond stress between plastic bellows and concrete or grouting material changes along the bond length, which lays a foundation for future research and calculation.

The boundary conditions are as follows:
when \( x = 0 \), \( \varepsilon_g = \varepsilon_c = 0, S = S_2 \),
when \( x = l \), \( \varepsilon_g = \frac{P}{E_g A_g}, \varepsilon_c = \frac{P}{E_c A_c}, S = S_1 \),
(14)

where \( S_1 \) is the loading end slip, \( S_2 \) is the free end slip, and \( l \) is the bond length.

The bond-slip constitutive relation used here is the equation model obtained by fitting the experimental data in the previous paper to study the trend of bond stress changing with bond length, without considering the deformation of the horizontal residual section of slip.

(1) \( 0 \leq S < S_1 \):
Substituting equation (2) into (13):
\[ \frac{d^2 S}{dx^2} - Q\left( A_1 e^{-A_1 x} - A_2 \right) = 0. \]  
(15)

We solve the equation
\[ S(x) = \frac{A_1 Q}{A_2} e^{-\frac{A_1 x^{2}}{2}} + \frac{A_1 Q}{A_2} x + C_1. \]  
(16)

Substituting equation (15) into (16):
\[ C_1 = (A_1 Q/A_2), C_2 = S_2 - (A_1 Q/A_2), \]  
and then, equation (16) becomes
\[ S(x) = \frac{A_2 Q}{A_1} e^{-\frac{A_2 x^{2}}{2}} + \frac{A_1 Q}{A_2} x + S_2 - \frac{A_1 Q}{A_2}. \]  
(17)

According to equation (11), we get
\[ \sigma_g = \frac{4}{d_g} \left( \frac{A_1 Q}{A_2} e^{-\frac{A_1 x^{2}}{2}} - A_2 x + \frac{A_1 Q}{A_2} \right). \]  
(18)

According to equations (13) and (17), we get
\[ \tau(x) = A_1 e^{-\frac{A_1 x^{2}}{2}} - A_2. \]  
(19)

(2) \( S_1 \leq S < S_2 \):
Substituting equation (3) into (13), we get
\[ \frac{d^2 S}{dx^2} - Q\left( B_1 S^2 + B_2 S + B_3 \right) = 0. \]  
(20)

Let \( (ds/dx) = P; \)
\[ \frac{d^2 S}{dx^2} = \frac{dP}{ds} \frac{ds}{dx} = P \frac{dP}{ds}. \]  
(21)

Substituting equation (21) into (20), we get
\[ P \frac{dP}{ds} - Q\left( B_1 S^2 + B_2 S + B_3 \right) = 0. \]  
(22)

Thus,
\[ PdP = Q\left( B_1 S^2 + B_2 S + B_3 \right) ds. \]  
(23)

Taking the integral on both sides, we get
\[ P = \left( \frac{2}{3} QB_1 S^3 + QB_2 S^2 + 2QB_3 S + C \right)^{1/2}. \]  
(24)

Substituting equations (15) and (16) into (24), we get
\( C = 0 \).
Thus,
\[ \frac{ds}{dx} = \left( \frac{2}{3} QB_1 S^3 + QB_2 S^2 + 2QB_3 S \right)^{1/2}. \]  
(25)

We solve the equation as follows:
\[ S(x) = \frac{3A_1^2}{2A_1^2}(\tan^2 M), \]
\[ \sigma(x) = \frac{3E\sqrt{QA_3}}{2A_1}\tan M \cdot \sec^2 M, \] (26)
\[ \tau(x) = \frac{3QA_3^2\sqrt{QA_3}}{4A_1}(2\tan^2 M \cdot \sec^4 M + \sec^2 M), \]
where
\[ M = \frac{1}{2}x\sqrt{QA_2} - 1. \] (27)

1. \[ S_2 \leq S < S_3; \]
2. Substituting equation (4) into (13), we get
\[ \frac{d^2S}{dx^2} - Q(B_1S + B_2) = 0. \] (28)
We solve the equation, as follows:
\[ S(x) = C_1e^{QB_1S} + C_2e^{-QB_1S} \cdot \frac{B_2}{B_1}. \] (29)
Substituting equations (15) and (16) into (29), we get
\[ C_1 = C_2 = \frac{S_2}{2}, \]
\[ B_1 = \frac{\tau_3 - \tau_2}{S_3 - S_2}, \]
\[ B_2 = \frac{\tau_2 - \tau_3S_2}{S_3 - S_2}, \] (30)
\[ S(x) = \frac{S_2}{2}e^{QB_1S} + \frac{S_2}{2}e^{-QB_1S} \cdot \frac{B_2}{B_1}. \]

According to equation (11):
\[ \sigma(x) = \frac{B_3S_2}{d_\sigma^2}\left(e^{QB_1S} + \frac{S_2}{2}e^{-QB_1S}\right). \] (31)
According to equations (13) and (30):
\[ \tau(x) = \frac{QB_1^2S_2}{8}\left(e^{QB_1S} + \frac{S_2}{2}e^{-QB_1S}\right). \] (32)

4. \[ S_3 \leq S < S_4; \]
Substituting equation (5) into (13):
\[ \frac{d^2S}{dx^2} - Q[D_1(S - S_3)^2 + D_2] = 0. \] (33)
Let \( (ds/dx) = P. \)

Thus,
\[ \frac{d^2S}{dx^2} = \frac{dP}{ds} = \frac{dP}{dx} = \frac{dP}{ds} = \frac{P}{ds}. \] (34)
After further calculation, we get
\[ P \frac{dP}{ds} = Q[D_1(S - S_3)^2 + D_2] = 0. \] (35)
Thus,
\[ P \frac{dP}{ds} = Q[D_1(S - S_3)^2 + D_2]ds. \] (36)
We then take the integral on both sides:
\[ \frac{ds}{dx} = \left(\frac{2}{3}QD_1(S - S_3)^3 + QD_2S^2 + C\right)^{1/2}. \] (37)
Substituting equations (15) and (16) into (37):
\[ C = 0. \]
Thus,
\[ \frac{ds}{dx} = \left(\frac{2}{3}QD_1(S - S_3)^3 + QD_2S\right)^{1/2}. \] (38)
We solve the equations as follows:
\[ S(x) = 3S_3 + 3\tan^2 M, \]
\[ \sigma(x) = 6E\sqrt{QD_1S_3} \cdot \tan M \cdot \sec^2 M, \] (39)
\[ \tau(x) = 3S_3QD_1\left[\sec^4 M + 2\tan^2 M \cdot \sec^2 M\right], \]
where
\[ M = \frac{1}{2}QB_1S_3 \cdot x. \] (40)

4.5. Comparison among Test Results, Simulation Results, and Theoretical Results. Figure 14 depicts the bond-slip test results, constitutive model curves derived in this study, and the simulation results. As indicated in the figure, the derived constitutive model curve is more similar and consistent with the experimental curve than the simulation results. In Figure 9(b), the fitting curve of the plastic bellow concrete structure with an inner diameter of 90 mm and bond length of 135 mm is more consistent with the test data curve. This is because we used the specimen model (90 mm inner diameter and 135 mm bond length) to deduce the bond-slip constitutive model; the coincidence degree of the model reached more than 90%. The curve relations in other figures in Figure 14 indicate that the coincidence degree of the entire rising section of the fitting curve with the test data is...
substantially greater than that observed in the falling section of the curve.

The curves of the FE simulation model (Figure 14) differ from the experimental results to a certain extent. As observed in the displacement cloud diagram of the loading end (Figure 8(a)), the displacement is primarily caused by the stressed grout material and its surrounding concrete. Additionally, its deformation expands circularly outward along the loading end of the grout material, which is different from the deformation observed in the actual test. Although the

**Figure 14**: Comparison of test results, fitting curve, and simulation results. (a) D90-L90. (b) D90-L135. (c) D90-L180. (d) D80-L120. (e) D110-L165.
grout material at the loading end and surrounding concrete are affected to a certain extent during the test, the surrounding concrete structure produces a small displacement. Furthermore, certain plastic bellow concrete structures exhibit small cracks on the outer surface before the test loading, which also results in a few errors.

4.6. Peak Bond Stress and Slip Analysis. The parameters of the derived bond-slip constitutive relationship are determined by each characteristic point of the test curves, namely \((S_1, \tau_1), (S_2, \tau_2), (S_3, \tau_3),\) and \((S_4, \tau_4)\). Therefore, the corresponding values of the bond-slip constitutive relationship at each stage (OA, AB, BC, and CD) are consistent with the test results. The average error of the FE model is 0.0964 and that of the slip value calculated by the FE model is 0.0588.

As indicated in Figure 14 and Table 4, the basic trend and value of the calculated curve of theoretical fitting and the curve analyzed using the FE model are predominantly consistent with the test results; however, minor differences are observed, which could be verified by the regression model, utilized to analyze the relationship of stimulation values with test and fitting results for peak bond stress and slip. Great \(R^2\) could be found for the peak bond stress and slip among the stimulation, test, and fitting results. For the peak bond stress, 0.9873 and 0.9354 of \(R^2\) could be calculated in the relationship of stimulation value with test and fitting values, respectively. For the slip, 1 and 0.9951 of \(R^2\) could be calculated in the relationship of stimulation value with test and fitting values, respectively.

(1) Although the calculated and FE model curves exhibit certain errors when compared to the test values, the upward and downward trends of the model are predominantly consistent. This can be used to investigate the bond-slip curve model of plastic bellow concrete structure. The calculated residual section is a straight line, which differs slightly from the experimental value. The bond-slip section of the test curve has a slight upward trend after attaining a stable level, which can be attributed to the action of the bellows of the pipe resulting in bond failure and cracks on certain contact surfaces during the test. Despite the rapid development of the crack and the increase in the amount of slip, the crack does not run through the entire bonding area. The bonding stress continues to exist and impacts the contact surface without damage.

(2) In the FE calculation, the bond-slip curve obtained from the test results is considered as the parameter of the spring element. Therefore, the calculated bond stress and slip amount are predominantly consistent with those observed in the experimental results.

(3) The ascending section of the curve is more consistent with the test curve than the descending section. This can be attributed to the spring unit stiffness setting. Therefore, the FE model is more ideal in calculation and analysis than the simulation.

(4) The peak stress value calculated by ANSYS is smaller than that obtained from the test result. This can be attributed to the tilting or movement of bellows when the concrete vibrates during the manufacturing of the specimen, which changes the bonding area or penetrates the concrete to the bellows. These issues are not considered separately in ANSYS calculations.

Accurate bond stress and slip value can be obtained using the ANSYS FE software to simulate the bond-slip behavior between plastic bellows and concrete or grout material. The bond-slip between plastic bellows and concrete or grout material can also be analyzed further using the ANSYS FE simulation.

5. Conclusions

In this study, a single-end compression test was performed on the grout material inside plastic bellows and a concrete specimen to explore the bond-slip relationship of the specimen. The influence of bond length and contact area on the experimental results was analyzed. The results indicate that the loading process of plastic bellow concrete can be divided into six stages, namely the micro-slip, slip, fluctuation, failure, descending, and horizontal residual stages. The bond stress of plastic bellow concrete structure decreases with the increase in the bond length, whereas the contact area does not affect the bond stress significantly. The basic trend and characteristics of the bond-slip constitutive model were entirely reflected by fitting the test curve. ANSYS nonlinear FE software was used to simulate the single-end compression test of the plastic bellow concrete specimen. The relationship curve of the bond stress and slip was predominantly consistent with test data and fitting curves, which explained the bond-slip trend and process. The ANSYS simulation results indicate that the bond strength of plastic bellow concrete decreases with the increase in the bond length. When the bond length is larger than the inner diameter, the bonding stress reduces gradually and continues to decrease with the increase in the bond length.
bond length. With the increase in the contact area, there is no obvious linear relationship between bonding stress and contact area.

**Data Availability**

The data used to support the findings of this study are available from the authors upon request.

**Disclosure**

Eryu Zhu and Teng Li should be regarded as co-first authors.

**Conflicts of Interest**

The authors declare that they have no conflicts of financial interest or personal relationships that could have influenced the work reported in this study.

**Authors’ Contributions**

Eryu Zhu and Teng Li contributed equally to the study.

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**References**


