

Article

An Experimental Study on the Bond–Slip Relationship between Rebar and Ultra-High-Performance Concrete Grouted in Bellows

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Abstract: Ultra-high-performance concrete (UHPC)-filled duct connection is an innovative solution for joining assembled structures, in which the anchorage performance of the rebar and UHPC filled in bellows plays a critical role in determining the overall connection effectiveness. To establish a reliable anchorage length and a bond–slip relationship between rebar and UHPC within a bellow, a total of 16 specimens were conducted, and pullout tests were carried out. Two parameters were considered, including the diameter ratio (D/d), representing the proportion of the diameter of the bellow D to the diameter of the steel bar d , and anchorage length (L). By analyzing the failure modes, load versus deflection curves, and steel strain data, the influences of the diameter ratio and anchorage length on the anchorage performance were discussed. The test results showed that the failure mode changed from rebar pullout to rebar breakage as the anchorage length increased from $3d$ to over $10d$. The reliable anchorage length of the rebar was recommended to be at least $10d$ with a diameter ratio (D/d) of 2.4. Moreover, a fitting bond–slip model was proposed based on the experimental bond–slip curves between the rebar and UHPC interface within the bellows with high precision. These findings constitute a crucial basis for the comprehensive stress analysis of assembled structures connected using UHPC grouted in bellows.

Keywords: anchorage performance; pullout tests; diameter ratio; anchorage length; bond–slip



Citation: Wang, Z.; Zheng, X.; Wang, Q.; Wang, Q. An Experimental Study on the Bond–Slip Relationship between Rebar and Ultra-High-Performance Concrete Grouted in Bellows. *Buildings* **2023**, *13*, 2375. <https://doi.org/10.3390/buildings13092375>

Academic Editor: Giuseppina Uva

Received: 1 August 2023

Revised: 1 September 2023

Accepted: 11 September 2023

Published: 18 September 2023



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1. Introduction

With the rapid development of the construction industry worldwide, the Earth's environment urgently needs to be protected. Green construction has become a focus in recent years [1,2]. Technological innovation [3,4] and novel materials [5,6] for green construction were developed to reduce the carbon footprint and lower costs from the building industry. Accelerated bridge construction (ABC) is assuming an increasingly pivotal role in urban bridge construction worldwide due to its high quality, rapid construction, minimum interference in traffic, and ability to reduce environmental pollution [7–9]. A prefabricated column is a typical precast element, and the connections between columns and cap beams and its foundations are critical to the integrality and seismic performance of a bridge [10,11]. To date, various connections for precast columns have been developed, such as socket connections [12], pocket connections [13], bar couplers [14], and grouted ducts [15]. Many studies [12–15] have been conducted to verify the feasibility and effectiveness of these connections. To enhance the effectiveness of these connections, high-performance materials such as ultra-high-performance concrete (UHPC) [16] were proposed for use in the joint region due to their excellent mechanical properties, durability, and bond behavior.

Grout-filled duct connections have gained increasing attention recently as a convenient method in precast column construction. In this type of connection, the straight longitudinal

bars of the column are anchored within corrugated ducts that are subsequently grouted, as depicted in Figure 1a. Experimental results have proved that grout-filled duct connections are emulative of cast-in-place construction specimens [17].

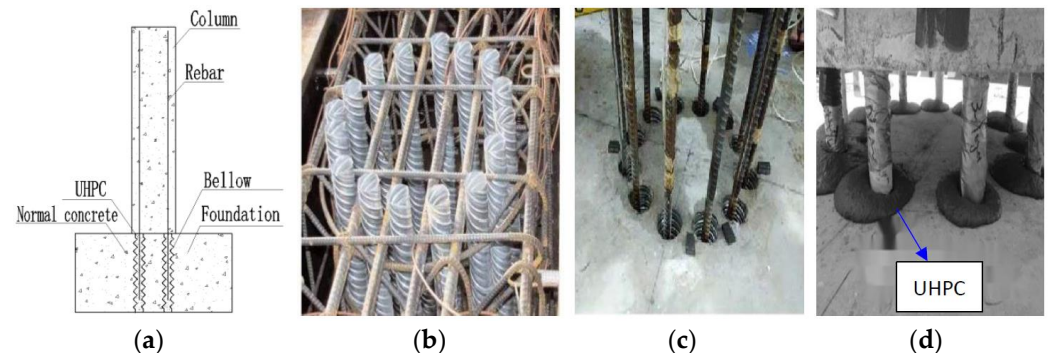


Figure 1. UHPC-filled duct connection technology. (a) Precast column, (b) pre-buried bellows, (c) splicing, (d) grouting UHPC.

Ultra-high-performance concrete (UHPC) has emerged as a promising grout to enhance bond behavior and reduce the required embedment length of bars [18,19]. UHPC is a cementitious material formulated by mixing Portland cement, fine silica sand, silica fume, quartz flour, water reducer, and steel fibers. Compared to normal concrete (NC), UHPC exhibits significantly higher strength and ductility, and especially stronger bonding performance with steel bars [20,21]. The use of UHPC is becoming more widespread in new construction and retrofitting activities in civil engineering [22–24].

Some experimental studies [17,18,25–30] have been conducted in recent years to investigate the seismic performance of precast columns by using UHPC-filled duct connections. Experimental results have shown that no UHPC-filled duct connection damage such as bar pullout, duct pullout, or conical failure of the footing was observed, and the longitudinal bars of columns were well-anchored. It is worth noting that the seismic resilience of precast columns interconnected via UHPC-filled ducts closely approximates that of conventional cast-in-place construction specimens. Evidently, the UHPC-filled duct connection method shows immense potential for enhancing the efficiency and seismic performance of precast columns in civil engineering applications.

The anchoring performance of both the rebar and the UHPC filled within the bellows plays a pivotal role in facilitating force transmission between the structural members and determining the overall mechanical behavior of the structure. To conduct a comprehensive structure stress analysis by using UHPC-filled duct connections, it is essential to understand the bond–slip relationship between the rebar and the UHPC interface. Although numerous researchers [31–37] have directed their efforts toward investigating the interfacial bonding performance of rebar and UHPC through pullout tests, limited attention has been given to the distinctive scenario in which UHPC is infused within the bellows. In this scenario, the forces are different from the forces experienced when rebar is directly embedded in UHPC, as illustrated in Figure 2. It is necessary to consider this difference as it can potentially impact the overall connection performance.

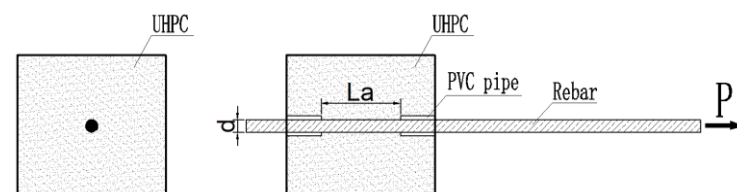


Figure 2. Schematic diagram of rebar-UHPC tensile test [27].

Su et al. [31] conducted direct shear tests to investigate the shear mechanism and strength of a novel gravity-type grouted sleeve connection using UHPC. Their findings indicated that the UHPC-based connection exhibited shear strength at least 50% higher than that of traditional connections. Moreover, the failure mode of the UHPC-based connection resembled that of cast-in-place (CIP) specimens. Fehling et al. [32] explored the impact of different protective layer thicknesses and anchorage lengths on the anchorage performance of rebar-UHPC connections through pullout tests. They discovered that for rebar with a diameter of 12 mm, the reliable anchorage lengths were $4d$, $6d$, and $8d$, corresponding to protective layer thicknesses of $2.5d$, $2d$, and $1.5d$, respectively. Yuan and Graybeal [33] investigated the effects of rebar diameter, spacing, and coating on the anchorage performance of rebar-UHPC connections using pullout tests. Their results revealed that rebar with diameters of 13 mm and 25 mm exhibited average bond strengths from 20 MPa to 35 MPa. For a protective layer thicknesses of $3d$ and spacing between rebar of $2d$, the minimum reliable anchorage length for the rebar was $8d$. Vidya Sagar Ronanki et al. [34] conducted rebar pullout tests to study the effect of rebar diameter (ranging from 13 mm to 22 mm), anchorage length ($6d$ to $10d$), protective layer thickness, and maintenance age on the anchorage performance of rebar-UHPC connections. Their experimental results demonstrated that the average bond strength of rebar-UHPC was approximately 5 times (9.7 MPa to 16.6 MPa) that of rebar–ordinary concrete bond strength, with the average bond strength increasing with the rise in rebar anchorage length. The bond stress was non-uniform, with the majority being distributed along the anchorage length within $2.5d$. Aoxiang Hu et al. [35] conducted a series of pullout tests to investigate the bond characteristics of deformed high-strength steel bars embedded in ultra-high-performance concrete (UHPC). Their results indicated that UHPC significantly increased the bond strength of deformed reinforcing steel bars, with the bond strength increasing with bar diameter. Additionally, the average bond stress of deformed reinforcing steel bars embedded in UHPC increased with increasing steel fiber volume content (up to 3%), concrete cover, and bar grades; it decreased with an increase in bar embedment length. Qi et al. [36] explored the bond behavior of reinforcing bars in ultra-high-performance concrete (UHPC) through both experimental and theoretical pullout tests. They found that inadequate concrete cover depth led to splitting failure, while a short embedment length resulted in concrete cone failure, leading to lower bond strengths. The bond strength increased by up to 229.8%, and the pullout energy increased by 401.4% as the concrete cover depth increased from $0.5d$ to $2d$. They recommended development lengths of $6d$ and $8d$ corresponding to concrete cover depths of $2d$ and $1.5d$, respectively. Liu et al. [37] conducted central unidirectional pullout tests on 54 prismatic specimens with deformed steel bars embedded in UHPC without lateral constraints. Their results revealed that when the anchorage length exceeded two times the diameter of the steel bar, the maximum strain occurred at approximately 1.5 times the diameter away from the loading end. The maximum bond stress decreased with increasing anchorage length but increased with increasing concrete cover. But excessive concrete cover did not yield a noticeable gain effect.

It is essential to highlight that the previous investigations into the anchorage performance of the rebar-UHPC interface were focused solely on a single interface between rebar and UHPC, as illustrated in Figure 3a. They did not take into account the specific connection technology of UHPC grouted in bellows, where the rebar is embedded inside the UHPC within the bellows (Figure 3b). Furthermore, the protective layer thickness of the rebar is linked to the diameter D of the grouted bellows and the diameter d of the longitudinal rebar, defined as the diameter ratio D/d . However, there are very limited studies that address the anchorage performance of rebar confined by UHPC filled within bellows, and the relevant interfacial bond–slip model is rarely reported in the existing literature. This gap in research needs to be addressed to gain a comprehensive understanding of the performance of the connections of UHPC grouted in bellows.

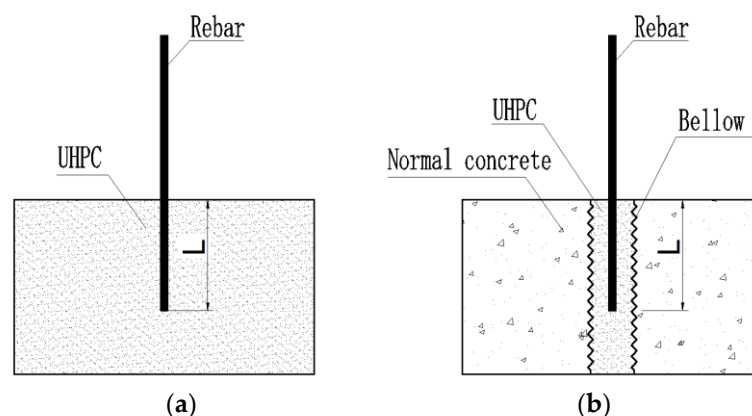


Figure 3. Interface of connections of UHPC grouted in bellows. (a) Interface of rebar-UHPC, (b) interface of rebar-UHPC grouted in bellows.

In this research, the anchorage performance of the rebar-UHPC grouted in bellows was experimentally investigated, specifically considering the actual situation in which the rebars were anchored by UHPC in the bellows. The focus of this study was on the interface between the rebar and the grouted UHPC inside the bellows, as depicted in Figure 3b. To achieve this objective, a series of tests on 16 specimens comprising metal corrugated pipes filled with UHPC and rebar were conducted, considering various diameter ratios (D/d) and anchorage lengths (L), and they were subjected to tension. The failure modes, load versus deflection curves, and steel strain data were analyzed to determine the reliable anchorage length and establish the bond–slip relationship between the rebar and UHPC within the bellows. These findings serve as a fundamental basis for the widespread adoption and application of the UHPC grout-filled bellow connection technology.

2. Experimental Program

2.1. Specimens and Test Matrix

The study primarily focused on two key factors: the diameter ratio (D/d), representing the proportion of the bellow diameter (D) to the rebar diameter (d), and the anchorage length (L). To investigate the effect of these factors, pullout tests were designed and performed on the specimen illustrated in Figure 3b.

Based on previous literature [31–37], it became evident that when the anchorage length (L) of the rebar inserted into the UHPC grouted in bellows exceeded 10 times the rebar diameter ($10d$), no observable bond damage occurred at the interface between the rebar and UHPC, which indicated a reliable anchorage. If the anchorage length (L) was less than $10d$, it was possible for bond damage to occur. Therefore, the specimens in this study were categorized into two series: Series A, with anchorage length (L) exceeding $10d$, was utilized to explore the impact of the diameter ratio (D/d) and anchorage length (L) on the anchorage performance. Series B, characterized by an anchorage length (L) that could lead to bond damage due to being less than $10d$, was employed to study the interfacial bond–slip relationship between the rebar and the UHPC grouted in bellows. These distinct series allowed for a comprehensive analysis of the anchorage behavior and bond–slip characteristics under varying conditions.

In this study, HRB400 steel bar with a diameter of 25 ($\Phi 25$) was used. Series A was composed of four groups, each with a different anchorage length ($10d$, $15d$, $20d$, and $24d$), and contained one specimen per group. On the other hand, Series B included 4 groups based on the anchorage length ($3d$, $5d$, $7d$, and $10d$), with two specimens in each group, resulting in a total of 8 groups and 16 specimens, as detailed in Table 1.

Table 1. Grouping of pullout tests for rebar-UHPC grouted in bellows.

Test Matrix	Anchorage Length L	Rebar Diameter d	Bellows Diameter D	D/d	Specimen ID	The Number of Specimens
Series A	24 d	25	60	2.4	$\Phi 25-60-24d$	1
		25	80	3.2	$\Phi 25-80-24d$	1
	20 d	25	60	2.4	$\Phi 25-60-20d$	1
		25	80	3.2	$\Phi 25-80-20d$	1
	15 d	25	60	2.4	$\Phi 25-60-15d$	1
		25	80	3.2	$\Phi 25-80-15d$	1
	10 d	25	60	2.4	$\Phi 25-60-10d$	1
		25	80	3.2	$\Phi 25-80-10d$	1
Series B	10 d	25	80	3.2	$\Phi 25-80-10d$	2
	7 d	25	80	3.2	$\Phi 25-80-7d$	2
	5 d	25	80	3.2	$\Phi 25-80-5d$	2
	3 d	25	80	3.2	$\Phi 25-80-3d$	2

In the table, the specimen named $\Phi 25-60-24d$ indicates that the diameter of the steel bar was 25 mm, the diameter of the bellow was 60 mm, and the anchorage length was 24 d .

2.2. Specimen Fabrication

In Series A, the specimens were positioned on three ordinary concrete anchor blocks measuring 1200 mm $\times$ 1200 mm. Among them, two blocks had a height (H) of 600 mm, while one had a height (H) of 800 mm, accommodating different anchorage depths. The concrete grade used for the anchor blocks was C50. To mitigate any potential influence between individual specimens, the spacing between adjacent bellows was set at 300 mm [38], as illustrated in Figure 4a.

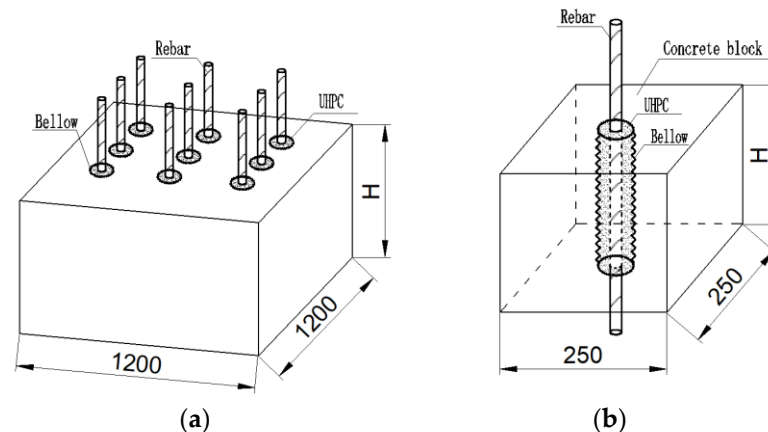


Figure 4. Schematic diagram of the specimens. (a) Series A ($L \geq 10 d$), (b) Series B ($L \leq 10 d$).

As for Series B, the objective was to investigate the interfacial bond–slip relationship between the rebar and the UHPC grout-filled bellow. Each specimen was independently fabricated, and the corrugated pipe was pre-buried in C50 concrete test blocks. These test blocks had dimensions of 250 mm $\times$ 250 mm, and the heights (H) were set at 320 mm, 250 mm, and 200 mm, respectively, according to the anchorage length, as shown in Figure 4b.

To prevent stress concentration at the ends of the connection between the rebar and the concrete specimen block from affecting the interfacial bonding performance, a section of PVC pipe was pre-fixed at the connection ends. This section of PVC pipe acted as an unbounded section for the rebar, thus controlling the different anchorage lengths of the rebar. The metal bellows used in the specimens had a diameter of 80 mm.

Figure 5 shows the fabrication process of series A and series B specimens. The main steps included the pre-burial of the bellows $\rightarrow$ casting and curing the anchor block con-

crete → the positioning of the rebar → filling the bellows with UHPC → curing and forming the UHPC.

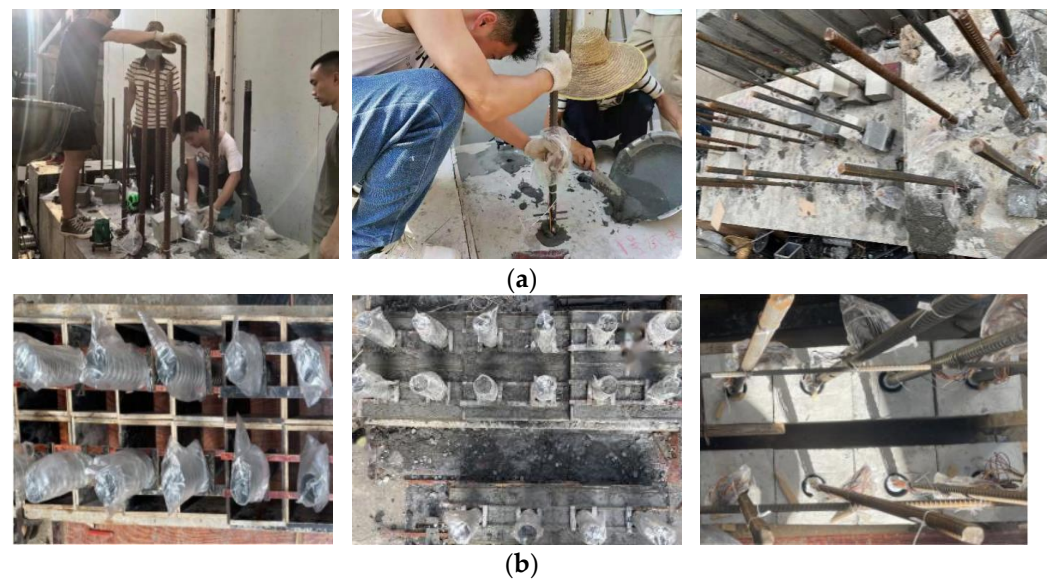


Figure 5. Specimen fabrication. (a) Series A specimen fabrication. (b) Series B specimens.

2.3. Material Properties

The specimens were composed of various materials, including normal concrete (NC) for the anchor blocks, $\Phi 25$ rebar, UHPC, and $\Phi 80$ metal bellows. The mechanical properties of the bellows were provided by the manufacturer, while the mechanical properties of the other main materials were tested and recorded, as depicted in Figure 6.

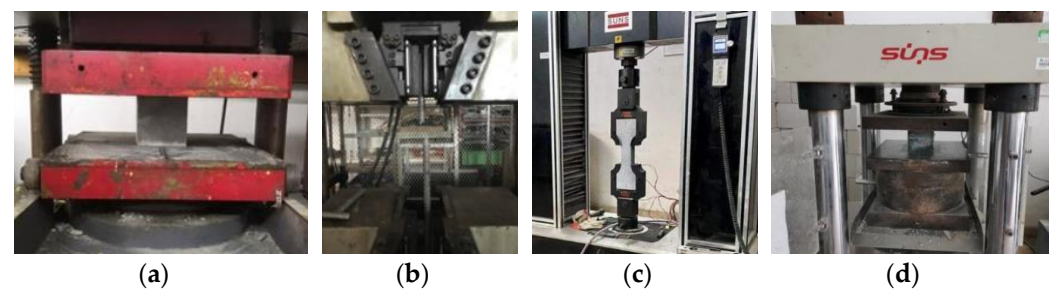


Figure 6. Test of mechanical property for materials. (a) Compressive test of NC, (b) tensile strength of rebar, (c) compressive test of UHPC, (d) tensile strength test of UHPC.

The composition of the UHPC grouting material included cement, mineral powder, silica fume, quartz sand, water reducer, and water. The water-to-cement ratio was 0.19, while incorporating a steel fiber volume fraction of 2%. The steel macro-fiber used here is produced by Ganzhou Daye fibers Company in China. The total length of a single steel fiber was 13 mm with the diameter of 0.2 mm. The tensile strength of the steel fiber was 2850 Mpa. The mix proportions of UHPC are summarized in Table 2.

The test results revealed that the compressive strength of the ordinary concrete used for the anchor blocks was 51.2 MPa, with a modulus of elasticity of 35.0 GPa. As for the $\Phi 25$ rebar, the average values for yield strength, tensile strength, and modulus of elasticity were 445.1 MPa, 615.1 MPa, and 205.5 GPa, respectively. Under normal temperature curing conditions, the average 28-day tensile strength of UHPC was determined to be 8.4 MPa. Additionally, the average compressive strength of UHPC at the 28-day mark was recorded as 116.1 MPa. The properties of the materials are summarized in Table 3.

Table 2. UHPC mix proportions.

Materials	kg/m ³
Cement	700
Mineral powder	250
Silica fume	150
Quartz sand	1260
Water reducer	11.8
Water	209

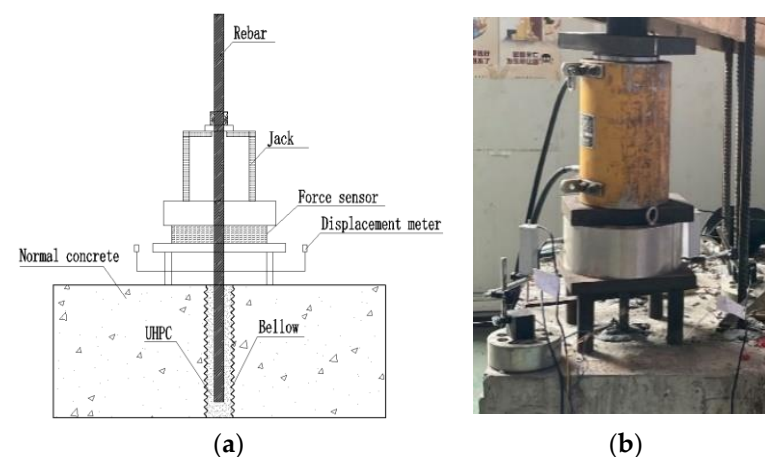
Table 3. The properties of the materials.

Materials	Items	Value
Normal concrete	Compressive strength	51.2 MPa
	Elastic modulus (E_c)	35.0 Gpa
Steel bars	Elastic modulus (E_s)	205.5 Gpa
	Yield strength	445.1 MPa
	Tensile strength	615.1 MPa
UHPC	Tensile strength	8.4 MPa
	Compressive strength	116.1 MPa

2.4. Test Set-up and Instrumentation

2.4.1. Loading Solutions and Instrumentation

Test set-up and the loading instrumentation are shown in Figure 7. For continuous loading in a load-controlled manner, a through-core electro hydraulic jack with a capacity of 100 tons was employed. The loading speed was maintained within the range of 15–20 kN/min until the bar yielded, after which, it was adjusted to 8–10 kN/min. Once the steel bar was pulled out or experienced breakage or the concrete block cracked, the test stopped immediately.

**Figure 7.** Loading instrumentation diagram. (a) Schematic diagram, (b) loading equipment.

During the tests, the tensile force (F) in the axial direction of the rebar was measured using a force sensor in the jack. Simultaneously, the displacement at the loading end of the rebar was recorded with a displacement meter.

2.4.2. Arrangement and Testing of Strain Gauges on Rebar

To measure the bond stress at the contact interface between the rebar and UHPC, strain gauges were affixed to the rebar uniformly. The strain measurements were taken using a strain test analyzer, specifically model DH3816, with an acquisition frequency of 1 Hz.

The arrangement of strain gauges is illustrated in Figure 8. In Series A, the first strain gauge (Gauge 1) was positioned 50 mm above the surface of the concrete block, and a total of 5 additional strain gauges were evenly spaced downward in the anchorage section of the rebar. This resulted in 6 strain gauges being placed at 50 mm intervals from one another. The spacing of strain gauges in Series B was 20 mm, as shown in Figure 8b. The number of strain gauges used was dependent on the anchorage length (L) of the specimen.

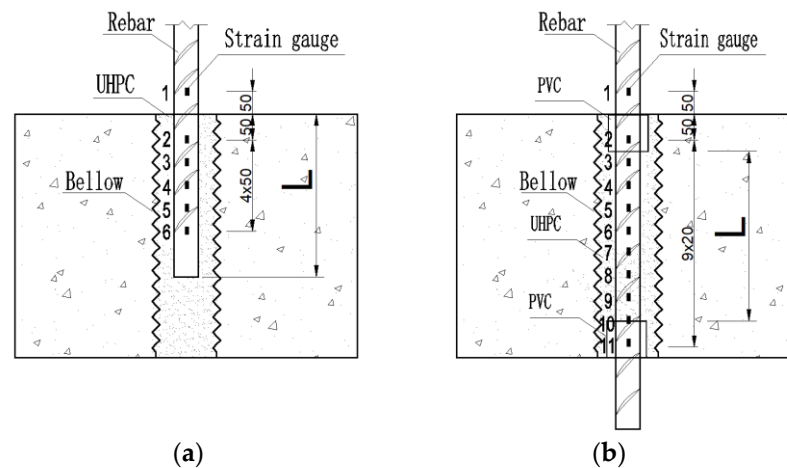


Figure 8. Location of strain gauge. (a) Series A, (b) Series B.

3. Results and Discussion

3.1. Failure Mode

The failure modes and characteristic load values of each specimen are summarized in Table 4. It is evident that when the anchorage length exceeded $10d$, all the steel bars in the specimens in Series A fractured due to tension, as depicted in Figure 9a. This observation confirms that the rebars were reliably anchored, ensuring a robust connection.

Table 4. Specimen failure mode and characteristic load values.

Series	Specimen No.	Failure Mode	Yield Load (kN)	Yield Strength (MPa)	Ultimate Load (kN)	Ultimate Strength (MPa)
A	Φ25-60-24d	Tensile failure of rebar	234.79	478.55	335.58	683.98
	Φ25-80-24d		245.19	499.75	315.24	642.53
	Φ25-60-20d		223.55	455.66	309.57	630.97
	Φ25-80-20d		245.36	500.10	315.69	643.44
	Φ25-60-15d		215.02	438.26	275.69	561.92
	Φ25-80-15d		234.15	477.25	318.72	649.62
	Φ25-60-10d		205.05	417.94	273.65	557.76
	Φ25-80-10d		236.85	482.75	316.41	644.91
B	Φ25-80-10d	Tensile failure of rebar	223.6	455.8	327.8	668.1
	Φ25-80-7d	Rebar pullout	217.1	442.5	292.5	596.2
	Φ25-80-5d	Rebar pullout	Not yielded	--	213.1	--
	Φ25-80-3d	Rebar pullout	Not yielded	--	208.7	--

Regarding specimens in Series B, with an anchorage length (L) below $10d$, two typical failure modes were observed: (1) As for the specimens with anchorage lengths of $10d$ (Φ25-80-10d), the rebar experienced tensile failure, indicating that the anchorage length was sufficient, and the anchorage was reliable. (2) With anchorage lengths of $3d$, $5d$, and $7d$, the rebar underwent pullout, indicating that bonding failure occurred at the rebar-UHPC interface, as shown in Figure 9b.

Table 4 presents the failure mode and characteristic load values of each specimen, where the load characteristic values are averaged for two specimens with the same anchorage length in Series B.

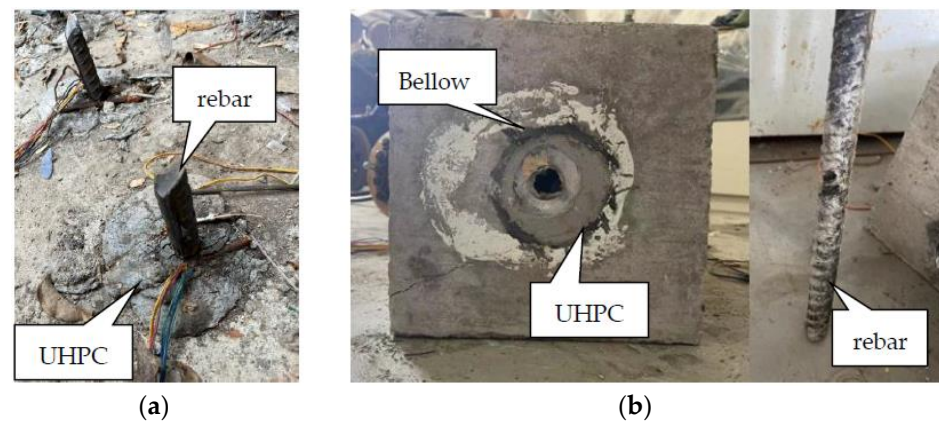


Figure 9. Typical failure mode. (a) Tensile failure of rebar ($\Phi 25-80-10d$). (b) Rebar pullout ($\Phi 25-80-3d$).

3.2. Load versus Deflection Curves

Figure 10 displays the load versus deflection curves of the specimens. In general, the curves of two series of specimens exhibited significantly different load-deflection behaviors due to different anchorage lengths (L). When the anchorage length was more than $10d$ (Series A), the load-displacement curve showed better ductility due to the reliable anchorage. The curves displayed a three-stage development process, characterized by linear growth, yielding, and strengthening, which is similar to the load-displacement curve of the steel bar under tension. When the anchorage length was less than $10d$ (Series B), distinct behaviors were observed based on the anchorage length. When L was equal to $7d$ and $10d$, the load-displacement curves of these two groups of specimens showed good ductility characteristics, indicating that the steel bar has a yield phenomenon. However, when L was set at $3d$ and $5d$, the curves dropped suddenly after the peak load, indicating that the interface between the rebar and UHPC slipped. That is to say, when the anchorage length was less than $7d$, the steel bar was not effectively anchored, and the interface was damaged.

Figure 10a is a comparison of the load-displacement curves of two specimens with the same anchorage length but different diameter ratios. It can be seen that when the anchoring length was the same, the larger the diameter ratio (D/d) and the stronger the anchoring load. With the increase in anchorage length, the influence of the diameter ratio on the bearing capacity reduced. When L was $24d$, the influence of D/d could be neglected. Figure 10b is the load-displacement curve of two specimens within the same group in series B with the same anchorage length and diameter ratio. It is obvious that the curves of the two specimens in each group were close to each other.

3.3. Analysis of Factors Influencing Anchorage Performance of Rebar-UHPC Grouted in Bellows

3.3.1. Diameter Ratio D/d

The load versus deflection curves for specimens with different diameter ratios (D/d) are presented in Figure 10a. The experimental results indicate that effective anchorage of the rebar was achieved when the diameter ratio (D/d) was greater than 2.4.

Additionally, among specimens with the same anchorage length (L), those possessing a diameter ratio (D/d) of 3.2 exhibited higher yield and ultimate loads compared to those with a ratio of 2.4. This trend is substantiated by the strength characteristic values detailed in Table 4. For series A specimens, the ultimate loads increased by 15.47%, 8.89%, and 9.75% for anchorage lengths of $10d$, $15d$, and $20d$, respectively. This trend highlights that using metal bellows with a larger diameter (D) provides enhanced anchorage force and stronger anchorage performance for rebars of the same diameter (d).

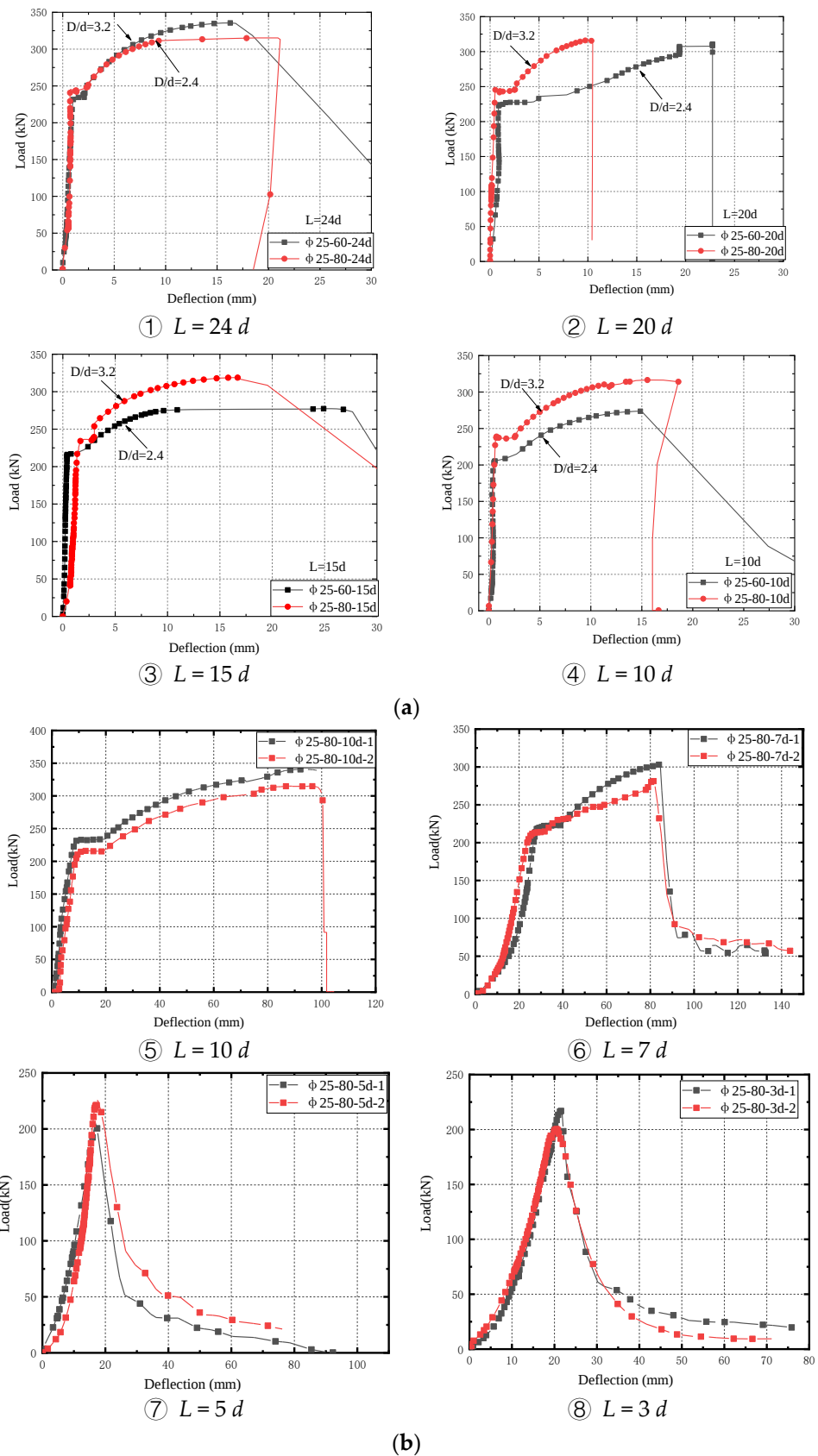


Figure 10. Load versus deflection curves. (a) Series A. (b) Series B.

3.3.2. Anchorage Length L

Figure 11 presents a comparison of the load versus deflection curves for specimens with the same diameter ratio (D/d) but different anchorage lengths (L).

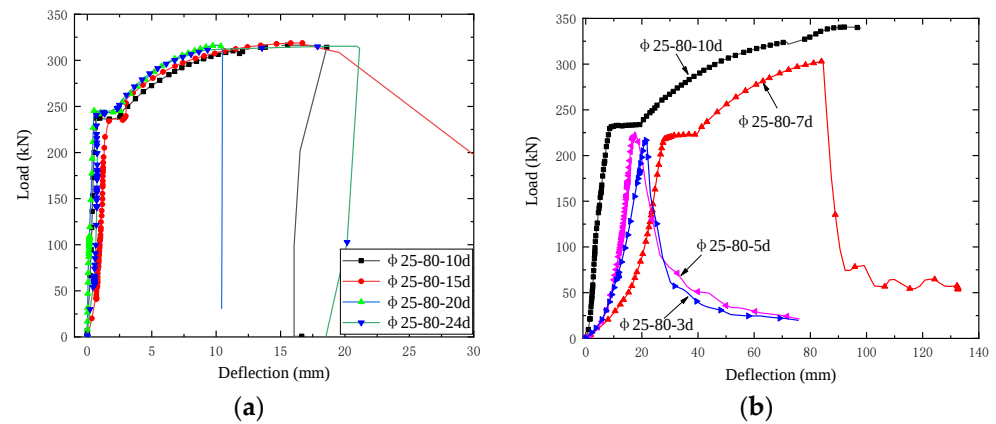


Figure 11. Load–deflection curves for specimens with different anchorage lengths L . (a) Series A (b) Series B.

Figure 11a is a comparison of the load–displacement curves of specimens in series A with the same diameter ratio of 3.2. It can be seen that the curves were very close, because the steel bar was reliably anchored when the anchorage length was enough, i.e., when $L = 10d$, $15d$, $20d$, and $24d$, and all the specimens had the same mechanical behavior. The bonding performance of the interface between the reinforcement and the UHPC inside the bellows was reliable, and there was no slip. Therefore, the effective anchorage length (L_a) is recommended to be more than $10d$ when using UHPC-filled duct connections.

Figure 11b presents the comparison of load–displacement curves of specimens in Series B with different anchorage lengths ($3d$, $5d$, $7d$, and $10d$) and the same diameter ratio of 3.2. It can be seen that when the anchorage length was less than $10d$, the anchorage length had a significant effect on the load–displacement curves. When L was $10d$, the load–deflection curve exhibited a three-stage development process, similar to the curve characteristics observed in Series A, which indicated the anchorage was reliable. When L was $7d$, the load–deflection curve also showed ductility characteristics, and the rebar yielded. However, bond failure occurred at the interface between the rebar and UHPC as the load increased. Finally, the steel bar was pulled out and the load suddenly dropped. For the two groups of specimens with $L = 5d$ and $3d$, the load–displacement curve showed obvious brittle failure characteristics. Bond failure at the interface happened before the rebar yielded due to the insufficient anchorage, resulting in the rebar being pulled out. The ultimate bearing capacity of the two groups of specimens was reduced by 35.0% and 36.3%, respectively, compared to that of specimens with $L = 10d$.

Clearly, the diameter ratio (D/d) and anchorage length (L) are two crucial factors influencing the anchorage performance of the rebar in UHPC grouted in bellows. The experimental results show the conditions for the reliable anchorage of the rebar are $D/d \geq 2.4$ and $L \geq 10d$.

4. Bond–Slip Relationship of the Interface of Rebar–UHPC Grouted in Bellows

4.1. Load–Strain Curves (F – ϵ)

To establish the bond–slip relationship curve at the interface between the rebar and the UHPC grouted in bellows, a comprehensive strain analysis was executed for the specimens in Series B, where interfacial bond damage had occurred. The strain variation curves along the rebar of Series B specimens, correlating with load (F – ϵ), are illustrated in Figure 12.

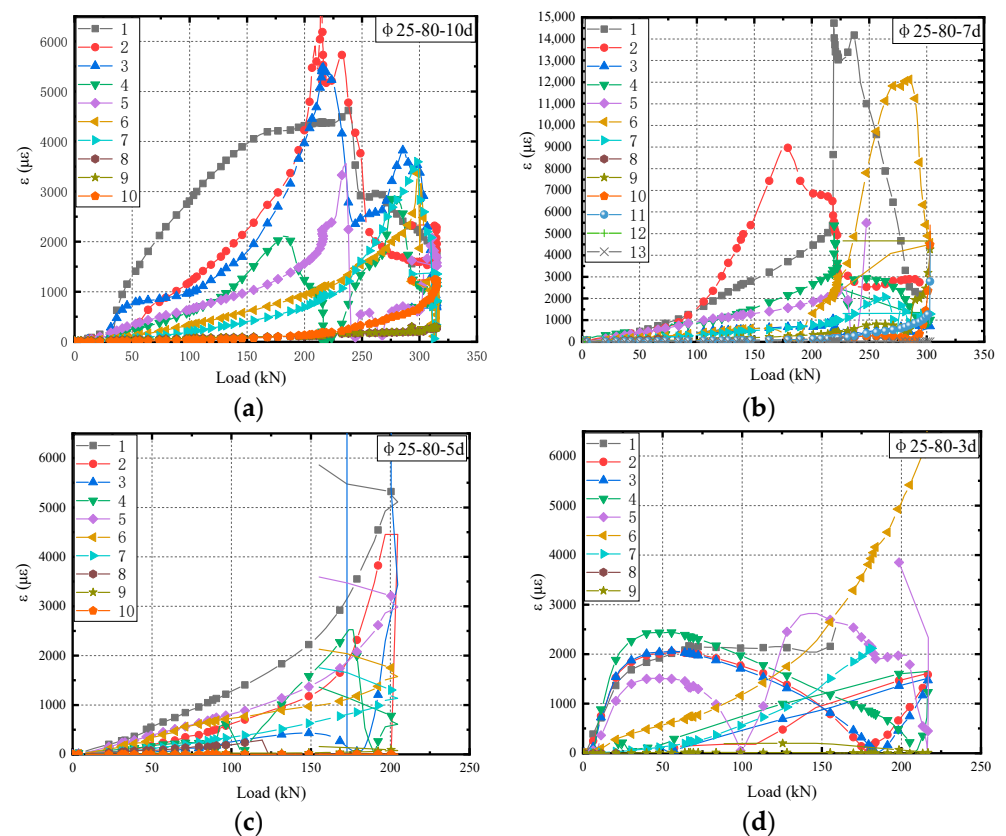


Figure 12. Load–strain curve of specimens of series B. (a) $L = 10$ d (b) $L = 7$ d (c) $L = 5$ d (d) $L = 3$ d.

As the load increased, the force transmission from the upper part of the anchorage section to the remote end occurred through the interfacial bond, leading to varying strains in the test specimens.

When considering an anchorage length of 3 d, several strain values near the loading end (1–5) initially increased followed by a subsequent decline. This phenomenon can be attributed to the relatively limited anchorage length, causing the upper part of the anchorage zone to start slipping when the load reached 90 kN. Consequently, this led to a reduction in the strain value for the upper part of the anchorage section.

With an anchorage length of 7 d, several strain measurement points near the loading end (1, 2, and 4) suddenly increased when the load reached approximately 225 kN. This occurrence was due to the rebar entering the yield platform, while the displacement at the loading end continued to increase even when the load remained constant, resulting in a sudden rise in strain values.

4.2. Experimental Curve for Bond–Slip Relationship

4.2.1. Standardization of Strain Positions

To explore the force transfer mechanism of rebar within UHPC grouted in bellows, the arrangement of strain measurement points along the anchorage section was standardized by defining an x-coordinate axis aligned with the rebar's direction. This axis denoted the downward direction as positive direction, and it corresponded to the anchorage length, with the origin (0) placed at the beginning of the anchorage section. Each strain gauge's position (x) was normalized by dividing the total anchorage section length (L); then, the relative position of each measurement point was determined. The coordinate axis is illustrated in Figure 13.

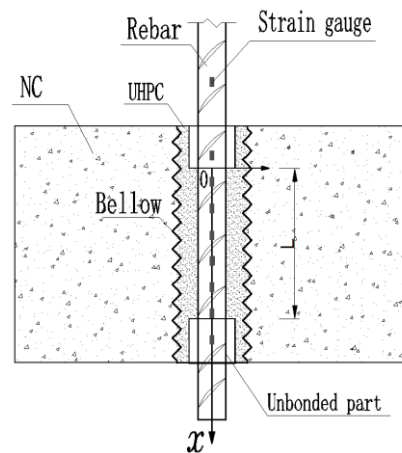


Figure 13. Coordinate system diagram of anchorage positions.

The strain–position curves following position standardization are depicted in Figure 14. Remarkably, as the anchorage length increased, the strain peak gradually shifted closer to the loading end. Furthermore, as the anchorage length extended, the shift of the strain peak towards the loading end became more pronounced. For instance, at anchorage lengths of $3d$ and $5d$, the strain peaks appeared at $x = 0.5L$ and $x = 0.18L$, respectively. Within the range of $7d \leq L \leq 10d$, the strain peaks emerged near $x = 0.12L$. Notably, when $L = 10d$, and the specimen neared its damage point, the strain–position curve transitioned into to a bimodal shape. In this configuration, two peaks emerged around $x = 0.12L$ and $x = 0.35L$. This behavior indicates complex force transfer characteristics within the anchorage section as the specimen approached its ultimate limit.

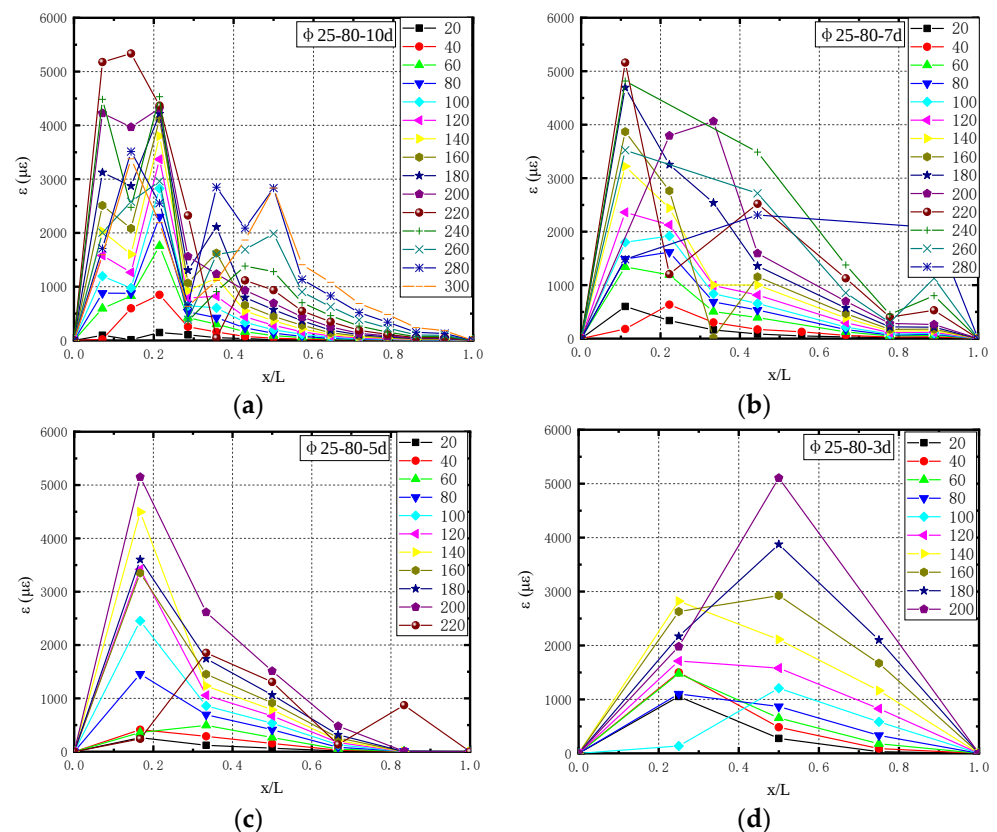


Figure 14. Strain distribution curves under different loads. (a) $L = 10d$, (b) $L = 7d$, (c) $L = 5d$, (d) $L = 3d$.

4.2.2. Interfacial Bond–Slip Relationship Curves

Drawing from reference [39,40], when strain gauges are closely positioned, the average bond stress between two adjacent gauges can be approximated as the bond stress at that specific point. This approximation can be expressed through Equation (1):

$$\tau = \frac{E_s d (\varepsilon_i - \varepsilon_{i-1})}{4 \Delta x} \quad (1)$$

In Equation (1), d represents the diameter of the rebar, Δx denotes the distance between the two measurement points, and E_s stands for the modulus of elasticity of the rebar.

The displacement at the loading end of the rebar consists of two main components. The first part corresponds to the elongation of the rebar, while the other part accounts for the slip occurring between the rebar and the UHPC grouted in bellows across all sections of the surface. The slip (s) can be calculated using the following formula:

$$s = \frac{(s_1 + s_2 - \Delta l)}{2} \quad (2)$$

In the context of Equations (1) and (2), s_1 represents the displacement at the loaded end of the test, s_2 represents the displacement at the free end, and Δl signifies the elongation of the rebar from the loaded end to the upper surface of the bonded section of the anchored rebar.

Using Equations (1) and (2), the bond stress–slip (τ - s curve) test curves for three groups of specimens ($L = 3d$, $5d$, and $7d$) in which interfacial bond–slip damage occurred were calculated from the strain data, as illustrated in Figure 15.

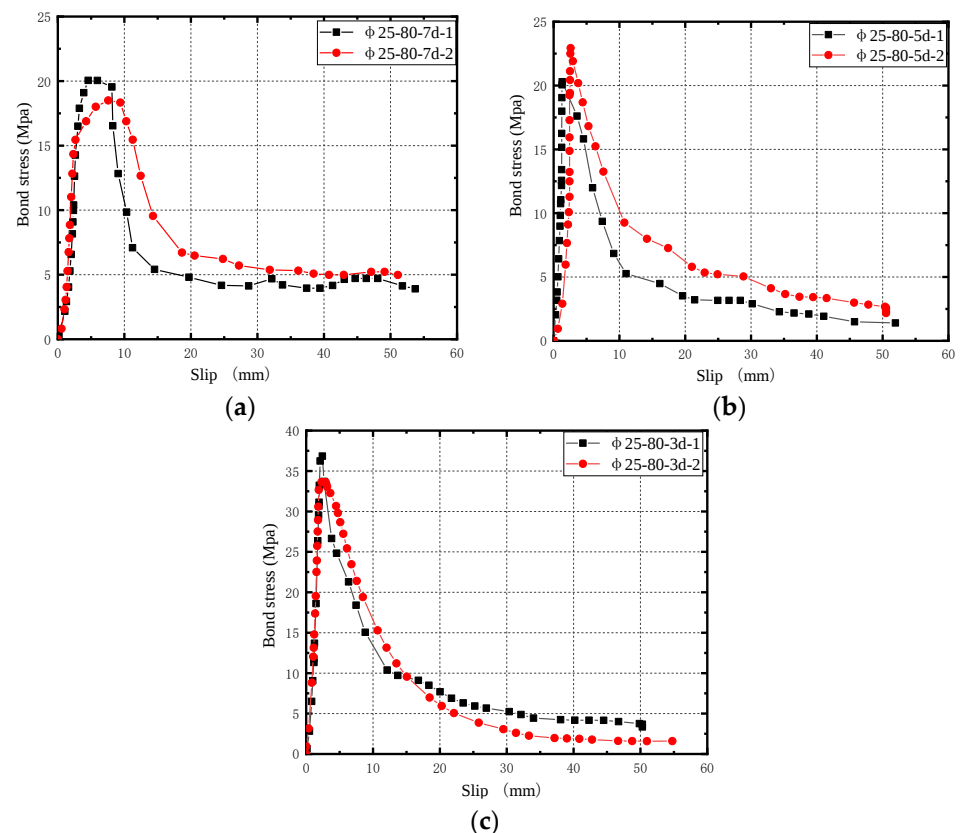


Figure 15. Experimental curves of bond–slip. (a) $L = 7d$, (b) $L = 5d$, (c) $L = 3d$.

4.3. Model for Bond–Slip Relationship

The τ - s curves obtained from the tests were standardized by normalizing the horizontal axis (slip) by dividing it by the maximum value (s_u) and the vertical axis (bond stress) by dividing it by the maximum value (τ_u). The standardized curves are presented in Figure 16, illustrating a consistent form for the τ - s curves of each group of specimens after standardization.

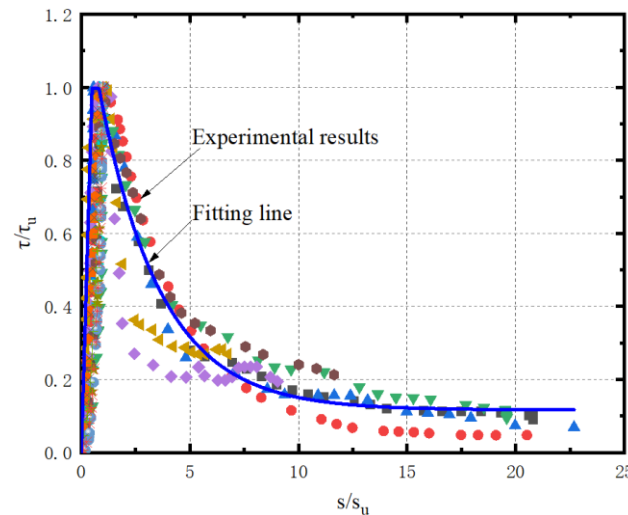


Figure 16. τ - s curves after standardization.

By using the anchorage length (L) and the diameter ratio (D/d) as parameters, a fitting process for the standardized bond stress–slip curve and characteristic eigenvalues was conducted. As a result, the following model for the bond stress–slip relationship in rebar-UHPC grouted in metal bellows was established:

$$\tau(s) = \begin{cases} \frac{\tau_u}{s_u} \cdot s & (0 < s \leq s_u) \\ 0.116 + 1.174e^{-0.353s} & (s_u \leq s \leq s_r) \\ \tau_r & (s > s_r) \end{cases} \quad (3)$$

The model included the following parameters: τ_u , signifying the peak bond stress; s_u , denoting the corresponding peak slip; τ_r as the residual bond stress; and s_r , representing the corresponding residual slip.

Based on the experimental data, the fitting results for each eigenvalue are as follows:

$$\tau_u = -30.410 + 44.44 \frac{d}{L} + 14.33 \frac{d}{D} \quad (4)$$

$$s_u = -53.18 + 321.70 \frac{d}{L} + 17.126 \frac{d}{D} - 230.891 \left(\frac{d}{L} \right)^2 - 76.555 \frac{d}{L} \cdot \frac{d}{D} \quad (5)$$

$$\tau_r = 0.256\tau_u \quad (6)$$

$$s_r = 3.864s_u \quad (7)$$

where d is the diameter of the rebar, L is the anchorage length, and D is the diameter of the bellows.

5. Conclusions

This study was focused on exploring the anchorage performance of the UHPC grout-filled bellow connection technology used in precast columns. To investigate this, a total of

16 steel-UHPC specimens grouted in metal bellows were designed and used, considering varying diameter ratios (D/d) and anchorage lengths (L), in pullout tests. The influence of D/d and L on the anchorage behavior of the rebar and UHPC grouted in the bellows was analyzed. A bond–slip model for the interface between the rebar and the UHPC within the bellows was established by fitting the experimental results. The main conclusions extracted from this study are as follows:

(1) The anchorage length (L) was the dominant factor affecting the anchorage performance of the rebar in the UHPC grouted in bellows. When the anchorage length (L) was more than $10d$, the rebar anchorage was dependable, with all specimens with rebar exhibiting tensile failure. As a result, to ensure dependable rebar anchorage in the context of UHPC grouted in bellows, it is imperative to employ anchorage lengths (L) of at least $10d$.

(2) When the diameter ratio (D/d) was more than 2.4, specimens with an anchorage length (L) of $10d$ achieved reliable anchorage via UHPC-filled bellows. The ultimate bearing capacity of specimens with D/d of 3.2 was 15.5% higher than that of specimens with D/d of 2.4. With the increase in anchorage length, the influence of the diameter ratio on the bearing capacity was reduced. When L was $24d$, the influence of D/d could be neglected.

(3) The strain distribution along the interface between rebars and UHPC exhibited a single peak distribution. The position of peak strain moved closer to the loading end as the anchorage length increased. After standardization, the experimental bond stress–position curves were obtained. The maximum bonding stress appeared at a distance of approximately $0.14L$ from the loading end.

(4) The proposed three-stage bond–slip model based on the experimental curves can effectively describe the bond behavior of the interface between the rebar and UHPC grouted in bellows.

The research presented in this paper can provide a basis for the design and application of precast columns connected by using UHPC-filled ducts. It should be noted that the model proposed in this study is preliminary and needs more experiments and finite element analyses to further verify and improve it.

Author Contributions: Investigation, Z.W., Q.W. (Qiqi Wang) and Q.W. (Qian Wang); Data curation, Z.W., Q.W. (Qiqi Wang) and Q.W. (Qian Wang); Writing—original draft, Z.W.; Writing—review & editing, X.Z.; Project administration, X.Z.; Funding acquisition, X.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Guangdong Provincial Natural Science Foundation grant number 2019A1515012222, and Guangzhou Science and Technology Planning Project grant number 202102080446.

Conflicts of Interest: The authors declare no conflict of interest.

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