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Research on the Distributive Relationship between Bond Force and Bearing Pressure for Anchorage Force by Headed Bars

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Abstract: Anchorage force comprises bond force and bearing pressure when headed bars are used. Pull-out tests were conducted on 120 concrete specimens to derive a method for calculating the bond force for reinforcement in straight anchor sections at the yield moment. The parameters include the diameter d , embedded length l_{ae} , and yield strength f_y of the reinforcement, as well as the strength grade of the concrete f_{cg} . The experimental results indicated that the specimens underwent three failure modes depending primarily on the embedded length l_{ae} . The nominal average bond stress τ^u concept was proposed and the difference between τ^u and the actual average bond stress τ caused by the headed bars was observed. To reduce the difference between the τ^u and τ values, the correction coefficient γ was proposed. Analysis indicated that γ increased with an increase in the l_{ae}/d (on average, 146% higher than the initial value) and decreased with an increase in the f_y/f_t (on average, 33% less than the initial value). A formula was developed to calculate γ , and the bond force in the straight anchor sections at the yield moment for the reinforcement was determined. Thus, a distributive relationship was established for the anchorage force, the bond force, and the bearing pressure.

Keywords: anchorage force; bond stress; distributive relationship; embedded length; headed bars; nominal average bond stress



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1. Introduction

High-strength reinforcements have recently emerged as a prominent development trend in the construction industry. It is difficult to achieve reliable and effective anchorage when reinforcements with a higher strength and larger diameter are used in concrete structures. The interweaving of the primary and bending reinforcements leads to congestion in the beam–column joint reinforcement arrangement and affects the quality of concrete casting at the joint. Installing headed bars at the end of the reinforcement significantly reduces the anchorage length and resolves interweaving issues to ensure high-quality concrete pouring [1–7]. Research on reinforcements using headed bars began in the 1960s [8]. Nelson Stud was the first to test the anchorage performance of headed bars, which were later used by a welding company and Lehigh University in the connection between a concrete slab and steel beams. Since then, great progress has been made, and fruitful results have been achieved in this field.

To ensure adequate shear transfer, appropriate connection systems are required for the joints of precast reinforced concrete structures. However, conventional connection

methods for precast components are susceptible to damage under seismic loads. To address this issue, Singhal et al. conducted an experimental investigation on a connection system using headed bars. They investigated the anchorage behaviours of the reinforcements with headed bars based on different failure modes, changes in the bond force, and slip values. The test results showed that precast reinforced concrete wall–column connections using headed bars performed significantly better than dowel bar connections [9,10]. To evaluate the effectiveness of T-headed bars as shear reinforcements, Yang et al. conducted 12 tests. Their findings showed that the specimens reinforced with T-headed bars exhibited higher shear strength than those reinforced with conventional stirrups. This observation indicates that T-headed bars have the potential to replace traditional reinforcements [11]. To investigate the impact of joint concrete strength, transverse reinforcement, geometric shape, and out-of-plane tolerance on joint performance, Vella et al. conducted a series of tensile and bending tests on joints featuring headed bars. The reinforcement had a diameter of 25 mm, and the headed bars were square-shaped with a side length of 70 mm. Based on both experimental and numerical results, a design procedure for headed bar joints was established using a model incorporating struts and tie rods [12–14].

Headed bars could also be used to reinforce structural members, such as beam–column joints. Paknejadi et al. investigated the anchorage performance of beam–column joints in steel fibre-reinforced concrete using headed bar reinforcement. Their results indicated that headed bars with higher anchorage capacity, better ductility, and good stiffness response could significantly replace conventional reinforcements [15]. Chiu et al. identified six potential failure mechanisms for headed bars embedded in concrete under tensile loads. These mechanisms were reinforcement yield or fracture, bar-to-head connection failure, pull-out failure, concrete breakout failure, side-face blowout failure (SBF), and splitting failure. Experiments were conducted to prevent the occurrence of SBF, which is a critical failure mode. The test results and finite element analysis showed that when the diameter of the headed bar embedded in external beam–column joints was not larger than 35 mm, the minimal net concrete cover could be reduced to the diameter multiplied by 1.5 [16]. Chun and Lee assessed the contribution of headed bars to the anchorage force in external beam–column joints, specifically in the bearing and bond components. They found that the bearing components of the headed bars remained consistent, regardless of their embedded length [17–21]. However, further investigations have been conducted on the relationship between the bond stress and bond slip. Eligehausen et al. developed a constitutive model that included a power function in the rising section and a peak platform based on the analysis on the pull-out test data [22]. This model was ultimately adopted by the CEP-FIP Model Code 2010 [23]. Xu et al. proposed a segmented constitutive model that was in excellent agreement with the measured data, and this model was adopted by the GB50010-2010 Code in China for the design of concrete structures [24–27].

While some studies have examined headed bars and bonding properties, insufficient attention has been given to the relationship between bond force and bearing pressure. This study addressed this gap by restricting the minimum embedded length and bearing area of the headed bars. However, these restrictions resulted in a longer anchorage length of the reinforcement and a larger bearing area of the headed bars.

Specific standards for headed bars are provided by JGJ 256-2011 (technical specification for the application of headed bars) [28], as follows:

- (1) when using a partial anchorage head for the rebar, the bearing area of the headed bars must be at least nine times as large as the sectional area of the reinforcement;
- (2) when using the full anchorage head for the rebar, the bearing area of the headed bars must be at least 4.5 times as large as the sectional area of the reinforcement, and the reinforcement's nominal diameter must not exceed 40 mm;
- (3) the thickness of the headed bars should not be less than the nominal reinforcement diameter.

A partial anchorage head refers to a reinforcement bond that partially bears the anchorage force, whereas a full anchorage head indicates that no reinforcement bond bears

the anchorage force. These specific standards lead to the inefficient use of resources and can create complications due to overly detailed regulations. If the requirements are not fulfilled, the corresponding inspection methods are not provided. To address this, it is essential to determine the distributive relationship between the bond force and bearing pressure when headed bars are used. Understanding this relationship makes it possible to select appropriate dimensions for the headed bars and an appropriate embedded length for the reinforcement.

This study conducted a total of 120 pull-out tests to address this issue. The influences of the diameter d , embedded length l_{ae} , yield strength f_y , of the reinforcement, and strength grades of the concrete, f_{cg} were studied. This study established a method for calculating the bond force in straight anchor sections at the yield moment of the reinforcement. This method determined the distributive relationship between the bond force and bearing pressure, shifting the design concept of headed bars from passive checking to active selection.

2. Experimental Program

2.1. Design of the Specimens

A total of 120 concrete specimens with headed bars were prepared according to GB50010-2010. The cross-sectional dimensions of the pull-out specimens were $150\text{ mm} \times 150\text{ mm}$, and the longitudinal reinforcement consisted of headed bars positioned at the centroid of the section. HRB500 and HRB600 high-strength reinforcements were selected as the longitudinal reinforcements in the test, and the diameters d were 20, 22, and 25 mm. The various diameters d correspond to different sizes of the headed bars, with dimensions of $40\text{ mm} \times 40\text{ mm} \times 16\text{ mm}$, $45\text{ mm} \times 45\text{ mm} \times 16\text{ mm}$, and $50\text{ mm} \times 50\text{ mm} \times 16\text{ mm}$. Perforated plug welding was utilised to join the reinforcement and headed bars, enabling them to function in unison. In addition, four HPB300 bars with a diameter of 8 mm were used as erection reinforcements to facilitate construction. The stirrup in the concrete specimen was made of an HPB300 steel bar with an 8 mm diameter and a stirrup spacing of 100 mm. In addition, the protective layer thickness c in this study is the distance from the longitudinal reinforcement to the outermost edge of the specimen. Figure 1 shows a representative specimen.

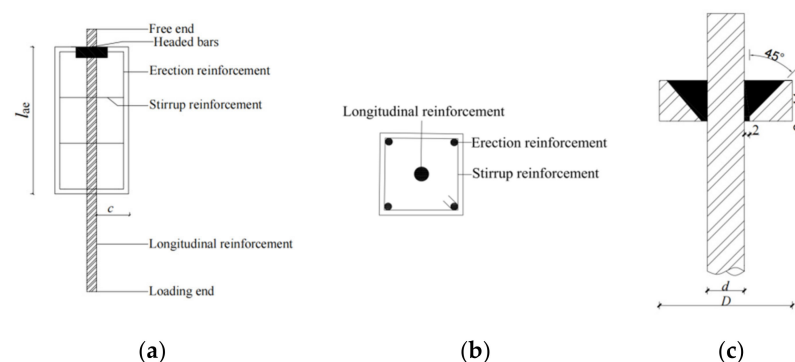


Figure 1. Representative specimen: (a) Front view of specimen; (b) Top view of specimen; (c) Perforated plug welding between reinforcement and headed bars.

According to GB50010-2010, when the yield strength of the reinforcement f_y is at least 400 MPa, the concrete strength grade f_{cg} must not be lower than C25 [24]. The concrete strength grades used in the tests ranged from C30 to C70 and tests included five distinct concrete strength grades. Concrete strength grades ranged from C30 to C60 when HRB500 longitudinal reinforcing bars were used, and from C40 to C70 when HRB600 longitudinal reinforcing bars were used. The specimens were classified into 24 groups based on their identical reinforcement yield strength f_y , reinforcement diameter d , and concrete strength grade f_{cg} . Each group consisted of five specimens with different embedded lengths l_{ae} . The embedded lengths were calculated based on different ratios to the basic embedded

length l_{ab} . The basic embedded length of the reinforcement l_{ab} was calculated according to Equation (1) in the code for the design of concrete structures (GB50010-2010).

$$l_{ab} = \alpha \frac{f_y}{f_t} d \quad (1)$$

The groups and numbers of specimens are listed in Table 1, where β is the ratio of the embedded length l_{ae} to the basic embedded length l_{ab} . When the reinforcement was HRB500, the diameter of reinforcement was 20 mm, and the concrete strength grade was C30, the group would be named “500-20-30”. The specific specimens were named by adding the embedded length based on the group, such as “500-20-30-140”. The naming principles and numbers for the other groups were the same.

Table 1. Groups and numbers for the specimens.

Group	No.	β	Group	No.	β	Group	No.	β
500-20-30	500-20-30-140	0.28	500-20-40	500-20-40-120	0.28	500-20-50	500-20-50-110	0.28
	500-20-30-180	0.36		500-20-40-160	0.36		500-20-50-140	0.36
	500-20-30-220	0.43		500-20-40-190	0.44		500-20-50-170	0.42
	500-20-30-260	0.50		500-20-40-230	0.53		500-20-50-200	0.51
	500-20-30-300	0.61		500-20-40-260	0.63		500-20-50-230	0.58
500-20-60	500-20-60-100	0.28	500-22-30	500-22-30-160	0.29	500-22-40	500-22-40-140	0.28
	500-20-60-130	0.36		500-22-30-210	0.37		500-22-40-180	0.37
	500-20-60-160	0.45		500-22-30-260	0.46		500-22-40-220	0.46
	500-20-60-180	0.49		500-22-30-310	0.56		500-22-40-270	0.56
	500-20-60-210	0.59		500-22-30-360	0.65		500-22-40-310	0.63
500-22-50	500-22-50-130	0.31	500-22-60	500-22-60-110	0.28	500-25-30	500-25-30-200	0.33
	500-22-50-160	0.38		500-22-60-150	0.39		500-25-30-260	0.43
	500-22-50-200	0.47		500-22-60-180	0.46		500-25-30-320	0.52
	500-22-50-240	0.56		500-22-60-220	0.55		500-25-30-380	0.62
	500-22-50-270	0.64		500-22-60-250	0.67		500-25-30-410	0.67
500-25-40	500-25-40-170	0.32	500-25-50	500-25-50-150	0.30	500-25-60	500-25-60-140	0.33
	500-25-40-220	0.41		500-25-50-200	0.43		500-25-60-180	0.41
	500-25-40-270	0.51		500-25-50-240	0.51		500-25-60-220	0.50
	500-25-40-330	0.62		500-25-50-290	0.61		500-25-60-270	0.64
	500-25-40-380	0.71		500-25-50-340	0.70		500-25-60-310	0.70
600-20-40	600-20-40-140	0.27	600-20-50	600-20-50-130	0.28	600-20-60	600-20-60-120	0.30
	600-20-40-190	0.38		600-20-50-170	0.38		600-20-60-150	0.36
	600-20-40-230	0.45		600-20-50-210	0.47		600-20-60-190	0.48
	600-20-40-270	0.53		600-20-50-240	0.53		600-20-60-220	0.53
	600-20-40-320	0.63		600-20-50-280	0.62		600-20-60-250	0.60
600-20-70	600-20-70-110	0.29	600-22-40	600-22-40-170	0.31	600-22-50	600-22-50-150	0.30
	600-20-70-140	0.37		600-22-40-220	0.40		600-22-50-190	0.39
	600-20-70-170	0.46		600-22-40-270	0.49		600-22-50-240	0.49
	600-20-70-200	0.54		600-22-40-320	0.56		600-22-50-280	0.58
	600-20-70-230	0.61		600-22-40-370	0.67		600-22-50-320	0.66
600-22-60	600-22-60-140	0.32	600-22-70	600-22-70-120	0.29	600-25-40	600-25-40-200	0.30
	600-22-60-180	0.40		600-22-70-160	0.38		600-25-40-270	0.40
	600-22-60-220	0.49		600-22-70-200	0.49		600-25-40-330	0.48
	600-22-60-260	0.61		600-22-70-240	0.59		600-25-40-390	0.59
	600-22-60-300	0.70		600-22-70-280	0.69		600-25-40-450	0.69
600-25-50	600-25-50-180	0.29	600-25-60	600-25-60-170	0.29	600-25-70	600-25-70-150	0.31
	600-25-50-240	0.41		600-25-60-220	0.40		600-25-70-200	0.41
	600-25-50-290	0.49		600-25-60-270	0.50		600-25-70-250	0.51
	600-25-50-350	0.59		600-25-60-320	0.58		600-25-70-290	0.59
	600-25-50-400	0.67		600-25-60-370	0.68		600-25-70-340	0.68

2.2. Properties of Materials

Five specimens from each group were cast in the same batch. Nine concrete cubes with side lengths of 100 mm were used in each group. When the concrete strength grade was C60 or C70, at least three additional concrete cubes with a side length of 150 mm were included. The materials used in this study were silica sand with a mean particle size of 225 μm , Portland cement with a Blaine specific surface area of 4500 cm^2 , condensed silica fume, slag powder, and crushed stone with a max particle size of 30 mm. The SF had an amorphous SiO_2 content of 97.2% and its mean particle size was about 0.1–0.15 μm . Table 2 lists the mix proportions of the concrete, while Table 3 shows the mechanical properties of the concrete, including $f_{t,m}$ derived from $f_{c,m}$ according to the specifications in the GB50010-2010 code for the design of concrete structures. The mechanical properties of HRB500 and HRB600 reinforcements are listed in Table 4.

Table 2. Mix proportions of the concrete.

f_{cg}/MPa	Type of Cement	Water-Binder Ratio	Slump of Concrete	Material Consumption					
				Cement	Silica Fume	Slag Powder	Water	Sand	Stone
C30	P·O 42.5	0.52	70 mm	413	-	-	215	602	1169
C40	P·O 42.5	0.44	70 mm	430	-	-	190	610	1180
C50	P·O 42.5	0.35	70 mm	542	-	-	190	566	1100
C60	P·O 42.5	0.26	75 mm	654	-	-	173	551	1025
C70	P·O 52.5	0.20	75 mm	588	50	112	150	513	986

Table 3. Mechanical properties of the concrete.

f_{cg}/MPa	$f_{c,m}/\text{MPa}$	$f_{t,m}/\text{MPa}$
C30	29.62	2.96
C40	37.88	3.39
C50	46.40	3.79
C60	56.01	4.14
C70	67.02	4.51

Table 4. Mechanical properties of the reinforcing bars.

Steel Grade	d/mm	$f_{y,m}/\text{MPa}$	$f_{u,m}/\text{MPa}$
HRB300	8	340	400
	20	555	725
HRB500	22	555	716
	25	560	713
HRB600	20	633	825
	22	612	796
	25	684	901

2.3. Loading and Measurement Scheme

Pull-out tests were performed using a universal testing machine. The pull-out test setup is illustrated in Figure 2. The loading frame in Figure 2a consists of two square steel plates with a 50 mm thickness and a 400 mm side length. Four 8.8-grade high-strength screws with a diameter of 22 mm and matching nuts were used to assemble the loading frame, and the centre of the two square steel plates was provided with a 40 mm diameter round hole. The loading frame is shown in Figure 2b.

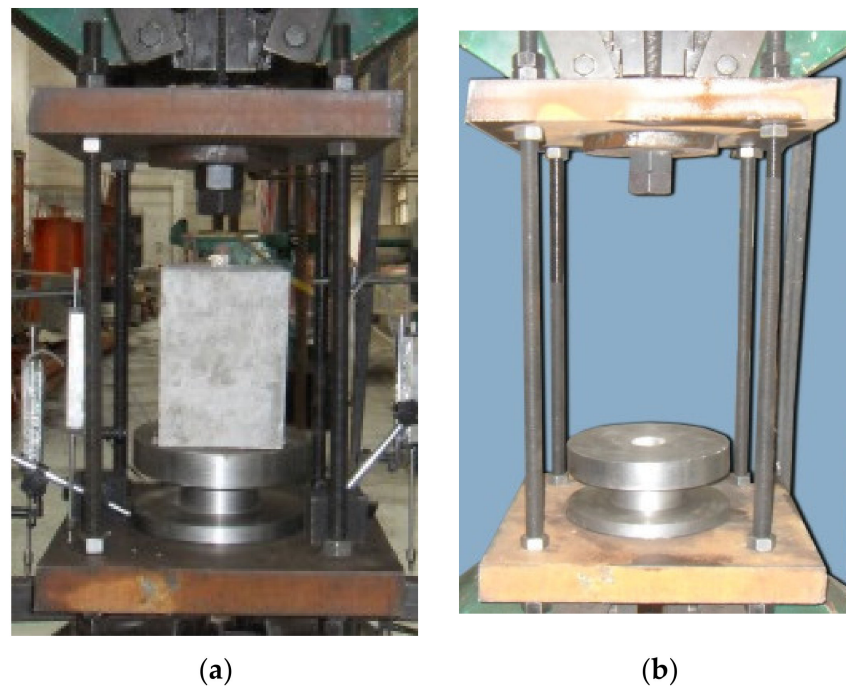


Figure 2. Test setup: (a) Pull-out test; (b) Load frame.

Prior to the formal loading, preloading was conducted to ensure the proper functioning of the instrument. The loading process consisted of two stages. In the first stage, the loading rate was controlled according to the load, until the tensile yield of the reinforcement was reached, at a loading rate of 0.15 kN/s. In the second stage, the loading rate was controlled according to the displacement, until the end of the test, at a rate of 1 mm/min. To obtain the strain variations rule for the reinforcement in the straight anchor section, a 4 mm × 4 mm groove was milled along the longitudinal reinforcement, and 1 mm × 2 mm strain gauges were arranged at a spacing of 30 mm. Finally, the grooves were sealed with planting glue. Figure 3 illustrates the arrangement of the strain measurement points.

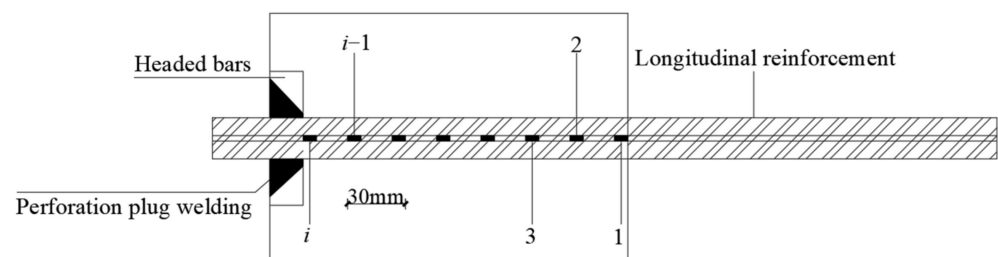


Figure 3. Arrangement of strain gauges.

Based on the number of strain gauges shown in Figure 3, the value of strain gauge 1 indirectly reflected the value of the load applied to the loading end of the reinforcement. i would indirectly reflect the load values of the headed bars. The bond force between the reinforcement and concrete in the straight anchor section can be calculated from the difference between the values of strain gauges 1 and i .

3. Experimental Phenomenon

By observing the test phenomenon, it was found that the bond stress between the reinforcement and concrete always existed before the reinforcement yielded. The presence of the headed bars in the reinforcement limited the slip at the free end. Therefore, most of the bond stresses in the straight anchor section did not reach the ultimate bond stress

in the bond–slip constitutive model. Based on Xu’s results, the embedded length l_{ae} was divided by the diameter d to create a dimensionless parameter for studying the effect of the relative embedded length l_{ae}/d on the observed phenomenon. The average bond stress varied depending on the embedded length, suggesting that altering the relative embedded length l_{ae}/d led to distinct failure modes, as demonstrated by the test results.

3.1. First Failure Mode of the Specimen

When the embedded length of the reinforcement l_{ae} was short, cracks appeared on the specimen surface and continued to develop as the load increased. These cracks were categorised as transverse and longitudinal ones. Longitudinal cracks emerged at the loading end of the specimen and progressed towards the free end, while transverse cracks appeared at the edge of the specimen and progressed towards its interior. As the load increased, a concrete wedge formed under the headed bars. The test was stopped when the displacement of the headed bars increased, and the load correspondingly decreased, resulting in serious damage to the specimen. For example, the cracks that occurred in the concrete specimen with the identification number No. “500-20-30-180” when the reinforcement yielded are shown in Figure 4a, and when the reinforcement fractured, in Figure 4b.

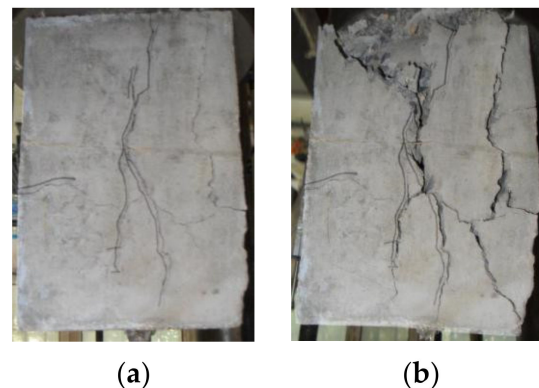


Figure 4. Cracks on the side of specimen No. “500-20-30-180”: (a) Cracks of the specimen when the reinforcement yielded; (b) Cracks of the specimen when the reinforcement fractured.

The smaller the embedded length l_{ae} , the larger the average bond stress between the reinforcement and concrete. The radial tensile stress caused by the average bond stress was relatively large. As the radial tensile stress surpassed the tensile strength of the concrete, cracks initially emerged at the loading end of the specimen. With a gradual increase in the radial tensile stress, a longitudinal crack developed towards the free end of the specimen. However, a smaller embedded length l_{ae} would cause a larger bearing pressure. The bearing effect of the headed bars primarily bore the anchorage force. The splitting effect of the bearing pressure aggravated the development of the longitudinal crack, leading to its propagation throughout the entire specimen upon fracture. Meanwhile, transverse cracks were caused by compressive strains in the concrete under the headed bars, as well as transverse expansion of the specimen, causing transverse cracks at the edge of the specimen. This failure mode was mainly concentrated in the specimens with $\beta \approx 0.3$ and $\beta \approx 0.4$.

3.2. Second Failure Mode of the Specimen

When the embedded length of the reinforcement l_{ae} was long, longitudinal cracks appeared at the loading ends of the specimens, and as the load increased, longitudinal cracks developed towards the free end. Despite the loading and fracture of the longitudinal reinforcement, crack development was slow, and only a few new cracks were created, failing to penetrate the entire specimen. Taking No. “600-20-40-320” concrete specimen as an example, the cracks of the specimen when the reinforcement yielded are shown in

Figure 5a, and the cracks of the specimen when the reinforcement fractured are shown in Figure 5b.

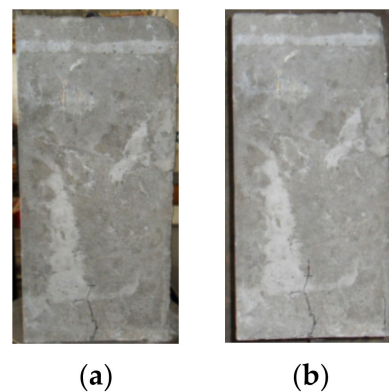


Figure 5. Cracks on the side of specimen No. “600-20-40-320”: (a) Cracks of the specimen when the reinforcement yielded; (b) Cracks of the specimen when the reinforcement fractured.

The increased embedded length l_{ae} resulted in a higher bond force between the reinforcement and concrete. The slip between the reinforcement and concrete at the loading end increased as the load increased. At this point, the radial tensile stress exceeded the tensile strength of the concrete, resulting in longitudinal splitting cracks. The anchorage force was then transmitted along the reinforcement to the free end of the specimen. As the distance from the loading end increased, the slip between the reinforcement and the concrete decreased gradually, and lower bond stresses came with smaller slip values. Due to the insufficient radial tensile stress caused by the bond stress, significant concrete cracking did not develop. However, an increase in the embedded length l_{ae} decreased the bearing pressure of the headed bars. Thus, the anchorage force was mainly sustained by the bond force between the reinforcement and the concrete. Any longitudinal or transverse cracks resulting from the bearing pressure of the headed bars remained inconspicuous. Only longitudinal cracks were observed in the specimens, and this failure mode was mainly concentrated in specimens with $\beta \approx 0.7$.

3.3. Third Failure Mode of the Specimen

When the embedded length of the reinforcement l_{ae} fell within the aforementioned range, the pattern of crack development was similar to that of the initial failure mode. The cracks primarily developed in the longitudinal and transverse directions. The difference was that the transverse cracks developed slowly before the reinforcement yielded but became more obvious after yielding. However, longitudinal cracks only developed before the reinforcement yielded and progressed more slowly after yielding occurred. Consequently, the longitudinal cracks tended to penetrate the specimen. Taking No. “600-25-50-240” concrete specimen as an example, Figure 6a shows the cracks of the specimen when the reinforcement yielded, while Figure 6b shows the cracks of the specimen when the reinforcement fractured.

The embedded length l_{ae} and the average bond stress were moderate. Longitudinal cracks appeared at the loading end and developed towards the free end as the load increased. However, as the reinforcement was pulled, the anchorage force was gradually borne by the bearing pressure of the headed bars, which resulted in the production of longitudinal split cracks. The development of cracks extended significantly between the loading and free ends, owing to the superposition of the longitudinal cracks at both ends. In addition, transverse cracks were observed at the edge of the specimen, owing to the bearing pressure of the headed bars. This failure mode was mainly concentrated in the specimens with $\beta \approx 0.5$ and $\beta \approx 0.6$.

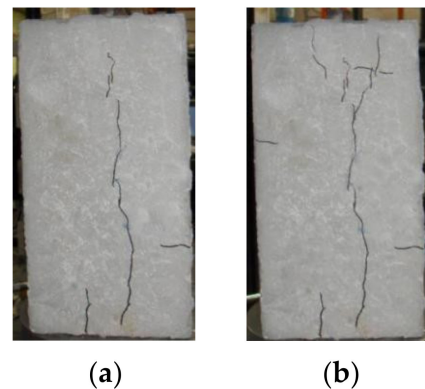


Figure 6. Cracks on the side of specimen No. “600-25-50-240”: (a) Cracks of the specimen when the reinforcement yielded; (b) Cracks of the specimen when the reinforcement fractured.

4. Results and Analysis

4.1. Results of Pull-Out Tests

When the longitudinal reinforcement was stressed, the anchorage force F_y was shared by the bond force between the reinforcement and concrete F_b and the bearing pressure of the headed bars F_p . According to the strain gauge numbering principle, F_b can be determined as the difference between F_y and F_p . The specific measured data for the reinforcement anchorage force F_y , the bond force F_b , and the bearing pressure F_p of each specimen when the longitudinal reinforcement at the loading end yielded are listed in Table 5.

Table 5. Key values of the pull-out specimens.

No.	F_p /kN	F_b /kN	F_y /kN	No.	F_p /kN	F_b /kN	F_y /kN
500-20-30-140	107.36	60.39	167.75	500-20-40-120	124.76	39.40	164.16
500-20-30-180	104.85	58.98	163.83	500-20-40-160	113.05	55.68	168.73
500-20-30-220	99.29	69.00	168.29	500-20-40-190	94.87	68.70	163.57
500-20-30-260	85.84	85.84	171.68	500-20-40-230	82.83	82.83	165.66
500-20-30-300	67.52	97.16	164.68	500-20-40-260	63.04	94.56	157.60
500-20-50-110	130.51	36.81	167.32	500-20-60-100	135.52	31.79	167.31
500-20-50-140	118.25	48.30	166.55	500-20-60-130	122.28	45.23	167.51
500-20-50-170	111.11	59.83	170.94	500-20-60-160	112.99	53.17	166.16
500-20-50-200	92.16	75.40	167.56	500-20-60-180	104.36	66.72	171.08
500-20-50-230	82.79	86.17	168.96	500-20-60-210	84.46	81.15	165.61
500-22-30-160	144.66	56.42	201.08	500-22-40-140	163.29	44.71	208.00
500-22-30-210	142.35	66.99	209.34	500-22-40-180	140.14	65.95	206.09
500-22-30-260	118.59	89.46	208.05	500-22-40-220	113.38	85.53	198.91
500-22-30-310	95.17	107.32	202.49	500-22-40-270	97.42	105.54	202.96
500-22-30-360	77.40	126.28	203.68	500-22-40-310	82.04	123.06	205.10
500-22-50-130	147.14	49.05	196.19	500-22-60-110	157.13	41.77	198.90
500-22-50-160	134.39	63.24	197.63	500-22-60-150	133.05	62.61	195.66
500-22-50-200	120.20	80.13	200.33	500-22-60-180	123.34	75.60	198.94
500-22-50-240	102.45	98.43	200.88	500-22-60-220	111.99	91.63	203.62
500-22-50-270	85.43	113.24	198.67	500-22-60-250	85.58	104.60	190.18
500-25-30-200	184.82	68.36	253.18	500-25-40-170	190.01	63.34	253.35
500-25-30-260	158.66	93.18	251.84	500-25-40-220	174.62	78.45	253.07
500-25-30-320	136.64	116.40	253.04	500-25-40-270	138.26	113.12	251.38
500-25-30-380	115.06	140.63	255.69	500-25-40-330	119.02	134.21	253.23
500-25-30-410	89.06	165.40	254.46	500-25-40-380	94.53	160.96	255.49
500-25-50-150	211.28	52.82	264.10	500-25-60-140	194.89	54.97	249.86
500-25-50-200	164.51	84.75	249.26	500-25-60-180	185.12	71.99	257.11
500-25-50-240	151.47	100.98	252.45	500-25-60-220	162.88	91.62	254.50
500-25-50-290	125.47	125.47	250.94	500-25-60-270	144.61	100.49	245.10
500-25-50-340	98.34	160.45	258.79	500-25-60-310	125.63	130.76	256.39

Table 5. Cont.

No.	F_p /kN	F_b /kN	F_y /kN	No.	F_p /kN	F_b /kN	F_y /kN
600-20-40-140	148.47	46.89	195.36	600-20-50-130	149.48	44.65	194.13
600-20-40-190	118.46	72.60	191.06	600-20-50-170	120.54	67.80	188.34
600-20-40-230	109.90	86.35	196.25	600-20-50-210	106.97	84.05	191.02
600-20-40-270	86.59	105.83	192.42	600-20-50-240	94.36	98.21	192.57
600-20-40-320	71.81	122.27	194.08	600-20-50-280	78.45	112.89	191.34
600-20-60-120	139.94	44.19	184.13	600-20-70-110	147.81	44.15	191.96
600-20-60-150	129.99	61.17	191.16	600-20-70-140	128.99	60.70	189.69
600-20-60-190	103.44	81.27	184.71	600-20-70-170	104.53	82.13	186.66
600-20-60-220	97.58	93.75	191.33	600-20-70-200	99.66	88.38	188.04
600-20-60-250	87.71	107.20	194.91	600-20-70-230	87.13	102.28	189.41
600-22-40-170	166.66	64.81	231.47	600-22-50-150	177.32	56.00	233.32
600-22-40-220	144.32	84.76	229.08	600-22-50-190	144.99	81.56	226.55
600-22-40-270	118.88	109.74	228.62	600-22-50-240	129.24	101.55	230.79
600-22-40-320	106.91	130.67	237.58	600-22-50-280	104.53	122.71	227.24
600-22-40-370	80.28	149.09	229.37	600-22-50-320	83.89	142.84	226.73
600-22-60-140	172.15	54.36	226.51	600-22-70-120	177.70	50.12	227.82
600-22-60-180	152.99	75.35	228.34	600-22-70-160	163.30	69.99	233.29
600-22-60-220	130.20	98.22	228.42	600-22-70-200	130.46	94.47	224.93
600-22-60-260	109.61	109.61	219.22	600-22-70-240	108.91	117.99	226.90
600-22-60-300	82.91	135.27	218.18	600-22-70-280	90.05	135.08	225.13
600-25-40-200	216.18	97.12	313.30	600-25-50-180	236.42	91.94	328.36
600-25-40-270	207.96	111.98	319.94	600-25-50-240	199.79	112.38	312.17
600-25-40-330	179.50	146.86	326.36	600-25-50-290	202.47	109.02	311.49
600-25-40-390	139.15	177.10	316.25	600-25-50-350	167.41	148.46	315.87
600-25-40-450	96.62	215.06	311.68	600-25-50-400	126.83	190.25	317.08
600-25-60-170	256.77	81.09	337.86	600-25-70-150	233.14	73.62	306.76
600-25-60-220	132.60	183.11	315.71	600-25-70-200	210.69	99.15	309.84
600-25-60-270	185.40	128.84	314.24	600-25-70-250	178.90	129.55	308.45
600-25-60-320	128.16	192.24	320.40	600-25-70-290	154.78	154.78	309.56
600-25-60-370	107.70	209.06	316.76	600-25-70-340	130.32	187.53	317.85

Based on Figure 7, the average bond stress τ was computed as the anchorage force F_y divided by the initial surface area of the embedded portion of the reinforcement, as follows:

$$\tau = \frac{F_y}{\pi d l_{ae}} \quad (2)$$

In Equation (2), F_y denotes the anchorage force of the reinforcement. To ensure that the reinforcement reached its yield strength, F_y was set to $f_y A_s$, with A_s being the cross-sectional area of the reinforcement, where l_{ae} is equal to βl_{ab} . These values are substituted into Equation (2) to derive Equation (3) as follows:

$$\tau = \frac{f_y A_s}{\pi d \beta l_{ab}} \quad (3)$$

Based on the superposition of Equations (1) and (3), the calculation formula for the average bond stress is derived as follows:

$$\tau^u = \frac{f_t}{4\alpha\beta} \quad (4)$$

In the theoretical derivation, $f_y A_s$ was introduced above. Moreover, since the actual embedded length of the reinforcement l_{ae} was less than the basic embedded length l_{ab} , the reinforcement could not reach its yield strength f_y when the embedded length was l_{ae} . The results calculated using Equation (4) represent the theoretical value τ^u . However, in this study, the reinforcement could reach its yield strength f_y owing to the existence of headed

bars, which could share part of the anchorage force. In addition, the headed bars limited the slip value of the free end of the reinforcement. Hence, when the reinforcement yields at the loading end, and the slip value at the free end is limited to 0, the average bond stress is defined as the nominal average bond stress τ^u and the formula is given in Equation (4). Notably, according to GB50010-2010, the shape factor of the reinforcement α in Equation (4) was set to 0.14.

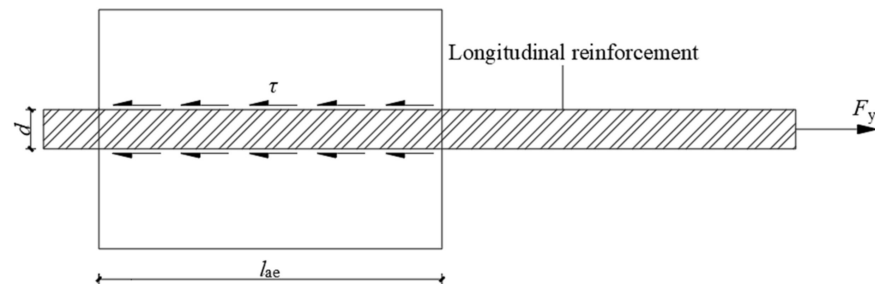


Figure 7. Calculation diagram of the average bond stress.

4.2. Analysis of the Influencing Parameters on γ

From the analysis, it can be inferred that there is a certain disparity between the nominal average bond stress τ^u and the actual average bond stress τ owing to the presence of headed bars. Therefore, a correction coefficient γ was introduced to modify the nominal average bond stress τ^u .

The correction coefficient γ is the ratio of the actual average bond stress τ to the nominal average bond stress τ^u , which could reflect the gap caused by the headed bars. Therefore, any factors that affect the bearing pressure of the headed bars F_p would also affect the value of γ .

4.2.1. Effect of the Relative Embedded Length l_{ae}/d

The embedded length l_{ae} significantly affects the bearing pressure of the headed bar F_p . The bond force between the reinforcement and concrete in the straight anchor section F_b increased proportionally with the embedded length l_{ae} . As the embedded length l_{ae} increased, the bearing pressure of the headed bars F_p decreased. This lower bearing pressure can result in a closer actual average bond stress τ to the nominal average bond stress τ^u . Therefore, the value of γ would positively correlate with an increase in the embedded length l_{ae} . The influence of the relative embedded length l_{ae}/d on γ was analysed under the same diameter d of the reinforcement, concrete strength grade f_{cg} , and reinforcement tensile strength f_y as conditions, and the results are presented in Figures 8 and 9.

As shown in Figures 8 and 9, the influence of the diameter d was limited when l_{ae}/d remained constant. Additionally, the coefficient γ increased linearly with the relative embedded length l_{ae}/d for a given reinforcement diameter d , concrete strength grade f_{cg} , and reinforcement tensile strength f_y .

4.2.2. Effect of f_y/f_t

The tensile strength of the concrete f_t is also a crucial parameter for determining the bearing pressure of the headed bars F_p . The bond force between the reinforcement and the concrete F_b decreased with the decrease in the tensile strength of the concrete f_t . The decrease in the tensile strength of the concrete f_t led to an increase in the bearing pressure of the headed bars F_p . A higher bearing pressure resulted in a greater distance between the actual average bond stress τ and the nominal average bond stress τ^u , leading to a decrease in the value of γ with the increase in the f_y/f_t . To analyse the influence of f_y/f_t on γ under the same diameter d of the reinforcement, the same reinforcement tensile strength f_y , and the similar embedded length of the headed bars l_{ae} , the test data were fitted, and the results

are shown in Figure 10. The maximum discrepancy in the embedded length l_{ae} was 20 mm, which was approximated as negligible.

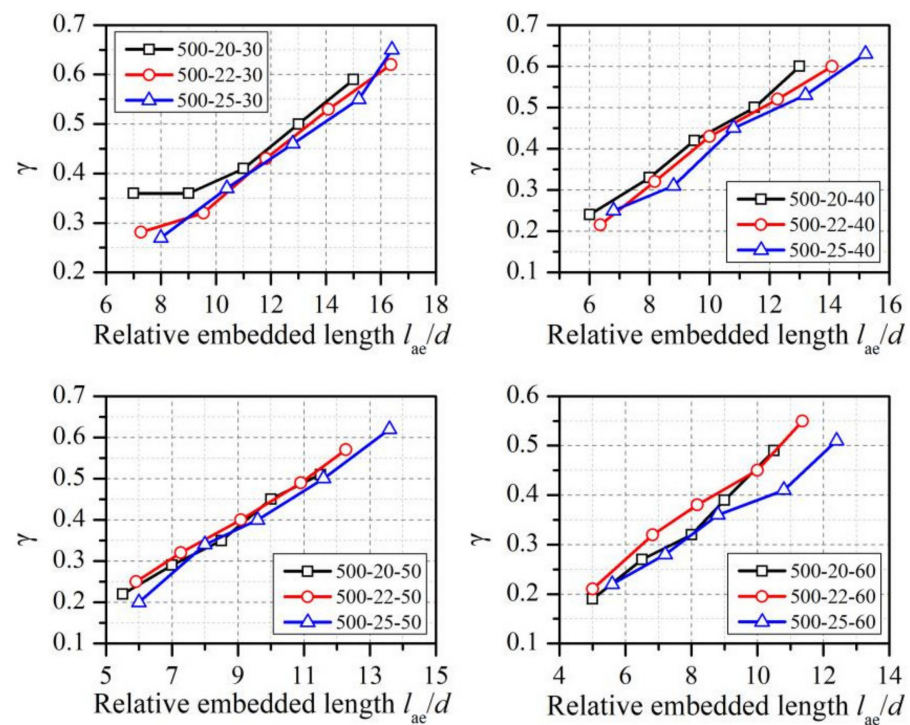


Figure 8. Effect of l_{ae}/d on γ for the reinforcement HRB500.

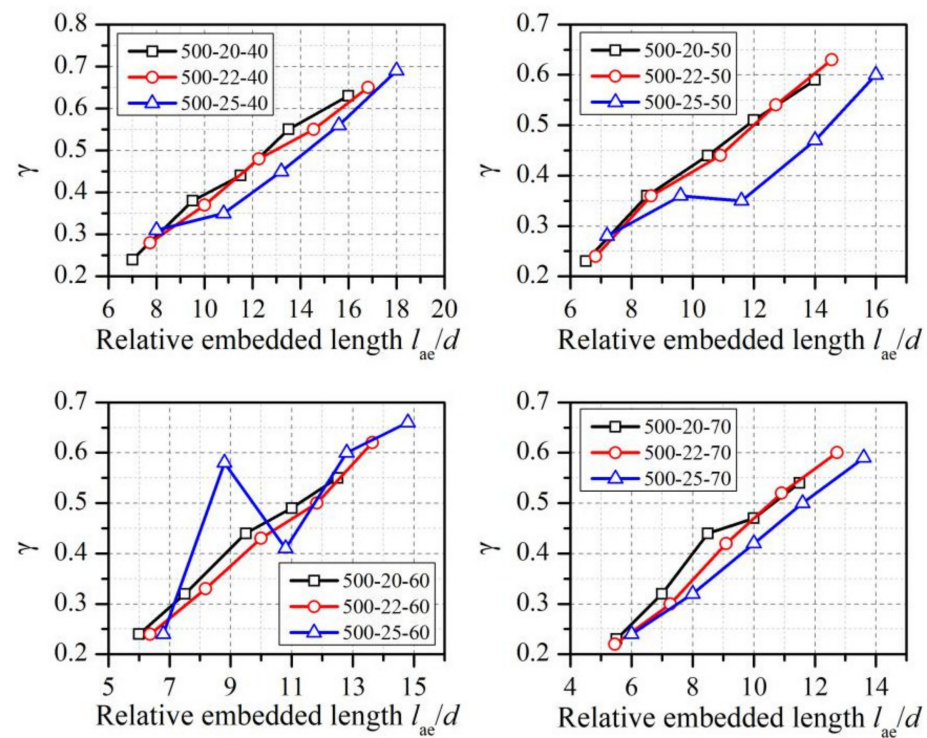


Figure 9. Effect of l_{ae}/d on γ for the reinforcement HRB600.

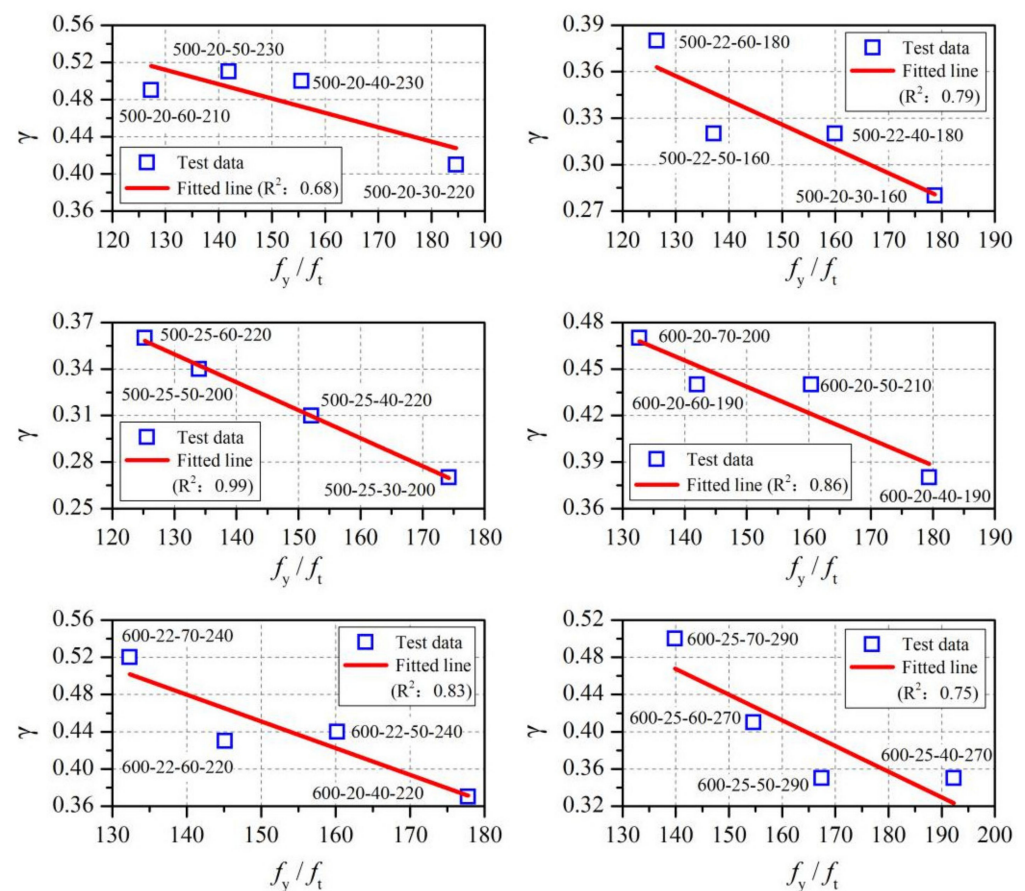


Figure 10. Effect of f_y/f_t on γ .

The analysis showed that increases in f_y/f_t led to similar decreases in γ according to the diameter d of the reinforcement, the reinforcement tensile strength f_y , and the embedded length of the headed bars l_{ae} . Furthermore, this relationship exhibited approximate linearity.

γ would increase with the increase in l_{ae}/d and decrease with the increase in f_y/f_t when the concrete strength classes were C30–C70, the longitudinal reinforcement was HRB500 or HRB600, and the reinforcement embedded lengths l_{ae} were 0.3–0.7 l_{ab} . After fitting the curve with a linear equation, the R^2 value was 0.916, indicating that the linear formula fit was highly accurate.

Thus, by considering l_{ae}/d and f_y/f_t as independent variables in the test data, Equation (5) is obtained for γ after fitting the curve.

$$\gamma = 4.38 \times 10^{-2} \frac{l_{ae}}{d} - 1.5 \times 10^{-3} \frac{f_y}{f_t} + 0.2038 \quad (5)$$

The test value of γ was obtained and compared to the values of γ_5 listed in Table 6. In the table, μ is the ratio of the test value to the calculated value γ_5 (obtained using Equation (5)). The average value μ , standard deviation, and the coefficient of variation were 0.999, 0.105, and 0.105, respectively.

Table 6. The values of γ and μ .

No.	γ (Test Value)	μ	No.	γ (Test Value)	μ	No.	γ (Test Value)	μ	No.	γ (Test Value)	μ
500-20-30-140	0.360	1.509	500-20-30-180	0.360	1.083	500-20-30-220	0.410	0.993	500-20-30-260	0.500	1.011
500-20-30-300	0.590	0.994	500-20-60-100	0.190	0.830	500-20-60-130	0.270	0.917	500-20-60-160	0.320	0.885
500-20-60-180	0.390	0.976	500-20-60-210	0.490	1.039	500-22-50-130	0.250	0.972	500-22-50-160	0.320	1.014
500-22-50-200	0.400	1.020	500-22-50-240	0.490	1.040	500-22-50-270	0.570	1.069	500-25-40-170	0.250	0.919
500-25-40-220	0.310	0.861	500-25-40-270	0.450	1.002	500-25-40-330	0.530	0.959	500-25-40-380	0.630	0.988
600-20-40-140	0.240	1.026	600-20-40-190	0.380	1.087	600-20-40-230	0.440	1.024	600-20-40-270	0.550	1.052
600-20-40-320	0.630	1.001	600-20-70-110	0.230	0.956	600-20-70-140	0.320	1.037	600-20-70-170	0.440	1.166
600-20-70-200	0.470	1.064	600-20-70-230	0.540	1.068	600-22-60-140	0.240	0.904	600-22-60-180	0.330	0.961
600-22-60-220	0.430	1.017	600-22-60-260	0.500	0.978	600-22-60-300	0.620	1.048	600-25-50-180	0.280	1.106
600-25-50-240	0.360	0.970	600-25-50-290	0.350	0.762	600-25-50-350	0.470	0.838	600-25-50-400	0.600	0.927
500-20-40-120	0.240	1.024	500-20-40-160	0.330	1.046	500-20-40-190	0.420	1.082	500-20-40-230	0.500	1.057
500-20-40-260	0.600	1.091	500-22-30-160	0.281	1.109	500-22-30-210	0.320	0.937	500-22-30-260	0.430	0.971
500-22-30-310	0.530	0.964	500-22-30-360	0.620	0.958	500-22-60-110	0.210	0.904	500-22-60-150	0.320	1.016
500-22-60-180	0.380	1.023	500-22-60-220	0.450	1.008	500-22-60-250	0.550	1.059	500-25-50-150	0.200	0.792
500-25-50-200	0.340	0.965	500-25-50-240	0.400	0.953	500-25-50-290	0.500	0.984	500-25-50-340	0.620	1.052
600-20-50-130	0.230	0.947	600-20-50-170	0.360	1.066	600-20-50-210	0.440	1.043	500-25-50-240	0.510	1.051
600-20-50-280	0.590	1.027	600-22-40-170	0.280	1.031	600-22-40-220	0.370	0.990	600-22-40-270	0.480	1.013
600-22-40-320	0.550	0.977	600-22-40-370	0.650	0.967	600-22-70-120	0.220	0.908	600-22-70-160	0.300	0.946
600-22-70-200	0.420	1.039	600-22-70-240	0.520	1.079	600-22-70-280	0.600	1.066	600-25-60-170	0.240	0.956
600-25-60-220	0.580	1.634	600-25-60-270	0.410	0.924	600-25-60-320	0.600	1.139	600-25-60-370	0.660	1.070
500-20-50-110	0.220	0.945	500-20-50-140	0.290	0.968	500-20-50-170	0.350	0.973	500-20-50-200	0.450	1.048
500-20-50-230	0.510	1.034	500-22-40-140	0.215	0.898	500-22-40-180	0.320	0.997	500-22-40-220	0.430	1.051
500-22-40-270	0.520	1.032	500-22-40-310	0.600	1.033	500-25-30-200	0.270	0.926	500-25-30-260	0.370	0.930
500-25-30-320	0.460	0.917	500-25-30-380	0.550	0.910	500-25-30-410	0.650	0.988	500-25-60-140	0.220	0.834
500-25-60-180	0.280	0.853	500-25-60-220	0.360	0.899	500-25-60-270	0.410	0.829	500-25-60-310	0.510	0.916
600-20-60-120	0.240	0.948	600-20-60-150	0.320	1.030	600-20-60-190	0.440	1.084	600-20-60-220	0.490	1.057
600-20-60-250	0.550	1.047	600-22-50-150	0.240	0.929	600-22-50-190	0.360	1.044	600-22-50-240	0.440	1.000
600-22-50-280	0.540	1.032	600-22-50-320	0.630	1.044	600-25-40-200	0.310	1.146	600-25-40-270	0.350	0.904
600-25-40-330	0.450	0.925	600-25-40-390	0.560	0.933	600-25-40-450	0.690	0.972	600-25-70-150	0.240	0.931
600-25-70-200	0.320	0.932	600-25-70-250	0.420	0.973	600-25-70-290	0.500	0.998	600-25-70-340	0.590	1.012

Figure 11 shows the fitting results when l_{ae}/d and f_y/f_t are the independent variables and γ is the dependent variable.

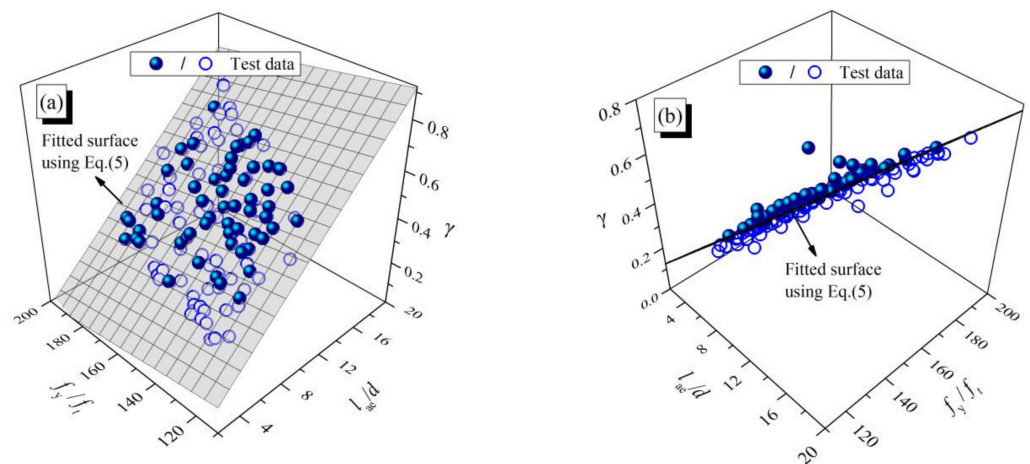


Figure 11. Fitting results. (a) The front view of test data and fitting surface. (b) The side view of test data and fitting surface.

4.3. Determination of the Distributive Relationship

To calculate the bond force between the reinforcement and the concrete F_b , the actual average bond stress τ needs to be determined.

The actual average bond stress τ can be obtained based on the superposition of Equations (4) and (5), as follows:

$$\tau = \frac{f_t}{4\alpha\beta} \left(4.38 \times 10^{-2} \frac{l_{ae}}{d} - 1.5 \times 10^{-3} \frac{f_y}{f_t} + 0.2038 \right) \quad (6)$$

The following can be used to calculate F_b at the yield moment of the reinforcement:

$$F_b = \frac{f_t}{4\alpha\beta} \left(4.38 \times 10^{-2} \frac{l_{ae}}{d} - 1.5 \times 10^{-3} \frac{f_y}{f_t} + 0.2038 \right) \pi d l_{ae} \quad (7)$$

Based on Equation (7), the distributive relationship for the anchoring force between the bond force and bearing pressure can be obtained:

$$\frac{F_b}{F_y} = \frac{f_t}{4\alpha\beta f_y A_s} \left(4.38 \times 10^{-2} \frac{l_{ae}}{d} - 1.5 \times 10^{-3} \frac{f_y}{f_t} + 0.2038 \right) \pi d l_{ae} \quad (8)$$

The test values for F_b/F_y were used to compare the $F_b/F_{y,8}$ values listed in Table 7. In this table, λ is the ratio of the test value to the calculated $F_b/F_{y,8}$ value (obtained using Equation (8)). The average value of λ is 1.016, the standard deviation is 0.120, and the coefficient of variation is 0.118. The value of F_b/F_y obtained using Equation (8) has a certain accuracy that meets the requirements for calculating the anchorage force of the reinforcement with headed bars.

Table 7. The values of F_b/F_y and λ .

No.	F_b/F_y (Test Value)	λ	No.	F_b/F_y (Test Value)	λ	No.	F_b/F_y (Test Value)	λ	No.	F_b/F_y (Test Value)	λ
500-20-30-140	0.360	1.508	500-20-30-180	0.360	1.082	500-20-30-220	0.410	0.993	500-20-30-260	0.500	1.010
500-20-30-300	0.589	0.993	500-20-60-100	1.004	1.000	500-20-60-130	0.270	1.109	500-20-60-160	0.319	1.070
500-20-60-180	0.389	1.180	500-20-60-210	0.490	1.256	500-22-50-130	0.250	0.971	500-22-50-160	0.320	1.013
500-22-50-200	0.400	1.019	500-22-50-240	0.490	1.039	500-22-50-270	0.570	1.068	500-25-40-170	0.250	0.918
500-25-40-220	0.310	0.861	500-25-40-270	0.450	1.002	500-25-40-330	0.530	0.959	500-25-40-380	0.630	0.987
600-20-40-140	0.240	1.025	600-20-40-190	0.380	1.086	600-20-40-230	0.440	1.024	600-20-40-270	0.550	1.052
600-20-40-320	0.630	1.000	600-20-70-110	0.230	1.157	600-20-70-140	0.320	1.254	600-20-70-170	0.440	1.409
600-20-70-200	0.470	1.287	600-20-70-230	0.540	1.291	600-22-60-140	0.240	0.903	600-22-60-180	0.330	0.960
600-22-60-220	0.430	1.016	600-22-60-260	0.500	0.977	600-22-60-300	0.620	1.047	600-25-50-180	0.280	1.105
600-25-50-240	0.360	0.969	600-25-50-290	0.350	0.761	600-25-50-350	0.470	0.838	600-25-50-400	0.600	0.926
500-20-40-120	0.240	1.024	500-20-40-160	0.330	1.046	500-20-40-190	0.420	1.081	500-20-40-230	0.500	1.057
500-20-40-260	0.600	1.090	500-22-30-160	0.281	1.108	500-22-30-210	0.320	0.937	500-22-30-260	0.430	0.971
500-22-30-310	0.530	0.964	500-22-30-360	0.620	0.957	500-22-60-110	0.210	0.904	500-22-60-150	0.320	1.015
500-22-60-180	0.380	1.022	500-22-60-220	0.450	1.007	500-22-60-250	0.550	1.059	500-25-50-150	0.200	0.791
500-25-50-200	0.340	0.965	500-25-50-240	0.400	0.953	500-25-50-290	0.500	0.983	500-25-50-340	0.620	1.051
600-20-50-130	0.230	0.947	600-20-50-170	0.360	1.066	600-20-50-210	0.440	1.043	600-20-50-240	0.510	1.050
600-20-50-280	0.590	1.026	600-22-40-170	0.280	1.031	600-22-40-220	0.370	0.989	600-22-40-270	0.480	1.013
600-22-40-320	0.550	0.977	600-22-40-370	0.650	0.967	600-22-70-120	0.220	0.907	600-22-70-160	0.300	0.945
600-22-70-200	0.420	1.039	600-22-70-240	0.520	1.078	600-22-70-280	0.600	1.065	600-25-60-170	0.240	0.955
600-25-60-220	0.580	1.633	600-25-60-270	0.410	0.924	600-25-60-320	0.600	1.139	600-25-60-370	0.660	1.069
500-20-50-110	0.220	0.944	500-20-50-140	0.290	0.968	500-20-50-170	0.350	0.973	500-20-50-200	0.450	1.047
500-20-50-230	0.510	1.033	500-22-40-140	0.215	0.898	500-22-40-180	0.320	0.996	500-22-40-220	0.430	1.051
500-22-40-270	0.520	1.032	500-22-40-310	0.600	1.032	500-25-30-200	0.270	0.926	500-25-30-260	0.370	0.929
500-25-30-320	0.460	0.916	500-25-30-380	0.550	0.910	500-25-30-410	0.650	0.988	500-25-60-140	0.220	0.834
500-25-60-180	0.280	0.852	500-25-60-220	0.360	0.899	500-25-60-270	0.410	0.828	500-25-60-310	0.510	0.916
600-20-60-120	0.240	0.947	600-20-60-150	0.320	1.029	600-20-60-190	0.440	1.084	600-20-60-220	0.490	1.056
600-20-60-250	0.550	1.047	600-22-50-150	0.240	0.929	600-22-50-190	0.360	1.043	600-22-50-240	0.440	0.999
600-22-50-280	0.540	1.031	600-22-50-320	0.630	1.043	600-25-40-200	0.310	1.146	600-25-40-270	0.350	0.904
600-25-40-330	0.450	0.925	600-25-40-390	0.560	0.932	600-25-40-450	0.690	0.972	600-25-70-150	0.258	0.931
600-25-70-200	0.320	0.932	600-25-70-250	0.420	0.973	600-25-70-290	0.500	0.998	600-25-70-340	0.590	1.012

5. Conclusions

Herein, pull-out tests on 120 reinforced concrete specimens were conducted, with concrete strength grades being within the range of C30–C70, longitudinal reinforcement performed using HRB500 or HRB600 grade steel bars, and the embedded lengths of the reinforcement with headed bars l_{ae} being within the range of 0.3–0.7 times the basic embedded length l_{ab} . The following conclusions can be obtained by observing the test phenomena and analysing the test data.

1. Different embedded lengths l_{ae} led to varying damage results. For small values of l_{ae} , failure was mainly due to the bearing pressure of the headed bars, resulting in longitudinal cracks throughout the specimen. For large values of l_{ae} , failure was primarily due to reinforcement fracture, and longitudinal crack development was not evident. For moderate values of l_{ae} , the joint action of the bearing pressure of the headed bars and the bond force between the reinforcement and concrete caused

failure, with longitudinal cracks developing along the specimen but not penetrating it entirely.

2. The concept of a nominal average bond stress τ^u was proposed. The correction coefficient γ was introduced to correct the difference between the actual average bond stress τ and the nominal average bond stress τ^u .
3. The correction coefficient γ would increase with an increase in the relative embedded length of the reinforcement l_{ae}/d (on average, 146% higher than the initial value) and decrease with an increase in the f_y/f_t (on average, 33% less than the initial value), with an obvious linear relationship. A formula for γ with l_{ae}/d and f_y/f_t as independent variables was established.
4. A calculation method could be derived for the bond force in straight anchor sections at the yield moment for the reinforcement. A distributive relationship for the anchorage force between the bond force and the bearing pressure was obtained. This enabled the direct and effective consideration and selection of influencing factors such as the dimensions of the headed bars, embedded reinforcement length, and concrete strength grade. Consequently, reinforcement design with headed bars can shift from passive checking to active selection.

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Nomenclature

A_s	Cross-sectional area of the reinforcement, mm ²
c	Distance from the longitudinal reinforcement to the outermost edge of the specimen, mm
d	Diameter of reinforcement, mm
F_b	Bond force between the reinforcement and concrete in the straight anchor section, kN
$F_b/F_{y,8}$	Calculated value using Equation (8)
F_p	Bearing pressure of the headed bars, kN
F_y	Anchorage force of reinforcement, kN
f_{cg}	Strength grade of concrete
$f_{c,m}$	Measured axial values concrete compressive strength, MPa
$f_{t,m}$	Measured axial values concrete tensile strength, MPa
$f_{u,m}$	Measured reinforcement ultimate strength, MPa
f_y	Yield strength of reinforcement, MPa
$f_y A_s$	Yield force of reinforcement, kN
f_y/f_t	Ratio of the yield strength of reinforcement to the tensile strength of concrete
$f_{y,m}$	Measured reinforcement yield strength, MPa
l_{ab}	Basic embedded length of reinforcement, mm
l_{ae}	Embedded length of reinforcement, mm

l_{ae}/d	Relative embedded length
τ^u	Nominal average bond stress, MPa
τ	Actual average bond stress, MPa
γ	Correction coefficient
β	Ratio of the actual embedded length to the basic embedded length
γ_5	Calculated value using Equation (5)
μ	Ratio of the test value to the calculated value γ_5
λ	Ratio of the test value to the calculated value $F_b/F_{y,8}$

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