Research Article

Analysis of Bonding Performance of Grouting Corrugated Pipes in Fabricated Bridge Structures

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Prefabricated bridge structures are highly popularized due to their simple construction, economy, and environmental protection. Relying on the prefabricated prestressed concrete box girder bridge project of Rongwu Expressway Section 6, this research studies the structural mode of grouting bellows and the mechanical properties of joints under different design parameters. The laboratory test was carried out by adjusting the two design parameters of aperture ratio and material properties, and the test data of joint mechanical properties under the influence of different factors were analyzed with the help of grey relational theory. The result goes like this: when the size of the metal bellows is certain, the aperture ratio becomes smaller, the internal space of the specimen becomes smaller, the internal restraint is weakened, and the bonding performance of the reinforcement becomes worse. When D/d = 2.6, the performance of the specimen is better. Comparing the grouting materials with different characteristics, the performance of the metal bellows specimen increases with the enhancement of the properties of the grouting material, but as the aperture ratio becomes smaller, the influence of the grouting material on the performance of the specimen becomes weaker. The comprehensive analysis is carried out with the grey relational theory and the correlation degree of the influence of the two factors on the specimen, and the correlation degrees γ1 = 0.66 and γ2 = 0.67 are obtained. Both of them have a strong correlation with the performance of the specimen, and the degree of influence is roughly similar. Based on the engineering application requirements and related design requirements, the construction method of selecting 100 MPa high-strength grouting material which is higher than the general standard, 65 mm corrugated pipe, and 22 mm steel bar is finally put forward. This research relies on engineering theoretical and experimental studies, which provide important theoretical support and technical guarantee for the research on the joint structure of prefabricated structures.

1. Introduction

The prefabricated bridge structure is widely popularized thanks to its advantages and the strong support of national policies. Compared with the traditional cast-in-place structure, the subsequent pouring joints are the weak links of the structure and have problems of unclear force mechanism, insufficient mechanical properties, poor durability, etc. The key difficulty in the construction of prefabricated bridge structures is the joints connection. Therefore, it is of great significance to research the joints stress mechanism and improve the mechanical properties of joints. There has been research on the bond-slip relationship between reinforcing bar and concrete [1], which inspired researchers to analyze the bond-slip effect between the slurry and the reinforcing bar by grouting the pipes [2], and then established the research basis of the prefabricated structural joints’ structural design [3, 4]. With the popularization of the concept of prefabricated structure, many researchers have carried out a lot of research on the feasibility of the application of grouting joints from the perspectives of material properties and structural forms [5, 6, 7, 8]. A variety of joint construction forms such as reinforcing bar sleeve connection, metal bellows grouting connection, socket type, and slot type are proposed and applied in engineering practice. Based on the feasibility study of joints structure, researchers
have combined theoretical analysis and practice to analyze joints performance by conducting indoor experiments [9, 10, 11], designing full-scale models [12], to evaluate the joints performance under the condition of high temperature environment, repeated loads [15, 16], and other special conditions. In addition, related research is carried out to enhance the bonding performance of reinforcing bars and grouting materials by improving the shear bond [17, 18] and optimizing materials. Metal bellows grouting connection is favored by construction parties and researchers because of its simple construction, low cost, and environmental protection. However, the research on the grouting connection of metal bellows is still in its infancy, and the related research has not revealed the influence of different properties of grouting materials on the structure of metal bellows grouting connection and ignored the restraint effect of metal bellows on the bond between the grouting material and the reinforcing bar. Therefore, further research is necessary. Based on the weak link of grouting connection of metal bellows, this research proposes the following research contents:

1. To change the properties of the grouting material and explore the bonding performance of reinforcing bars under the effects of different grouting materials and the mechanical properties and durability of metal bellows grouting specimens designed with different materials.
2. To change the design parameters of aperture ratio, the internal constraints of the corrugated pipe will change under different aperture ratio designs so as to explore the changes in the bonding performance of the grouting material and the reinforcing bars under different constraints and analyze the impact on the specimen properties under different constraints caused by pouring specimens with different grouting materials.

2. Background

Prefabricated bridges were first popularized and applied in south China. In recent years, prefabricated construction technology has become an important part of the construction of the transportation road network in the northern region under the instruction of the important documents such as “Guiding Opinions of the General Office of the State Council on Vigorously Developing Prefabricated Buildings” and “Guiding Opinions of the Ministry of Transport on Promoting the Construction of Highway Steel Structure Bridges”. With the advancement of major policies such as Xiog’an New Area and low-carbon buildings, the importance of developing prefabricated construction technology is further highlighted.

This study relies on the location of the project, Xiongan, which is located in the core area of Beijing-Tianjin-Hebei. As the core area of my country’s transportation network construction, its operation process mainly reflects the phenomenon of overloading and overspeeding in the northern region. According to the investigation reports, the load of some high-speed vehicles exceeds the specified 10%–35%; the speed of small vehicles is concentrated at 110–125 km/h, and the speed of large trucks is concentrated at 50–80 km/h. Therefore, it is of great significance to improve the engineering quality of prefabricated bridge structures.

This study relies on the ZT6 bid section of the new line of the Rongwu Expressway in the Xiongan New Area from the Beijing-Hong Kong-Macao Expressway to the Beijing-Taiwan Expressway. The starting point of the project is K70 + 146, the endpoint is K82 + 750, and the total length of the whole line is 12.6 km. The bridge in the bidding section adopts a prefabricated prestressed concrete double T-beam bridge, which is a fully prefabricated structure with eight lanes in both directions, a designed speed of 120 km/h, and an integral subgrade width of 42 m. The structural design of the sub-structure joints of the bridge adopts the grouting connection of metal bellows. The specific structure is shown in Figure 1.

3. Experimental Design

3.1. Specimen Structural Design. In this study, the grouting specimen of metal corrugated pipe is designed according to the engineering requirements. The main body of the specimen is composed of three parts: reinforcing bar, grouting material, and corrugated pipe. The reinforcing bar is an HRB400 reinforcing bar with nominal diameters of 20 mm, 22 mm, and 25 mm. The grouting materials are 28d up to 100 MPa high-strength grouting material A, 28d up to 60 MPa high-strength grouting material B, and early-strength grouting material C. The shape of the metal corrugated pipe with an inner diameter of 65 mm is a round steel pipe with closed annular corrugations. The anchorage length of the test piece is 300 mm. The detailed design parameters are shown in Table 1.

The specific structure and molding diagram of the test piece are shown in Figures 2 and 3.

3.2. Specimen Design Scheme. The design parameters of the test pieces are shown in Table 2. The specimen number in the specimen parameter table consists of three parts, which represent the diameter of the reinforcing bar, the diameter of the corrugated pipe, and the type of grouting material, respectively. For example, 20-65-A means that the diameter of the reinforcing bar is 20 mm, the diameter of the corrugated pipe is 65 mm, and the high-strength grouting material A is used to complete the pouring of the specimen. Table 2 is the design parameter table of the specimen. d—the diameter of the steel bar; D—the diameter of the corrugated pipe; l—a—is the anchorage length of the steel bar.

In this study, five specimens were designed under the number of each group of specimens, and the loading test was carried out on a group of five specimens. The maximum and minimum values in the loading results of each group of specimens were removed, and the average value of the remaining three specimens was calculated and avoid the influence of errors caused by external factors as much as possible by designing parallel experiments.
The three different design specimens showed different phenomena after the grouting. The grouting material A showed good fluidity after pouring and gradually formed after 4–5 hours. The grouting material B showed better fluidity in the early stage of pouring, gradually forming after 4–5 hours. The grouting material C had good fluidity in the early stage of pouring, and the temperature of the specimen increased rapidly, resulting in a relatively violent hydration heat reaction.

### 3.3. Loading Scheme Design

In the test, the WAW-2000 microcontrol electrohydraulic servo universal testing machine was used for continuous loading at a loading rate of 200 N/s. The test loading device is shown in Figure 4. During the loading process, the displacement of the marked position of the loading end and the free end before and after the test was recorded, and the average value was taken as the overall displacement of the specimen. During the loading process, the displacement of the marked position of the loading end and the free end before and after the test was recorded, and the average value was taken as the overall displacement of the specimen. At the loading end, the tensile force is read by the universal machine, and data such as control displacement and tensile force are collected at the same frequency simultaneously. The loading device is shown in Figure 4.

### 4. Test Results and Analysis

According to the research, it is expected that the failure modes of the specimens are mainly caused by the crushing of...
grouting material, the breaking of reinforcing bar, and the pulling out of reinforcing bar. In this study, it was determined that the failure modes of the specimens were mainly two types: reinforcing bar tensile failure and reinforcing bar slip failure, accompanied by the phenomenon of grouting material damage. The failure mode of the specimen is shown in Figure 5.

In the initial stage of loading of the specimen, the external force is mainly borne by the bonding force near the loading end. With the change of the loading degree, the force is transmitted to the free end along the anchorage length, and the stress of the steel bar is gradually transmitted from the loading end to the whole specimen [5]. As the bond between the reinforcing bar and the grouting material reaches the limit, the reinforcing bar of the specimen slips and reaches the ultimate failure load of the specimen. The sound of shear failure of the mechanical occlusal teeth between the grouting material and the steel bar forms a smooth and stable slip failure surface between the steel bar and the grouting material, which eventually leads to the failure of the specimen.

The loading test is carried out on the grouting specimen of the metal corrugated pipe. The mechanical properties of the specimen are mainly reflected in the bonding performance of the steel bar and the grouting material under the restraint of the corrugated pipe. Composition, in which the mechanical occlusal force formed by the bonding of steel ribs and grouting material, plays a leading role [9]. The reinforced rib and the grouting material are extruded from each other. The compressive strength of the grouting material C and the grouting material B is the same, but the bonding performance of the poured specimen is much weaker than that of the latter. This is because the early-strength agent is added to the grouting material C. Due to the rapid prototyping of the strength of the specimen, the internal reinforcement of the specimen and the grouting material were not fully engaged, so the mechanical properties of this type of specimen were poor.

Table 3 shows that the performance of the A-type grouting specimens is better than that of the B-type and C-type grouting specimens. Three groups of specimens poured with A-type grouting materials were analyzed, and different aperture ratios had a great influence on the properties of the specimens. Among them, the 22-65-A specimen performed the best in the loading test, with an ultimate bond strength of 11.793 MPa, and the failure load of the specimens can reach 244.518 kN. The failure load of the specimen is close to the load required for the fracture of the reinforcing bar, and the final failure form is the pull-out failure of the reinforcing bar. The metal bellows grouting specimen under this structural design has better mechanical properties.

4.1. Mechanical Performance Analysis of Grouted Corrugated Pipe Connections Based on Different Aperture Ratios. In this section, the effects of different aperture ratios on the mechanical properties of metal bellows grouting specimens are studied. The diameter of the corrugated pipe is 65 mm, and the HRB400 reinforcing bars with nominal diameters of 20 mm, 22 mm, and 25 mm are selected. The effects of different aperture ratio design parameters on the mechanical properties of the specimens are shown in Figure 6.

The test results reflect that only changing the design parameters of the aperture ratio of the specimen, the mechanical properties of the specimens poured with different grouting materials show a similar trend with the change of the aperture ratio. When the anchorage length is constant, the ultimate bond strength increases with the increase of the aperture ratio. When the aperture ratio reaches $D/d = 2.6$, the anchoring performance of the reinforcing bar is optimal.

The analysis shows that the bond strength increases with the increase of the aperture ratio, mainly because the diameter of the reinforcing bar increases, the contact area between the surface of the reinforcing bar and the grouting material increases, and the friction between the two is greatly enhanced. The area of the crescent rib on the side of the reinforcing bar with a larger diameter increases, it is easier to fit with the crescent rib during the grouting process, and the steel crescent rib forms an oblique pressure on the grouting material to improve the bond strength. In addition, with the increase of the diameter of the reinforcing bar, the internal space of the specimen decreases, and the circumferential restraint of the metal bellows increases, which has a strong inhibitory effect on the deformation of the grouting material. The research shows that when the diameter of the metal corrugated pipe is constant, the mechanical properties of the grouting specimen of the metal corrugated pipe are greatly enhanced with the increase of the diameter of the reinforcing bar.
4.2. Mechanical Performance Analysis of Grouting Corrugated Pipe Connections Based on Grouting Materials with Different Characteristics. In this section, the effects of different grouting materials on the mechanical properties of metal bellows grouting specimens are shown in Figure 7, and grouting materials A, B, and C are selected to pour the specimens. The loading result of the specimen is as follows.

The test results reflect that under the condition of a certain aperture ratio, the grouting material C cannot meet the use requirements, and its failure load can only reach 1/2 of the other two types of grouting materials.

The grouting materials A and B can make full use of the performance of the specimens. The mechanical properties and durability of the metal corrugated pipe grouting specimens poured with grouting material A are relatively excellent, but with the decrease of the aperture ratio, the influence of the performance of the grouting material is smaller and smaller. When the aperture ratio D/d = 2.6, the effect of the two types of grouting materials on the properties of the specimen is greatly weakened.

The analysis shows that the failure load of the metal bellows specimen poured with grouting material C is much smaller than that of the other two types of specimens. Due to the incorporation of the early-strength agent, its strength is formed faster, and its faster forming speed makes the grouting material unable to match the reinforcing bar. The fitting is more compact, which leads to the weakening of the mechanical occlusal force between the reinforcing bar and the grouting material, and the bonding performance of the two is greatly reduced, so this type of grouting material is not

Table 3: Test results.

| Specimen number | Failure load, F/kN | Ultimate bond strength, τ_u/MPa | Displacement, s_u/mm | Form of destruction            |
|-----------------|-------------------|--------------------------------|---------------------|--------------------------------|
| 20-65-A         | 228.124           | 12.102                         | 15.2                | Rebar fracture                  |
| 22-65-A         | 244.518           | 11.793                         | 9.0                 |                                |
| 25-65-A         | 254.612           | 10.806                         | 7.8                 |                                |
| 20-65-B         | 215.667           | 11.441                         | 13.4                |                                |
| 22-65-B         | 228.858           | 11.037                         | 11.1                |                                |
| 25-65-B         | 241.116           | 10.233                         | 9.2                 | Pull out to destroy            |
| 20-65-C         | 119.314           | 6.330                          | 8.7                 |                                |
| 22-65-C         | 127.324           | 6.141                          | 8.3                 |                                |
| 25-65-C         | 140.232           | 5.952                          | 7.5                 |                                |

Figure 5: Form of destruction. (a) Test piece pull-out failure diagram. (b) Grout broken diagram. (c) The fracture diagram of the steel bar of the test piece.
suitable for prefabricated structures. The performance of grouting material A is slightly better than that of grouting material B mainly because the strength of grouting material A is better than that of grouting material B. The initial performance of the two is similar, and the structure of grouting material A is more compact after forming. In the actual loading process, the crescent rib squeezes the grouting material obliquely, and the particles inside the grouting material are tightly connected and not dislocated easily, so the performance of the specimen is better.

In addition, the loading data of the specimen is fitted and analyzed, the data before and after yielding of the specimen are fitted, respectively, the intersection of the two fitting curves is the yield point of the specimen, and the displacement and load data at the yield point position are collected. The ratio of the failure load to the yield point load was used as a reference index for evaluating the ductility characteristics of the specimen. Among them, the displacement at the yield point is $s_\text{y}$, the load at the yield point is $F_{\text{y}}$, the displacement of the specimen under the maximum failure load is $s_{\text{max}}$, and the ductility evaluation index $EM = s_{\text{max}}/s_\text{y}$. The collection results are shown in Table 4.

According to the analysis of the data in Table 4, the mechanical properties of the grouting material C pouring specimens are far lower than those of the grouting material A and the grouting material B pouring specimens. The EM value of the grouting specimen A is about 6.5%–10% higher than that of the grouting specimen B, which proves that this type of specimen has better ductility under external action after reaching the yield state, and it is not easy to be damaged. In engineering applications, both safety and stability have excellent performance.

Figure 6: Influence of aperture ratio on specimen properties. (a) Grout A. (b) Grout B. (c) Grout C.
4.3. Grey Correlation Analysis of Ultimate Bond Strength.

In this section, with the help of grey correlation theory, this method analyzes the correlation of influencing factors in the system. In the process of system development, combined with the development trend of the system under the influence of various factors, the influence of different factors on the system is analyzed. The influence of different aperture ratios and material properties on the mechanical properties of metal bellows grouting specimens is analyzed. First, the experimental data is designed for data initialization. The reference sequence failure load is set to $X_0$, the comparison sequence aperture ratio is set as $X_1$, material strength is set to $X_2$. The initial setting results are shown in Table 5.

After completing the data initialization, the calculation of the proximity of the reference sequence and the comparison sequence is performed (that is, to find the absolute value of the difference between the reference sequence and the comparison sequence). The specific calculation formula is

| Specimen number | $F_q$/KN | $s_q$/mm | $s_{\text{max}}$/mm | EM |
|-----------------|---------|---------|-------------------|----|
| 20-65-A         | 165.336 | 21.860  | 21.860            | 1.83|
| 22-65-A         | 124.328 | 25.021  | 25.021            | 1.64|
| 25-65-A         | 83.786  | 26.124  | 26.124            | 1.36|
| 20-65-B         | 191.978 | 20.531  | 20.531            | 1.70|
| 22-65-B         | 191.978 | 23.027  | 23.027            | 1.54|
| 25-65-B         | 66.596  | 22.500  | 22.500            | 1.24|
| 20-65-C         | 208.362 | 18.165  | 18.165            | 1.71|
| 22-65-C         | 210.399 | 20.006  | 20.006            | 1.55|
| 25-65-C         | 86.205  | 11.980  | 11.980            | 1.92|

Figure 7: Influence of material properties on specimen performance. (a) 20 mm diameter steel bar. (b) 22 mm diameter steel bar. (c) 25 mm diameter steel bar.
5. Conclusion

In this study, the factors affecting the performance of metal bellows grouting specimens were studied. The research conclusions are as follows:

1. The size of the metal bellows is constant, the aperture ratio becomes smaller, the internal space of the metal bellows specimen becomes smaller, and the internal restraint effect becomes weaker. When \( D/d = 2.6 \), the performance of the specimen is better.

2. Comparing the grouting materials with different characteristics, when the properties of the grouting material are enhanced, the performance of the metal bellows specimen is enhanced, but as the aperture ratio becomes smaller, the influence of the grouting material on the performance of the specimen becomes weaker.

3. Combined with the grey correlation theory, a comprehensive analysis was carried out, and the correlation degree of the influence of different aperture ratios and material properties on the specimen was studied. The correlation degree caused by the two factors is calculated as \( \gamma_1 = 0.66 \), \( \gamma_2 = 0.67 \). The two design parameters are strongly correlated with the mechanical properties of the specimen, and the degree of influence is roughly similar.

4. Based on the requirements of the engineering application and related design, the construction method of selecting 100 MPa high-strength grouting material, which is higher than the general standard, 65 mm corrugated pipe and 22 mm reinforcing bar is finally proposed. The structural design can maximize the mechanical performance of the joint and maximize the mechanical performance of the joint under the optimal constraint of the metal bellows [13, 14, 9].

Data Availability

This study relies on the prefabricated prestressed concrete box girder bridge project of Rongwu Expressway Section 6. All data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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