

Article

Experimental Study on the Mechanical Properties of Vertical Corrugated Pipe Grout Anchor Connection Joints

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Abstract: Prefabricated buildings' quality, safety, and construction efficiency are closely related to the connections between various prefabricated components. This study optimizes the design of corrugated pipe-restrained grout anchor lap connections, further simplifying the construction methodology while ensuring reliable connection performance. The objective is to achieve cost savings and accelerate construction progress. A pull-out test of this new type of joint is conducted, generating two sets of 17 specimens each. The research examines the effects of grouting material strength, grout anchor steel bar anchorage length, and U-shaped stirrup spacing on the connection performance of corrugated pipe grout anchor connections. The results indicated that the specimens primarily experience two types of failure: anchorage failure with steel bar pull-out and steel bar tensile failure without anchorage failure. The strength of the grouting material and the anchorage length of the grout anchor steel bar positively correlate with bond anchorage performance. U-shaped stirrups contribute to restraint and enhance the bonding force between the corrugated pipe, grouting materials, and the grout anchor steel bar to a certain extent.

Keywords: corrugated pipe; grout anchor connection; prefabricated shear wall; vertical connection



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1. Introduction

In recent years, construction industrialization has emerged as a development trend within the construction industry. Prefabricated structures offer numerous advantages over conventional reinforced concrete structures, such as increased production and construction efficiency, reduced environmental impact, cost savings, and higher resource utilization rates [1]. However, certain drawbacks exist, including limited structural integrity and complex design challenges, which somewhat restrict their practical application [2,3]. Damage and failure in prefabricated structures predominantly occur not in the precast components but in the connection joints between key components. These joints, often termed the “weakest links”, significantly affect the overall performance of the structure [4]. Specifically, the quality of vertical grout anchor steel bar connections has a crucial impact on the overall seismic performance of prefabricated shear walls [5–7]. Therefore, selecting the appropriate connection type and ensuring the performance of joints and connection nodes between components constitute key research and development areas in prefabricated shear wall structures. Sustainable development in the prefabricated construction industry can be advanced via continuous innovation and improved connection technologies.

Existing vertical connection methods for prefabricated shear wall structures primarily include wet and dry connections. Wet connections mainly consist of grouted sleeve connections and restrained grout anchor lap joints [8,9]. Technologies within the restrained grout anchor lap connections include those restrained by spiral stirrups and those designed for prefabricated perforated metal corrugated pipes [10]. The working

principles of restrained grout anchor lap connections and grouted sleeve connections are similar; both transmit force via the bond between the grouting material and the steel bar to achieve joint connection. Even when the bond between the steel bar and the grouting material is compromised, the connection can maintain force transmission via interlocking forces [11,12]. The steel bars' lap length is critical in studying the structural performance of grout anchor lap joint connections.

Given the existing technology in grout anchor lap connections, numerous scholars have sought to enhance its efficacy. Liu et al. [13] introduced plug-in preformed hole grout steel bar lap connection technology in 2009. Subsequently, Jiang et al. [14] conducted a study which included a series of anchorage performance experiments and lap performance experiments employing the grout anchor lap method. Zhi et al. [15] discuss the seismic performance of nine full-scale shear walls, including seven precast specimens and two cast-in-place specimens, and proved that shear walls with metal bellows at the joint have good structural properties. Yu et al. [16] performed incremental tensile load tests on 16 grouted sleeve lap connectors and 3 grouted splice connectors, and it was found that the tensile capacities of the grouted sleeve lapping connectors were up to 2.45 times that of the grouted splice connectors when the sleeve inner surfaces were smooth. All of the grouted sleeve lapping connectors failed via a bar tensile fracture or bar-grout.

On the basis of previous studies, this study introduces a new type of corrugated pipe grout anchor connection technique, as illustrated in Figure 1. Two groups of 17 specimens were made, and the pull-out test on the new type of slurry anchor connection was carried out. The performance of the new type of corrugated pipe grout anchor connection is studied.

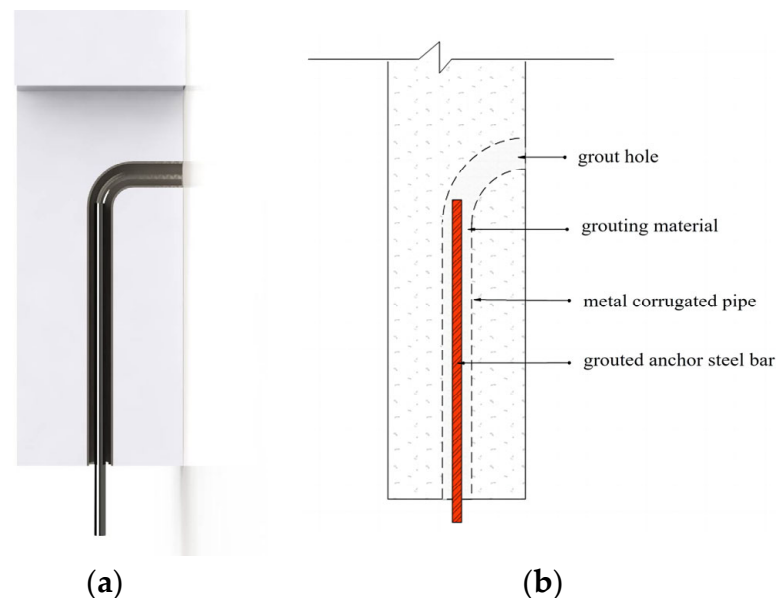


Figure 1. Prefabricated shear wall with the new corrugated pipe grout anchor joint. (a) Perspective view; (b) schematic diagram.

2. Overview of Contact Experiment

2.1. Specimen Design

In order to investigate the connection performance of the novel type of corrugated pipe-restrained grout anchor joint, 17 specimens were designed for pull-out experiments. The cross-sectional dimensions of the design components are $200 \times 200 \times 700$ mm, and the protective layer's thickness is 25 mm.

The main body of each specimen is composed of C30 ordinary concrete, and the corrugated pipe is filled with Wei Lan JW-E1 A, B, and C grouting materials, respectively. The compressive strengths of these three grouting materials are equivalent to those of C40,

C50, and C60 ordinary concrete. The grouting materials produced by Zhengzhou Jingwei Building Materials Technology Co., Ltd. (Zhengzhou, China). Exhibit characteristics such as self-compacting and non-shrinking hardening, meeting the requirements of the experiment. A centrally located steel plate is embedded within each specimen to mitigate eccentricity to ensure that the clamping end steel bars and the grout anchor steel bars are aligned on the same straight line. The vertical steel bars in the main body of the specimen are 4C12, where 4 indicates the number of bars, C indicates that the steel bar is grade 3, 12 indicates the diameter of the bar, and the stirrups are C8@200, where C indicates that the steel bar is grade 3, 12 indicates the diameter of the bar, @200 indicates the spacing of the stirrups. The explanation below is the same. The metal corrugated pipe has a diameter of 40 mm and a height of 600 mm. The anchorage lengths of the grout anchor steel bars are adjusted according to the experimental design, ensuring alignment with the center of the corrugated pipe before injecting the grouting material.

Based on the Chinese code GB 50010-2010 (the Code for Design of Concrete Structures), the basic anchorage length of the steel bar is calculated using the formula $L_{ab} = \alpha \cdot f_y / f_t \cdot d$, where the shape coefficient α for ribbed steel bar is 0.14, f_y is the tensile design strength of the steel bar, f_t is the design tensile strength of concrete, and d is the diameter of the steel bar. The anchorage length is determined by $L_a = k \cdot L_{ab}$, with k is the anchorage length coefficient. For this experiment, values of 0.4, 0.6, 0.8, 1.0, and 1.2 were selected for k . In order to assess the impact of U-shaped stirrups on the joint performance of grout anchor structures, 15 specimens were designed without U-shaped stirrups, while the remaining two included U-shaped stirrups for comparative analysis.

Figure 2 illustrates the construction and dimensions of the specimen. The clamping and grout anchor steel bars are aligned on the same straight line. Displacement gauges W1 and W2 are positioned adjacent to the clamping steel bar, while W3 and W4 are symmetrically arranged on the concrete surface near the grout anchor steel bar. Gauge W5 is placed on the welded steel bar at the interface between the grout anchor steel bar and the concrete. The structural schematic diagram of the center positioning steel plate is shown in Figure 3. The center-positioning steel plate has a thickness of 2 mm, and the steel bars are symmetrically placed on both sides at a spacing of 100 mm. HRB400 C14 steel is employed for the grout anchor steel bars, clamping steel bars, positioning steel plates, and distributed steel bars.

The specific parameters of the specimens in Group A are listed in Table 1. The specimen numbering format in the table employs an “A-B” scheme, where “A” denotes the concrete strength grade corresponding to the grouting material, and “B” signifies the influence coefficient of the basic anchorage length of the grout anchor steel bar. For instance, “50-0.8” is a specimen with grouting material corresponding to concrete strength grade C50 and a basic anchorage length coefficient of 0.8 L_{ab} .

Tests for Group B were designed to explore the impact of U-shaped stirrups on the connection performance of the grout anchor structure using the Group A experiments as a control. The specimens in Group B include U-shaped stirrups, which are uniformly distributed from the bottom to the top on the exterior of the corrugated pipe to provide confinement. The construction and dimensional diagrams of the supplementary specimens in Group B are illustrated in Figure 4. When the spacing of the U-shaped stirrups is either 200 or 400 mm, three or two strain gauges are installed, respectively.

Table 2 details the parameters for each specimen in Group B. The specimen code adopts an “A-B-C” format, where “A” and “B” have the same implications as in the Group A experiments, and “C” indicates the spacing of the U-shaped stirrups. For example, “50-0.8-400” describes a specimen with grouting material corresponding to concrete strength grade C50, a basic anchorage length coefficient of 0.8 L_{ab} , and a U-shaped stirrup spacing of 400 mm.

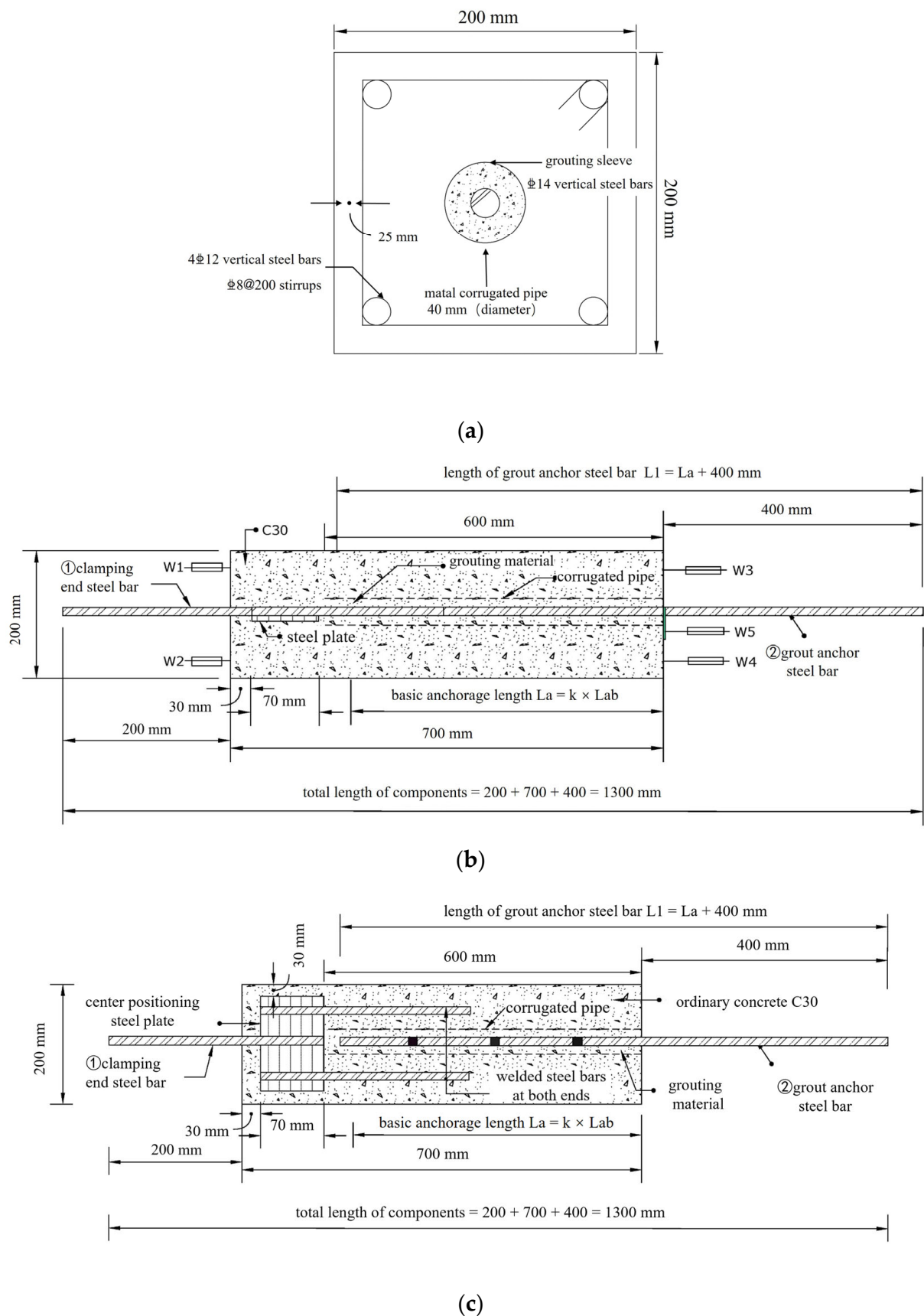


Figure 2. Construction and dimensional scheme of Group A specimens. (a) Cross-sectional view of the specimen; (b) main view of the specimen; (c) top view of the specimen.

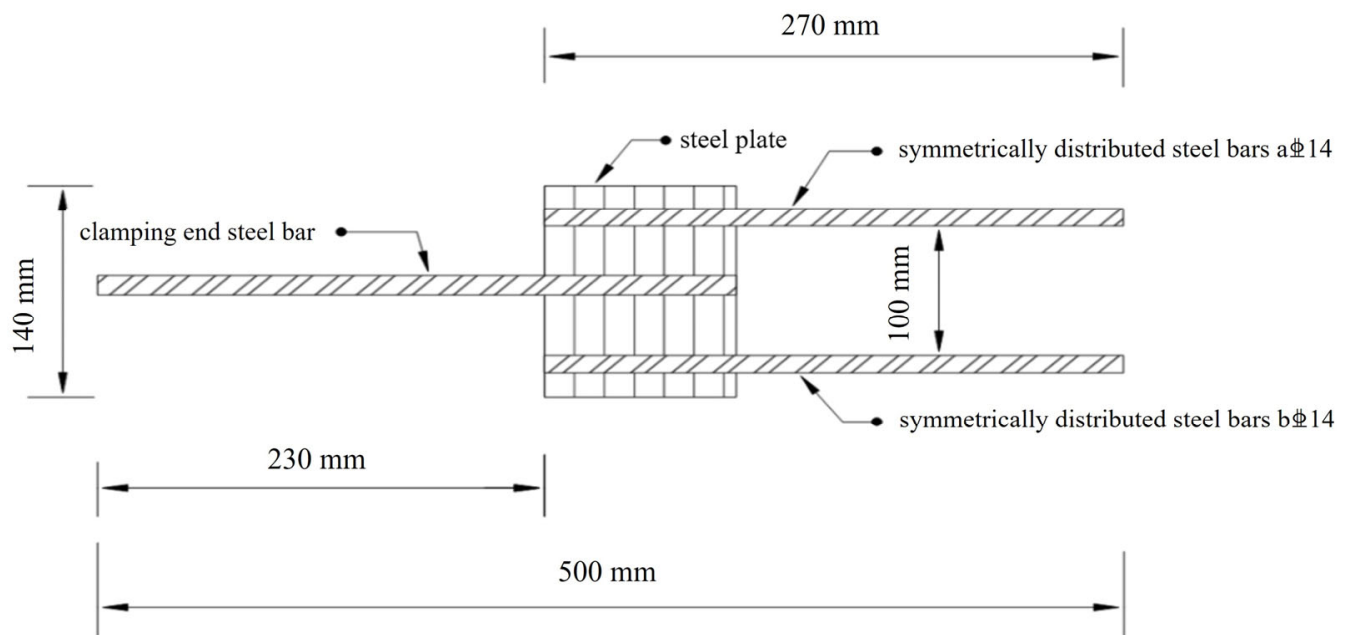


Figure 3. Center-positioning steel plate diagram.

Table 1. Parameters of specimens in Group A.

Specimen Number	Strength Grade of Grouting Material	Anchorage Lengths (mm)	Lengths of Grout Anchor Steel Bar (mm)
40-0.4	C40	165	565
50-0.4	C50	149	549
60-0.4	C60	138	538
40-0.6	C40	248	648
50-0.6	C50	224	624
60-0.6	C60	208	608
40-0.8	C40	330	730
50-0.8	C50	299	699
60-0.8	C60	277	677
40-1.0	C40	413	813
50-1.0	C50	373	773
60-1.0	C60	346	746
40-1.2	C40	495	895
50-1.2	C50	448	848
60-1.2	C60	415	815

Table 2. Parameters of Group B specimens.

Specimen Number	Strength Grade of Grouting Material	Anchorage Lengths (mm)	Spacing of U-Shaped Stirrups (mm)	Lengths of Grout Anchor Steel Bar (mm)
50-0.8-200	C50	299	200	699
50-0.8-400	C50	299	400	699

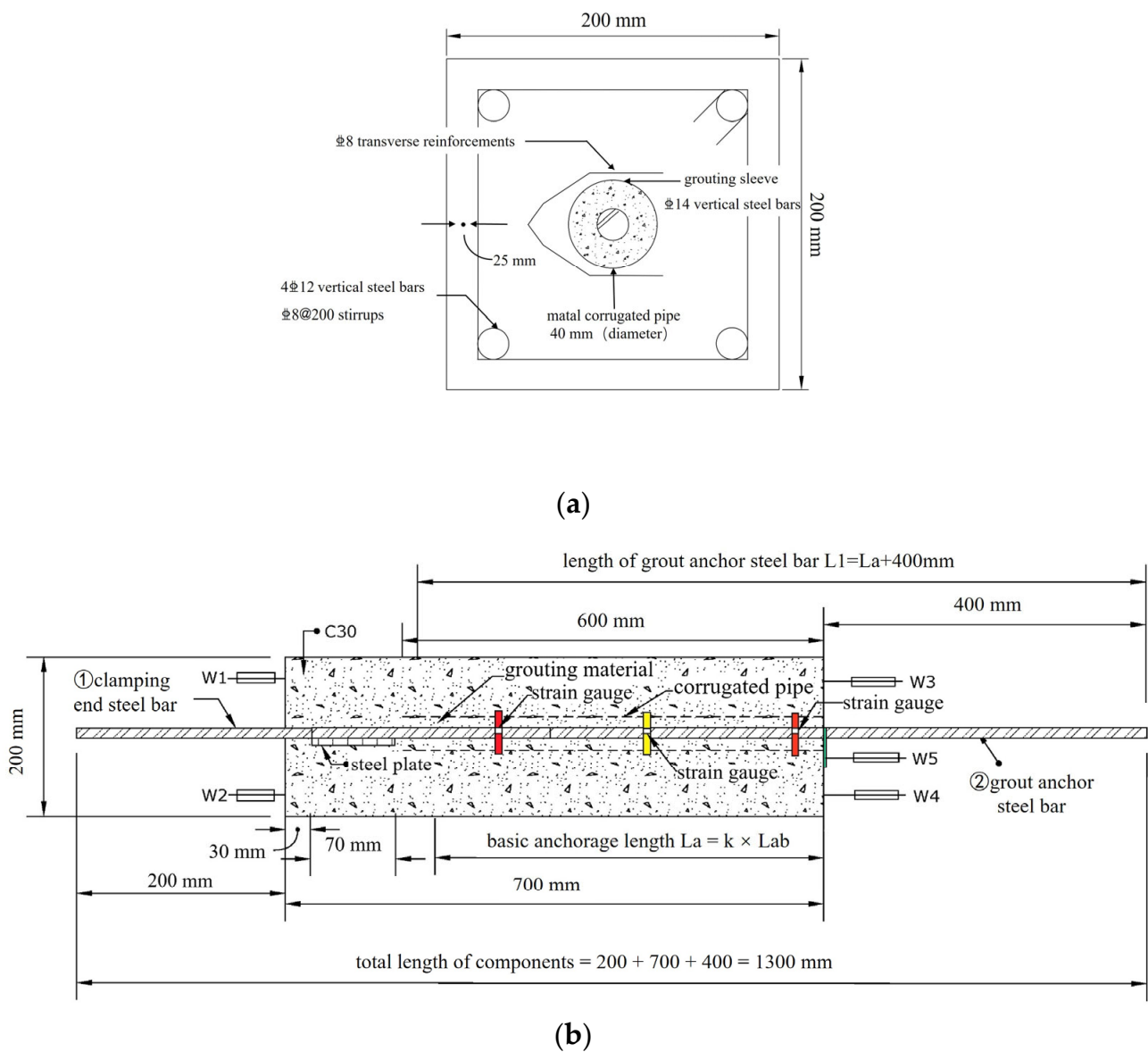


Figure 4. Construction and dimensional scheme of Group B specimens. (a) Cross-sectional view of the specimen; (b) U-shaped stirrup position diagram.

2.2. Material Performance Experiment

HRB400 hot-rolled steel bars with 8 and 14 mm diameters were utilized in this study. According to the metallic materials, tensile test at room temperature standard (GB/T228.1-2010) [17] tensile tests of the steel bars were conducted using a universal testing machine. Table 3 lists material performance parameters.

Table 3. Steel bar parameters.

Steel Bar Diameter (mm)	Yield Strength (MPa)	Ultimate Strength (MPa)	Elastic Modulus (MPa)	Elongation at Break (%)
8	455.53	540.94	1.95×10^5	19.83
14	469.96	637.94	2.05×10^5	21.34

Based on the standard test method for the mechanical properties of ordinary concrete, three standard cubic concrete specimens measuring $150 \times 150 \times 150$ mm were prepared and cured under identical conditions as the test specimens. Material performance tests were performed using a 200-T universal testing machine to ascertain the 28-day compressive strength of the concrete. The results are presented in Table 4.

Table 4. Concrete material properties.

Concrete Grade	Ultimate Pressure (kN)	28-Day Compressive Strength (MPa)	Average Compressive Strength (MPa)
40-0.4	722.69	32.12	33.93
50-0.4	770.12	34.23	
60-0.4	797.63	35.45	

Six standard cubes measuring $150 \times 150 \times 150$ mm were prepared using reserved grouting material and tested for 28-day compressive and splitting tensile properties. Table 5 lists the findings.

Table 5. Parameters of grouting materials.

Specimen Number	Ultimate Pressure (kN)	Compressive Strength (MPa)	Ultimate Tensile Strength (kN)	Split Tensile Strength (MPa)
JW-E1 A	938.48	41.71	95.49	2.70
JW-E1 B	1206.60	53.60	120.80	3.42
JW-E1 C	1453.58	64.60	152.94	4.33

2.3. Specimen Fabrication

The dimensions of the template, metal corrugated pipes, and steel bars are cut and processed based on the design drawings and data specified in the parameter table, utilizing specialized equipment. Skilled professionals process the steel templates and create corresponding holes at both ends. The diameter of these holes exceeds that of the steel bars, allowing the latter to protrude from both ends and ensuring the accurate insertion of the grout anchor steel bars into the centers of the metal corrugated pipes. Based on the design drawings, various components are assembled and positioned. The installation procedure comprises the following steps: Initially, the steel cage is assembled, and the center-positioning steel plate and metal corrugated pipes are placed in the mold. Subsequently, the steel bars are exposed through the holes at one end of the template. Before inserting the components into the mold, the interior of the template is coated with oil to facilitate subsequent demolding. The specimens are labeled before the concrete is poured, and the relative positions of the steel bars, center-positioning steel plate, corrugated pipes, and U-shaped stirrups are verified once more. The specimens are demolded after undergoing standard curing for 7 days and are cured for an additional 21 days before initiating the corrugated pipes' grouting and reinforcement insertion processes. Grouting and grout replenishment are executed using grouting machines, and the ends of the corrugated pipes' grout steel bars are sealed with foam boards to prevent grout leakage while also ensuring accurate positioning of the grout anchor steel bars within the corrugated pipes. Figure 5 illustrates the specimen fabrication process.

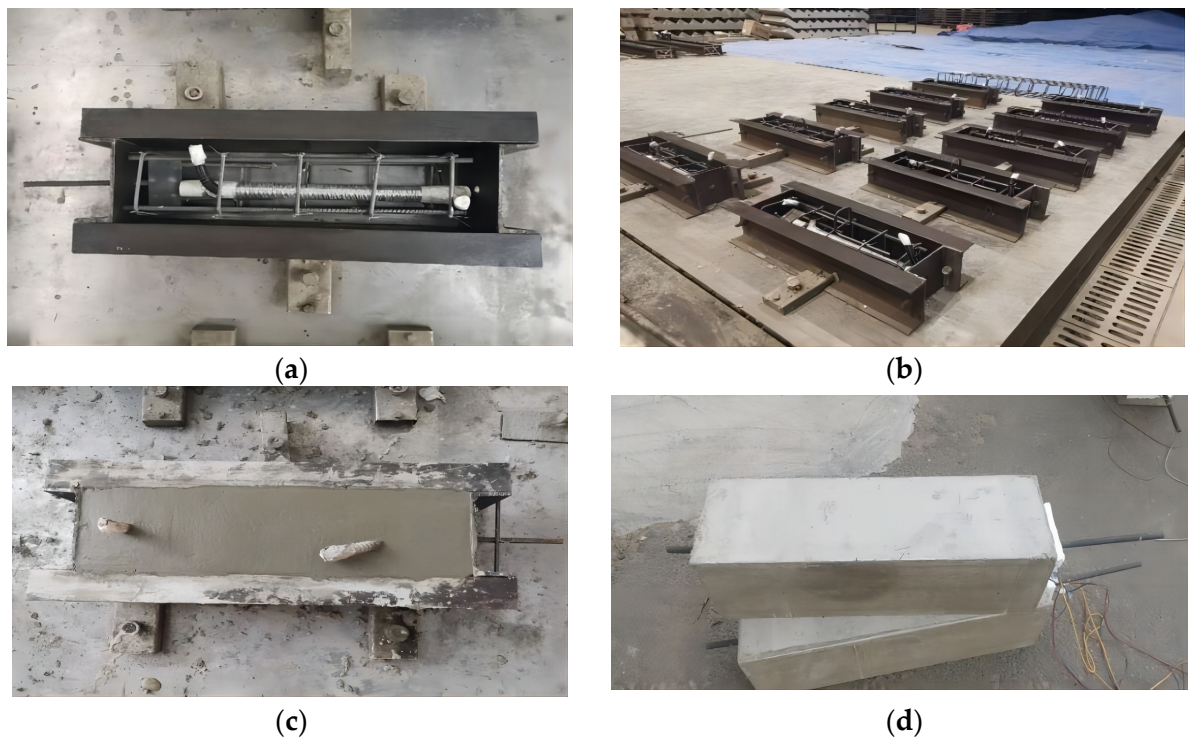


Figure 5. Process diagram of specimen fabrication. (a) Each component is placed into the mold; (b) each component is placed into the mold; (c) concrete pouring; (d) specimen forming.

2.4. Loading Method and Measurement Contents

Strain gauges are placed at four equidistant points along the inserted section of the bars to quantify the strain variation of the grout anchor steel bars during the loading process. After the installation of these gauges, epoxy resin is applied to their outer surfaces for protection. The layout of the strain gauges and the data acquisition system is depicted in Figure 6. Data collected during the experimental loading process primarily include load values, strain values of the grout anchor steel bars, and displacement values obtained from the displacement sensors.

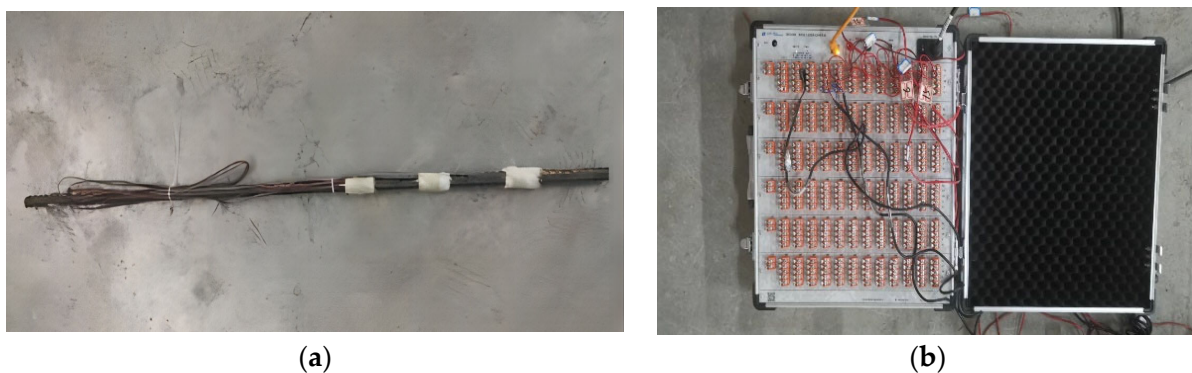


Figure 6. Strain gauge and data acquisition device arrangement. (a) Placement of strain gauges on grout anchor steel bars; (b) strain data acquisition device.

Based on the standard for test methods of concrete structures (GB 50152-2012) [18] and considering the specific conditions of the loading device, the step loading method is selected. Each stage is incremented by 10 kN, and the load is sustained for 30 s at each step until the grout anchor steel bar is extracted, the steel bar experiences tensile failure, or the specimen itself fails, at which point the test concludes. The loading device comprises a 50-T through-heart hydraulic jack and a specialized steel frame. The 50-T through-heart

hydraulic jack incorporates a hydraulic jack, operating lever, and digital pressure gauge. The specialized steel frame comprises four threaded steel columns, pressure-bearing steel plates, and bolts. Figure 7 depicts the loading device.

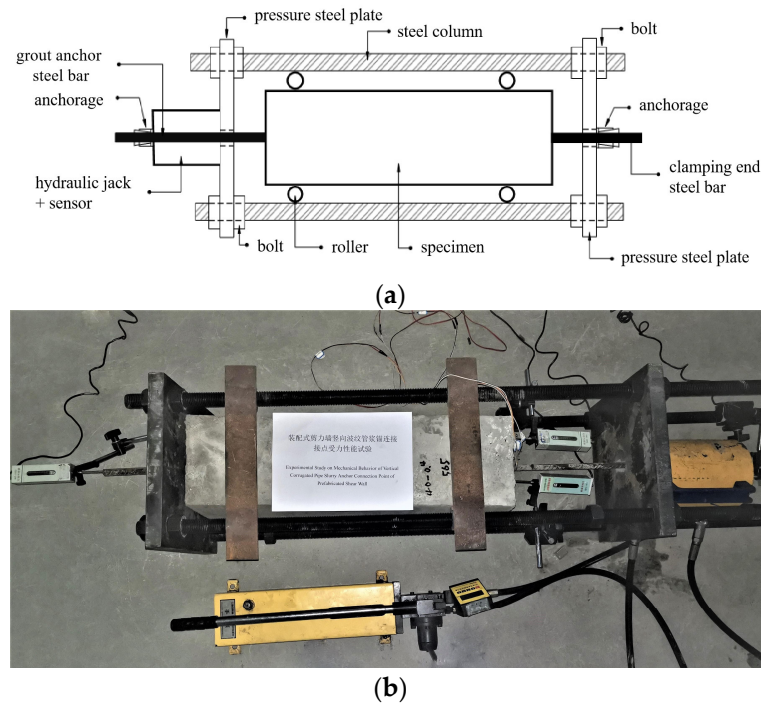


Figure 7. Physical diagram of the loading device. (a) Schematic diagram of the loading device; (b) physical diagram of the loading device.

3. Experimental Phenomena and Results

3.1. Experimental Phenomena

In uniaxial pull-out tests, the failure modes of the specimens primarily encompass bond anchor failure (steel bar pulled out) and anchorage intact (steel bar fracture), as illustrated in Figure 8.



Figure 8. Failure modes of the specimens. (a) Pull-out failure of steel bar; (b) tensile failure of steel bar.

Of the specimens, 11 exhibited bond anchor failure, characterized by the corrugated pipe being pulled out. These specimens had relatively shorter bond anchor lengths and showed no visible cracks on their surfaces throughout the loading process. For the five specimens that utilized high-strength grouting materials with strengths exceeding 60 MPa, slip occurred at the loading end, increasing incrementally with the load. Six specimens with anchor lengths of 0.4 and 0.6 L_{ab} experienced bond failure between the corrugated pipe and the concrete before reaching yield strength. Similarly, five specimens with anchor

lengths of $0.8 L_{ab}$ demonstrated signs of bond failure at the yield stage, accompanied by faint crackling sounds. Continued loading resulted in rapid decreases in load value as the bond anchorage was destroyed, and the corrugated pipe was pulled out, leading to specimen failure. At this point, the specimens displayed no visible cracks and maintained overall integrity.

The failure mode for the six specimens with anchorage lengths of L_{ab} and $1.2 L_{ab}$ was tensile fracture of the steel bar, accompanied by minimal slip. These specimens had larger anchorage lengths and relatively thicker protective layers. No discernible cracks were observed on their surfaces throughout the loading process. All specimens utilized medium- and low-strength grouting materials with strengths below 80 MPa. The slip occurred at the loading end and increased as the load escalated. When the loading value was between 60 and 70 kN, steel bar yielding commenced, accompanied by faint crackling sounds and the onset of bond failure between the corrugated pipe and the concrete. After the steel bar yielding, slip at the loading end primarily resulted from steel bar elongation, with negligible slip at the free end. Upon reaching the ultimate load, the steel bar fractured, culminating in specimen failure. No visible cracks were evident at this stage, and the specimens largely remained intact.

3.2. Experimental Results

Table 6 presents the data for the specimens examined in the experiment. Comparative analysis of the experimental results reveals that when the bonded anchorage lengths of the grout anchor steel bars are L_{ab} and $1.2 L_{ab}$, the failure mode is predominantly steel bar pull-out failure. This occurs even with low- to medium-strength grouting materials equivalent to C40, C50, and C60, corroborating the conclusion that the basic anchorage length prescribed in the code is reasonable. Conversely, when the anchorage length is less than L_{ab} , all specimens, regardless of grouting material strength, experienced slip during loading and exhibited anchorage failure and corrugated pipe pull-out failure before reaching the yield stage. The ultimate load in these cases was significantly lower than that observed with steel bar tensile failure, suggesting that using low-strength grouting materials can compromise the bond anchorage performance in grout anchor connections, thereby failing to meet their performance requirements.

Table 6. Experimental results.

Specimen Number	Yield Load (kN)	Ultimate Load (kN)	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation of Grout Anchored Steel Bar (mm)	Free-End Slip Displacement (mm)	Destruction Mode
40-0.4	—	20.22	—	131.35	14.0	—	anchor failure
40-0.6	—	35.21	—	228.73	15.3	—	anchor failure
40-0.8	62.61	70.32	406.92	456.81	38.7	—	anchor failure
40-1.0	63.23	90.32	410.75	586.73	79.9	3.8	tensile failure
40-1.2	65.95	90.72	428.42	589.33	65.9	1.7	tensile failure
50-0.4	—	20.53	—	133.37	13.1	—	anchor failure
50-0.6	—	35.26	—	229.05	14.0	—	anchor failure
50-0.8	62.45	80.05	405.68	520.01	48.0	—	anchor failure
50-1.0	64.41	90.31	418.42	586.67	82.1	2.7	tensile failure
50-1.2	68.04	90.35	441.99	586.92	59.2	1.8	tensile failure
60-0.4	—	50.22	—	326.24	14.5	—	anchor failure
60-0.6	—	53.21	—	345.66	20.0	—	anchor failure
60-0.8	63.09	80.25	409.84	521.31	47.5	—	anchor failure
60-1.0	67.58	90.33	439.01	586.79	65.1	1.9	tensile failure
60-1.2	69.68	96.05	452.65	623.95	61.6	0.9	tensile failure
50-0.8-200	63.12	83.62	410.03	543.21	48.1	—	anchor failure
50-0.8-400	63.16	84.25	410.29	547.30	47.8	—	anchor failure

4. Analysis of Factors Influencing Anchoring Performance

4.1. Strength of Grouting Material

The load values of steel bars and corresponding elongations were recorded during the testing process with digital pressure and displacement gauges. Subsequently, load-displacement curves were generated. The analysis evaluated the effects of the grouting material strength, bonding length of grout anchor steel bars, and the spacing of U-shaped stirrups on the anchorage performance of the test specimens. Figure 9 illustrates the load-displacement curves for specimens utilizing grouting materials of varying strengths. The following observations were made:

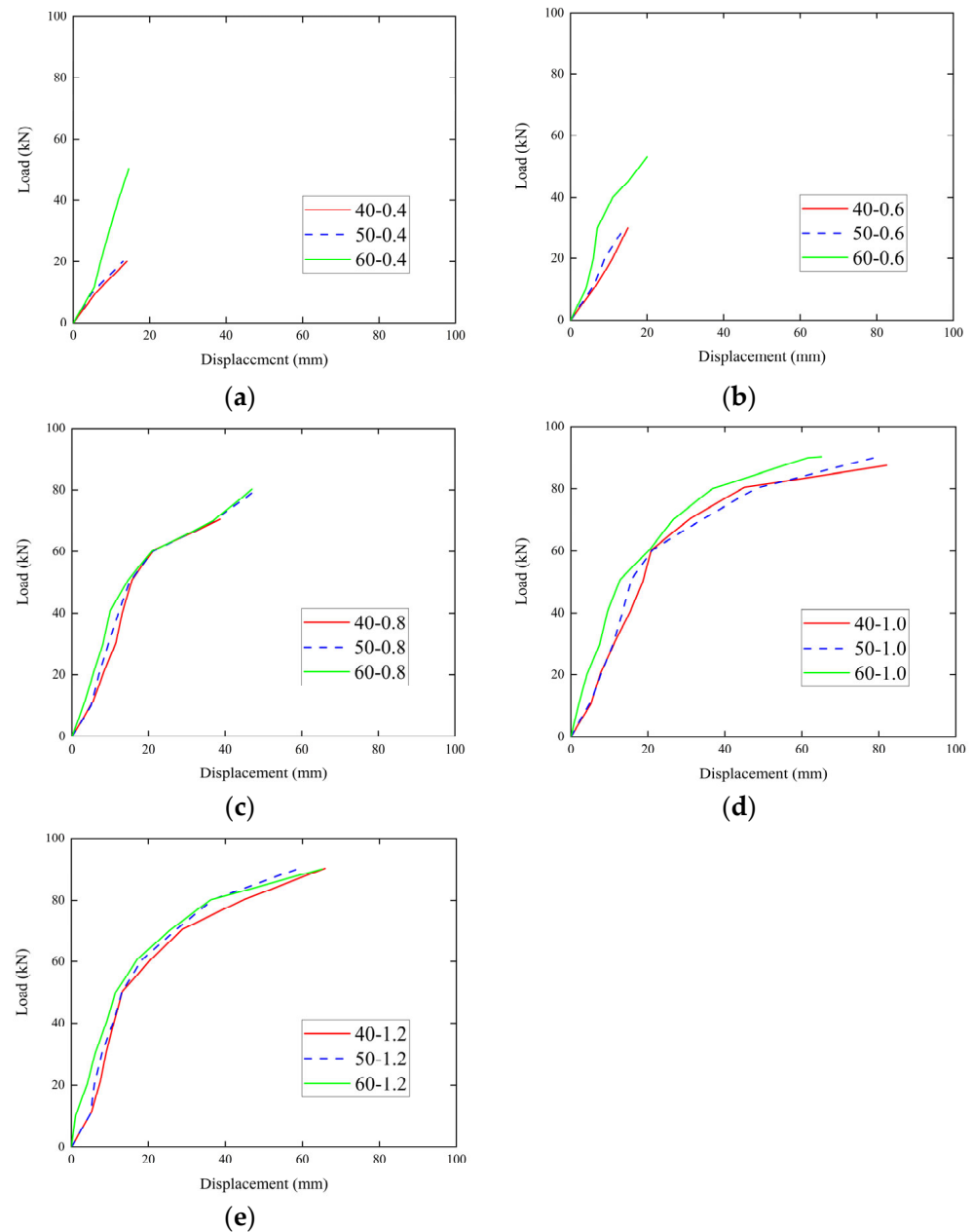


Figure 9. Load-displacement curves of specimens with different strengths of grouting material. (a) Specimen A-0.4; (b) Specimen A-0.6; (c) Specimen A-0.8; (d) Specimen A-1.0; (e) Specimen A-1.2.

(1) The load-displacement curve can generally be segmented into four distinct phases. During the initial loading phase, the specimen remains in an elastic stage, exhibiting an almost linear relationship between load and displacement. As the load increases, the

slope of the curve diminishes, signaling the specimen's transition into the yield stage, characterized by a yield plateau. This yield stage is modulated by the strength of the grouting material and is represented as a slanted straight line, indicative of stable load-bearing performance. Following the plastic deformation in the yield stage, the grout anchor steel bars enter a strengthening stage, where displacement consistently rises as the load intensifies. Upon attaining the ultimate state, the steel bars commence necking, eventually leading to pull-out and the specimen's failure.

(2) The strength of the grouting material exerts a considerable impact on the load-displacement curves. Analysis of results from specimens with anchorage lengths of 0.4 and 0.6 L_{ab} reveals that medium-strength C-type grouting material offers enhanced anchorage performance relative to low-strength A- and B-type materials. Although ultimate displacements across the specimens are essentially uniform, the requisite applied load shows a notable increase. Further comparative analysis of specimens with anchorage lengths of 0.8, 1.0, and 1.2 L_{ab} confirms the persisting influence of grouting material strength. However, as the anchorage length extends, the disparity in the required applied load for equivalent displacement diminishes.

(3) When all other variables remain constant, a higher grouting material strength results in a greater bonding force exerted on the steel bars, thus yielding superior anchorage performance. In addition, a decrease in ultimate displacement is observed when the specimen undergoes failure.

4.2. Anchorage Length of Grout Anchor Steel Bars

Figure 10 compares load-displacement curves for specimens with various anchorage lengths of grout anchor steel bars. The observations are as follows:

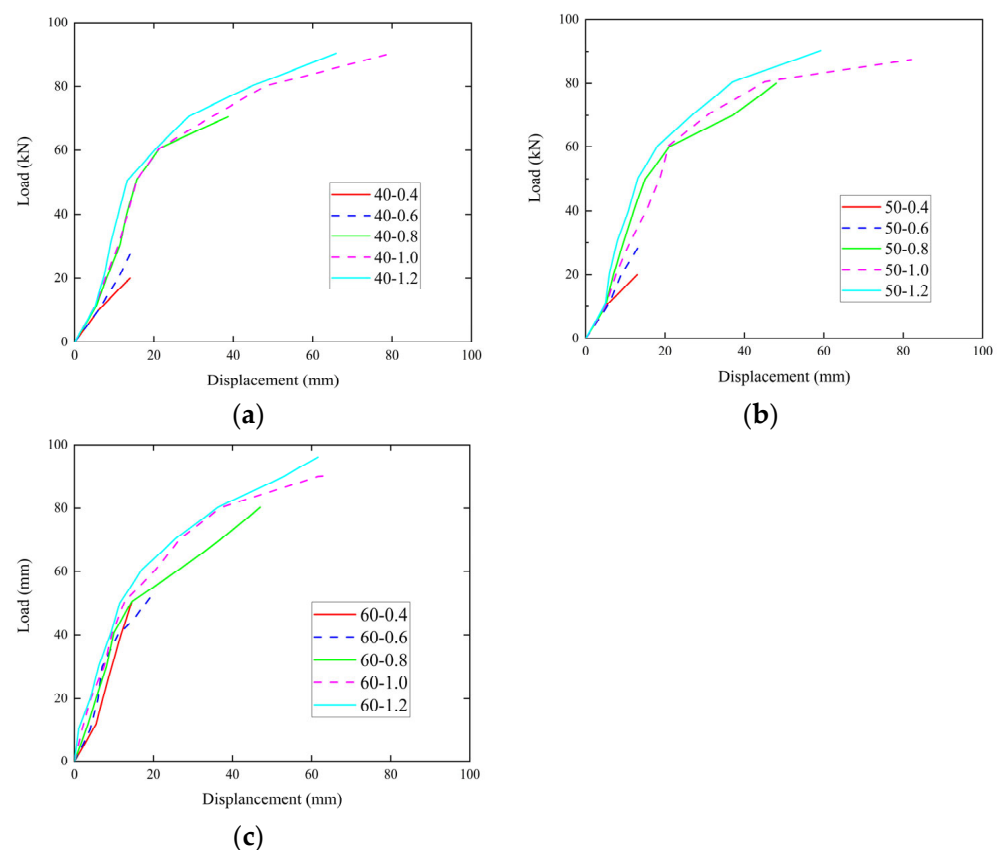


Figure 10. Load-displacement curves of specimens with different anchorage lengths of grout steel bar. (a) Specimen 40-B; (b) Specimen 50-B; (c) Specimen 60-B.

(1) For anchorage lengths of 0.4 and 0.6 L_{ab} , the specimens do not experience a pronounced yield stage; bond anchorage failure occurs prematurely, accompanied by significant steel bar slippage or pull-out. At an anchorage length of 0.8 L_{ab} , bond channel penetration and specimen failure ensue post-yield upon experiencing slippage before reaching the ultimate state. When the anchorage lengths are 1.0 and 1.2 L_{ab} , which meet or exceed the minimum code-specified lengths, the specimens undergo a complete progression of elastic deformation, yielding, strengthening, and steel bar necking. The dominant failure mode is tensile failure, and minimal slippage occurs during failure, indicating enhanced bond anchorage performance.

(2) In the case of the 40-B and 50-B specimens, when the anchorage length is less than or equal to the basic anchorage length, an increase in ultimate load correlates with increased anchorage length, significantly boosting bond anchorage performance. When the anchorage length reaches 1.2 L_{ab} , the ultimate load escalates, but the ultimate displacement at failure diminishes during the late stages of loading, culminating in tensile failure.

4.3. Spacing of U-Shaped Stirrups

Figure 11 displays the load-displacement curves for specimens with varying spacings of U-shaped stirrups. The ultimate states of the three specimens are quite similar, each exhibiting a failure mode characterized by the slippage of the anchor within the corrugated pipe following the yield of the steel bars. Notably, the specimen labeled 50-0.8-200, which contains the greatest number of U-shaped stirrups, necessitates the highest load to attain an equivalent displacement. These observations suggest that U-shaped stirrups can offer a degree of confinement, improving the restraint of the corrugated pipe and grouting material and enhancing the bonding force exerted on the grout steel bars, although the impact is relatively marginal.

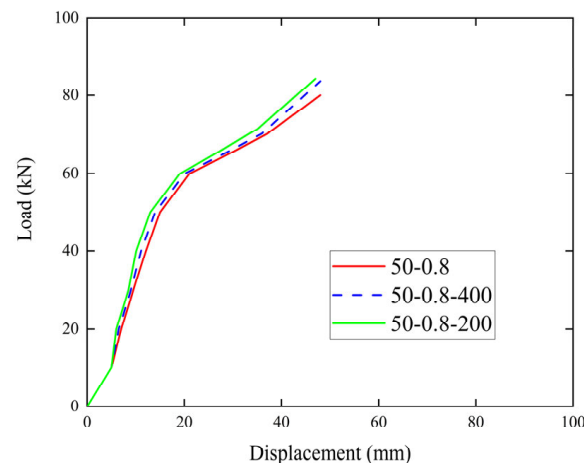


Figure 11. Load-displacement curves of specimens with different spacing of U-shaped stirrups.

5. Discussion

By integrating the technical advantages of both grouted sleeve connections and corrugated pipe grout anchor lap joints, this study introduces a new type of corrugated pipe grout anchor connection technique. It aims to streamline the grout anchor lap joint connection process, targeting cost reductions and expedited construction while maintaining structural seismic performance. Compared to the technique proposed by Liu et al. [13], this approach diminishes the constraint effect of spiral stirrups on the core region's grouting material and the grout anchor steel bars. Consequently, it is preliminarily believed that although the seismic performance and load-bearing capacity experience a slight decrease, this method demands less construction precision and proves more cost-effective. Hence, it is efficient and well-suited for implementation in areas with low seismic activity.

In the fourth section, the research examines the effects of grouting material strength, grout anchor steel bar anchorage length, and U-shaped stirrup spacing on the connection performance of corrugated pipe grout anchor connections. However, due to the limitations of time, manpower, and resources, and for other reasons, only two sets of 17 specimens were made, which may affect the wide applicability of the results; future studies may consider expanding the sample size. In addition, the seismic performance, fatigue performance, sustainability, and other aspects of this new type of corrugated pipe grout anchor connection technique have not been studied and analyzed in this paper; future studies can further discuss these aspects.

6. Conclusions

This study performs an optimized design to simplify construction while maintaining reliable connection performance based on the prevailing form of corrugated pipe-restrained grout anchor lap connections. It conducts mechanical performance tests on the corrugated pipe-restrained grout anchor lap connections to evaluate the influence of grouting material strength, anchorage length, and U-shaped stirrup spacing on grout anchor lap joints' bond strength and failure modes. From the experimental data, several conclusions can be drawn:

(1) The specimens predominantly underwent two failure modes: anchorage failure, characterized by the steel bar being pulled out, and tensile failure, where the steel bar fractured. Specimens experiencing anchorage failure had shorter anchorage lengths; at the time of failure, the grout channel was entirely penetrated, and the corrugated pipe was dislodged. In addition, no noticeable surface cracks were observed, indicating that the specimen's overall integrity was largely preserved. Conversely, specimens experiencing tensile failure of the steel bar had longer anchorage lengths and showed no significant surface cracks, maintaining overall structural integrity.

(2) The bond anchorage performance correlates positively with the strength of the grouting material and the anchorage length of the grout steel bar. Specimens with medium and low-strength grouting materials failed to meet the performance criteria specified. As the strength of the grouting material increased, so did the bonding force of the steel bar, leading to improved bond anchorage performance.

(3) The anchorage length of the grout steel bar markedly influences the specimens' anchorage performance. For a given grout strength, a longer anchorage length results in a higher strain value for the steel bar under identical loads. Once a specimen's anchorage length reaches the basic length stipulated in the relevant codes, it can progress through the complete stages of elasticity, yielding, strengthening, and necking of the steel bar. The failure mode is marked by the tensile failure of the steel bar, indicative of robust bond anchorage performance.

(4) The placement of U-shaped stirrups external to the corrugated pipe augments the confinement effects on the corrugated pipe and the grouting material while modestly enhancing the bonding force on the anchoring reinforcement.

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