Stress Test of Precast Concrete Materials for Prefabricated Buildings by Numerical Analysis

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Abstract. There are serious environmental pollution problems in traditional construction operations. To improve China's construction industry, precast concrete has become one of the important environmental protection materials. Therefore, the stress of precast concrete is deeply analyzed. Based on the numerical analysis, prefabricated concrete buildings and other theories, numerical analysis and finite element method are taken as the research methods to analyze the mechanical properties of precast concrete materials and of steel bars. Finally, the situation and level of the DW1 specimen and DW2 specimen after the influence of the sliding and rotation of the ground beam on the horizontal displacement of the vertex are expounded from various aspects. The research results show that in terms of the mechanical properties of precast concrete materials, the performance data of prefabricated wallboards are all above 37, which is higher than the average strength. In the analysis of mechanical properties of steel bars, the steel bar with a diameter of 8 has a yield strength of 456.4 Mpa, an ultimate strength of 617.3 Mpa, and an elongation of 25.6%. The steel bar with this diameter has the best properties. In DW1 specimen and DW2 specimen, with the continuous progress of the loading process, the overturning moment caused by horizontal loads is also gradually increasing. In the horizontal level of prefabricated building materials, the increase of the axial compression ratio increases the anti-overturning moment of the specimen, and the peak bearing capacity of the specimen increases significantly, but the ductility decreases significantly. In the bearing capacity, there is little difference between the measured bearing capacity and the calculated bearing capacity of each specimen with vertical force applied. Therefore, the force test of precast concrete materials in prefabricated buildings is deeply studied based on numerical analysis, which has an important guiding significance for the construction industry to improve business performance and market competitiveness.

Keywords: Functional materials; Smart materials; Material processing; Material testing.

1. Introduction

In recent years, with the continuous improvement of residents' living standards, more and more people choose green and environmentally friendly materials as building materials, and prefabricated concrete for prefabricated buildings is one of them. Precast concrete is poured elsewhere than at the final construction site. Fibers can be used for precast concrete of different sizes and shapes to enhance its reliability and toughness after cracking. According to the state at the time of production, its production process includes formwork process, flat die process, reverse-strike process, positive-strike process and so on. In addition, the construction industry is also a pillar industry in China's continuous development. The study of the stress of precast concrete materials for prefabricated buildings is also one of the important contents to be considered in the construction industry [1]. Precast concrete refers to concrete from which concrete products are made at a factory or construction site (not the final design location).

Du et al. (2021) conducted a quasi-static analysis of the cast-in-place beam-column and the fabricated integral beam-column specimens according to the beam-column joint connection method of transverse reinforcement welding, and found that the fabricated column with transverse welded reinforcement has good mechanical performance and superior seismic performance [2]. Xiao and Bhola (2021) conducted research on unbonded prestressed fabricated beam-column joints and found that unbonded prestressed always maintained an elastic state during the test, which was conducive to

ensuring the reliability of joint connections and produced large ductile deformation. The deformation and damage of the specimen are mainly concentrated in the beam-column connection, which is beneficial to the realization of post-earthquake repair [3]. Ha et al. (2021) proposed a new type of beam-column joint connection form of prefabricated concrete frame structure by using high-strength bolts to connect the structural steel embedded in the prefabricated beam-column to form "dark corbels". The prefabricated concrete frame joint with high-strength bolt-connected angle steel as the joint energy dissipation element has a shuttle-shaped hysteresis curve and has good plastic ability and deformability. The energy consumed under load is greater than that of cast-in-place joints, and the ductility is higher than that of cast-in-place joints [4]. Liu et al. (2021) pointed out a prefabricated prestressed concrete frame structure joint composed of ordinary steel bars and beam longitudinal bars of prestressed steel bars. The beam ends are provided with steel end plates, and the joint columns are high-strength steel-reinforced concrete columns, with a steel plate hoop. The beam end plate and the column steel plate hoop are connected by high-strength bolts, similar to the end plate bolt joints in the steel structure. This new type of connection "strong column and weak beam" has a full hysteresis curve and good seismic performance [5]. Hawile et al. (2021) used the finite element method to set up contact elements at the beam-column interface. Through numerical simulation, the effect of energy dissipaters with different parameters on the seismic performance of beam-column joints of prefabricated frame structures in the actual application process is analyzed [6].

In summary, firstly, numerical analysis and finite element method are used as research methods to analyze the mechanical properties of precast concrete and of steel bars. Secondly, the test and analysis of the precast concrete materials of the DW1 specimen and the DW2 specimen are carried out. Finally, the horizontal performance of the prefabricated building materials is expounded. The theories and methods of the above-mentioned experts and scholars only study a certain field from a single perspective, and lack a certain comprehensiveness. The innovation is that numerical analysis and finite element method are used as the research methods, and the stress of precast concrete materials is analyzed from various aspects, following the principle of first theory and then analysis. The purpose is to study the stress of prefabricated building materials and provide a methodological reference for promoting the long-term development of the construction industry. The disadvantage is that there is less analysis involved in the cost budget of precast concrete materials.

2. Materials and Methods

2.1 Prefabricated concrete

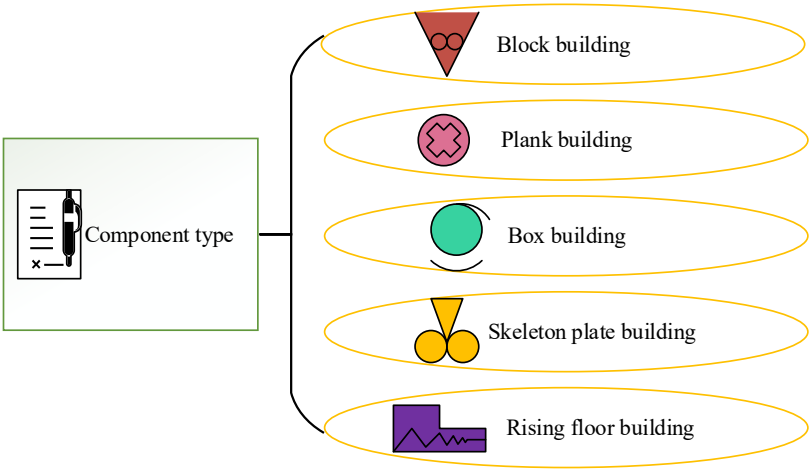


Figure 1. Types of components of prefabricated buildings

Prefabricated buildings refer to the transfer of a large number of on-site operations in traditional construction methods to factories, where building components and accessories (such as floors,

wallboards, stairs, balconies, etc.) are processed and fabricated, and transported to the construction site. Reliable connection methods are assembled and installed in the building in the field [7,8]. Prefabricated buildings mainly include prefabricated concrete structures, steel structures, modern wooden structures, etc. Because of the use of standardized design, factory production, prefabricated construction, information management, and intelligent applications, they are representative of modern industrial production methods [9]. The types of components of prefabricated buildings are mainly composed of the following types, as shown in Figure 1.

The specific characteristics are shown in Figure 2.

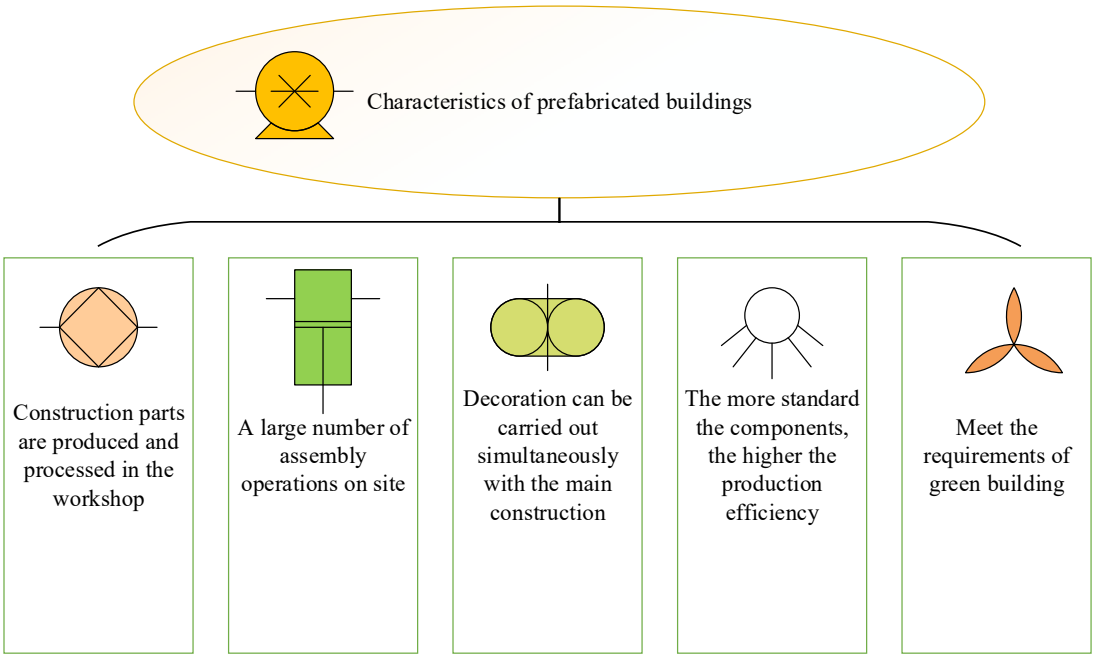


Figure 2. The characteristics of prefabricated buildings

The frame joints of prefabricated concrete require reliable performance, clear force transmission, easy construction, and quality control. To improve the overall seismic performance of prefabricated concrete structures, it can focus on rational design and optimization of the joint structure form [10]. According to whether on-site wet operation is required, the connection methods of prefabricated frame nodes are divided into dry connection and wet connection. Among them, the dry connection is divided into welding connection, prestressed connection, embedded bolt connection, corbel connection (open corbel connection and dark corbel connection), etc. Wet connections mainly include grout-anchor lap joints, sleeve grouting joints, post-cast integral joints, etc. [11,12]. The dry connection of prefabricated concrete frame columns refers to the joint construction form that does not need to pour concrete, directly embeds the connecting parts in the components, and connects by bolts, welding or prestressing. Wet connection refers to the joint method in which prefabricated columns are connected by concrete after pouring concrete at the joints when using steel bars, structural steel or anchoring at the joints. Precast concrete is the basic element of prefabricated buildings and an important part, which runs through the entire project of prefabricated buildings [13].

Besides, prefabricated concrete components refer to reinforced concrete components made by standard industrial production methods in prefabricated component factories, of which the main components are steel bars, concrete and embedded parts. The prefabricated components are produced in the prefabricated components according to the processing drawings given in the current architectural design. Then the designed drawing results are followed by the design and production of the prefabricated component molds, the arrangement and positioning of the steel bars and embedded parts, and the concrete is poured for standard maintenance. Finally, after passing the inspection and

acceptance, it will be transported to the construction site to complete the hoisting. Therefore, the characteristics of prefabricated structures can be summarized as follows: (1) According to the set standard, the production efficiency is relatively high. (2) The standardized process speeds up the operation and construction, and the construction time is shortened to a certain extent. (3) Due to the characteristics of the prefabricated structure itself, the final construction is more beautiful in appearance, so the quality is also passed. (4) Green environmental protection is the goal pursued by the current society. Precast concrete components can save the consumption of steel bars and other materials, thereby reducing the waste of excess materials. In addition, it can also reduce the environmental and noise pollution on the job site. (5) In the production process of prefabricated concrete, a series of standardized operation methods are adopted to reduce the influence of components such as temperature. Precast concrete can be divided into vertical components and transverse components according to the classification of its structure. The specific components of prefabricated concrete are also composed of steel bars, concrete and embedded parts. In prefabricated concrete materials, the detailed design of components is a significant link, and it is also a key stage in the refinement of design drawings, and it is also an intermediate bridge connecting the production stage of design prefabricated components. The stress-strain curve of concrete under uniaxial tension can be determined by the following equations.

$$\sigma = (1 - d_t)\varepsilon_c\varepsilon \tag{1}$$

$$d_t = \begin{cases} 1 - \rho_t[1.2 - 0.2x^5] & x \le 1 \\ 1 - \frac{\rho_t}{\alpha_t(x-1)^{1.7}+x} & x > 1 \end{cases} \tag{2}$$

$$x = \frac{\varepsilon}{\varepsilon_{t,r}} \tag{3}$$

$$\rho_l = \frac{f_{t,r}}{\varepsilon_{t,r}} \tag{4}$$

The stress-strain curve of concrete under uniaxial stress can be determined by the following equations.

$$\sigma = (1 - d_c)E_c\varepsilon \tag{5}$$

$$d_l = \begin{cases} 1 - \frac{\rho_c n}{n-1+x^n} & x \le 1 \\ 1 - \frac{\rho_c}{\alpha_c(x-1)^2+x} & x > 1 \end{cases} \tag{6}$$

$$\rho_c = \frac{f_{c,r}}{E_c\varepsilon_{c,r}} \tag{7}$$

$$n = \frac{E_c\varepsilon_{c,r}}{E_c\varepsilon_{c,r} - f_{c,r}} \tag{8}$$

$$x = \frac{\varepsilon}{\varepsilon_{c,r}} \tag{9}$$

In the above equations, d_t represents the evolution parameter of the concrete under pressure damage. α_t represents the uniaxial stress of the concrete. f_t shows the representative tensile value of the concrete. σ is the uniaxial tensile stress of the concrete. $\varepsilon_c\varepsilon$ expresses the peak tensile strain value of the concrete. x means the type of concrete material, and ρ_t means the strain curve value of the concrete. Equations (1) to (9) describe the algorithms used in the stress test of precast concrete from different perspectives.

2.2 Numerical analysis

Numerical analysis is a branch of mathematics, which is a discipline that studies and analyzes the numerical calculation methods and theories for solving mathematical problems with computers. It takes the theory and method of solving mathematical problems by computer as the research object and is the main part of computational mathematics [14]. The purpose of numerical analysis is to design and analyze some computational methods that can obtain approximate but sufficiently accurate

results for some problems [15,16]. The following are some of the problems that will be addressed using numerical analysis, as shown in Figure 3.

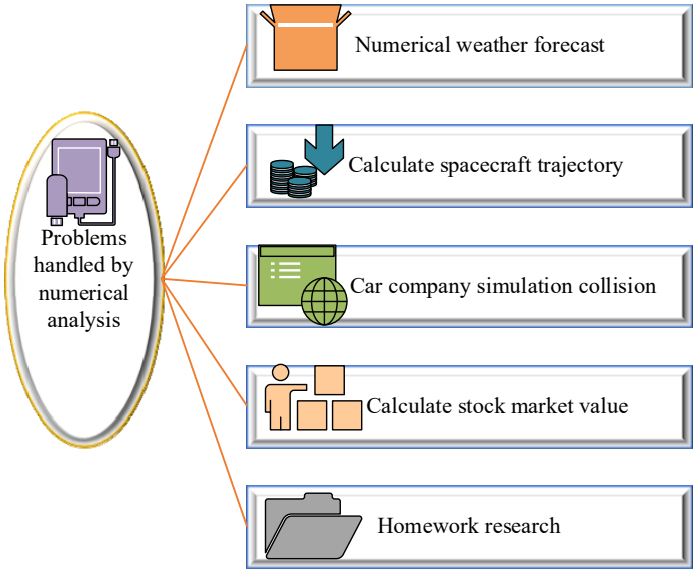


Figure 3. Problems handled by numerical analysis

Error is one of the important topics of numerical analysis, and the formation of error is mainly divided into several different reasons: firstly, the round-off error occurs when the equipment performing numerical analysis can only represent a real number with a finite number of digits [17,18]. Secondly, the discretization error means that when the numerical analysis of the iterative method reaches a certain level, the calculation is terminated, or some approximate mathematical programs are used. If the result obtained by the program is different from the exact solution, a truncation error will occur [19].

Due to the different problems to be solved, the fields involved in the numerical analysis method are also different, and the specific content is shown in Figure 4.

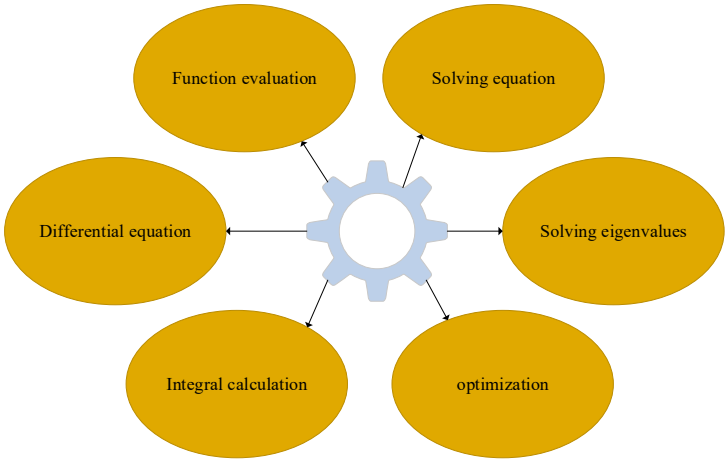


Figure 4. Research of numerical analysis

Besides, the finite element analysis method is also widely used in the analysis of prefabricated joints. The finite element method refers to a numerical technique for the approximate solution of boundary value problems of partial differential equation. When solving, the whole problem area is decomposed, and each sub-area becomes a simple part, and this simple part is called finite element [20,21]. The method uses variational methods to make the error function reach the minimum value and generate a stable solution. Analogous to the idea of connecting several tiny straight lines to

approximate a circle, the finite element method encompasses all possible methods that connect many simple equations over a small area called finite elements and use them to estimate the complexity over a larger area equation. It regards the solution area as consisting of many small interconnected sub-areas called finite elements, assumes a suitable or relatively simple approximate solution for each element. And then derives and solves the overall satisfying conditions of the area, such as the equilibrium conditions of the structure, etc., to obtain the solution of the problem [22]. This solution is not an exact solution, but an approximate solution because the actual problem is replaced by a simpler problem. Since most practical problems are difficult to obtain accurate solutions, however, finite element not only has high calculation accuracy, but also can adapt to various complex shapes, so it has become an effective engineering analysis method [23].

3. Results and Analysis

3.1 Design of the experimental environment

To analyze the stress of prefabricated concrete materials for prefabricated buildings, 4 pieces of prefabricated concrete material specimens are compared with 1 piece of full-scale cast-in-place shear wall specimens. The basic conditions of the specimens are shown in Table 1.

Table 1. The basic conditions of the specimens

Test piece No	Wall length	Wall height	Wall thickness	Axial compression ratio
XW	1510	1750	100	0.0
DW1	1530	1800	100	0.0
DW2	1550	1850	100	0.1
DW3	1570	1900	100	0.15
DW4	1590	1950	100	0.25

Four pieces of precast concrete material specimens are compared with one piece of full-scale cast-in-place shear wall specimens. Table 1 mainly introduces the length, height, thickness and axis compression ratio of the wall. Except the thickness of the wall is the same, other values are increased in a certain proportion.

3.2 Mechanical analysis of prefabricated concrete materials

According to the experimental environment designed above, the finite element and numerical analysis methods are used to analyze the mechanical situation of prefabricated concrete materials for prefabricated buildings. The specific situation is shown in Figure 5.

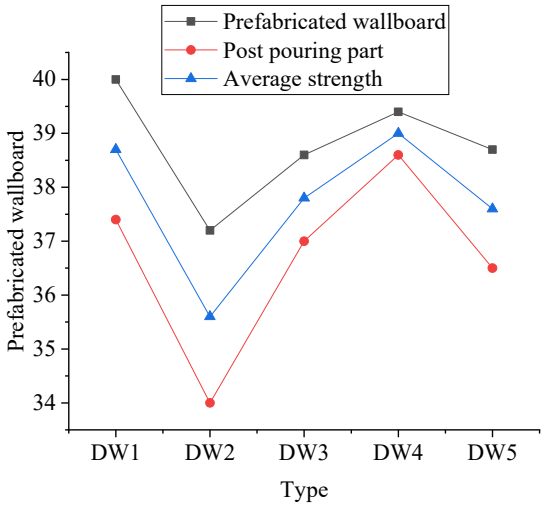


Figure 5. Mechanical analysis of prefabricated concrete materials

Figure 5 shows that the mechanical properties of prefabricated concrete with different numbers are different. The performance of the prefabricated wallboard with the specimen number DW1 is 40, the post-cast part is 37.4, and the average strength is 38.7. The performance of the prefabricated wallboard with specimen number DW2 is 37.2, the post-cast part is 34, and the average strength is 35.6. DW3 has prefabricated wallboard of 38.6, a post-cast section of 37, and an average strength of 37.8. DW4 has prefabricated wallboard of 39.4, a post-cast section of 38.6 and an average strength of 39. DW5 has 38.7 for prefabricated wallboards, 36.5 for post-cast sections, and an average strength of 37.6. From these data, it can be found that the performance of the prefabricated wallboard, the post-cast part and the average strength is not much different to a certain extent. Compared with the three data, the performance data of the prefabricated wallboard is the highest, followed by the average strength and finally the post-cast part.

Moreover, the mechanical properties of the steel bars of the prefabricated concrete material of the prefabricated building are shown in Figure 6.

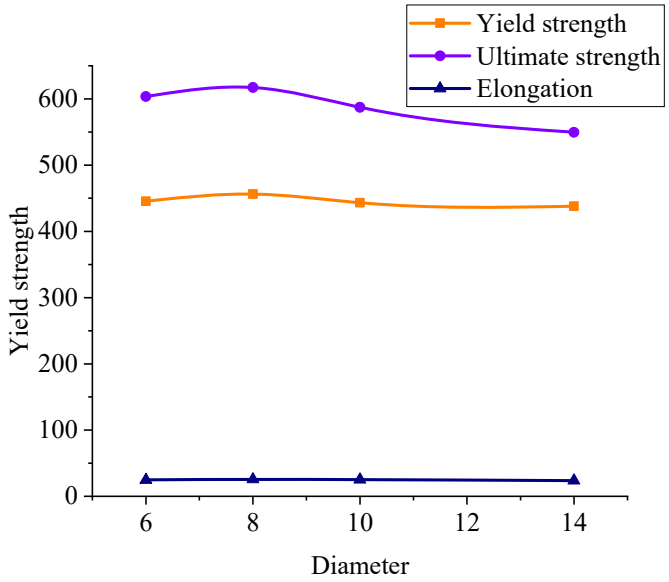


Figure 6. Analysis of the mechanical properties of the steel bars of the prefabricated concrete

Figure 6 indicates that in the analysis of the mechanical properties of the steel bars of prefabricated concrete, when the diameter is 6, the yield strength is 445.5Mpa, the ultimate strength is 603.7Mpa, and the elongation is 24.8%. When the diameter is 8, the yield strength is 456.4 Mpa, the ultimate strength is 617.3Mpa, the elongation is 25.6%. When the diameter is 10, the ultimate strength is 443.2Mpa, the ultimate strength is 587.2Mpa, and the elongation is 25.2%. When the diameter is 14, the yield strength is 438.1Mpa, the ultimate strength is 549.6Mpa, and the elongation is 23.8%. It can be seen from the above data that among the different diameters of steel bar, the bar with a diameter of 8 has the highest yield strength, ultimate strength and elongation, followed by the bar with a diameter of 6, with a diameter of 10, and finally the bar with a diameter of 14.

3.3 Analysis of stress test of prefabricated concrete materials

After the influence of the sliding and rotation of the ground beam on the horizontal displacement of the vertex, the stress of the precast concrete material is processed and analyzed through the experimental data according to the finite element analysis method. The specific results are shown in Figure 7.

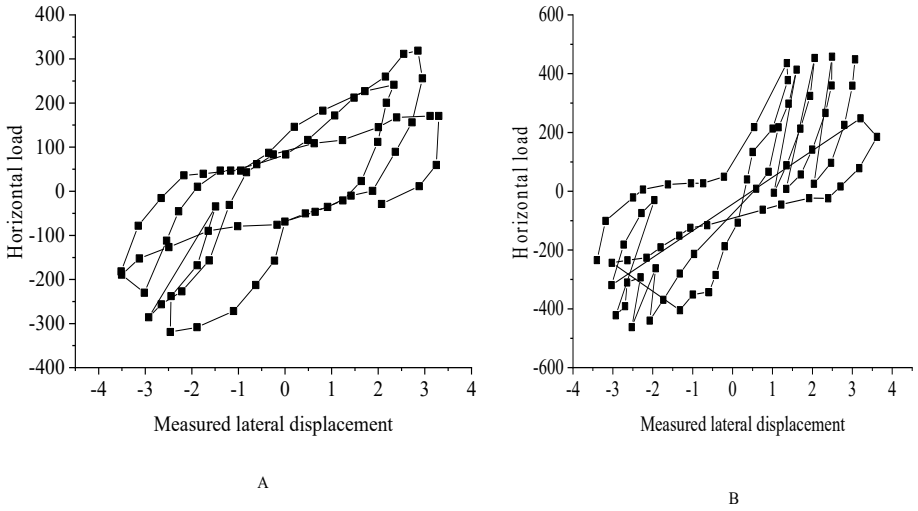


Figure 7. The stress of the precast concrete material (A shows the stress test of DW1. B means the stress test of DW2)

Figure 7 (A) shows the stress test of DW1. Figure 7 (B) means the stress test of DW2. Figure 7 indicates that in the initial stage of the test loading of the DW1 specimen, the prefabricated concrete wall of the prefabricated building has not yet developed cracks. The hysteresis curve is still presented in the form of a straight line, but the area enclosed by the hysteresis loop is not large. It can basically return to the origin of the coordinates, and the residual deformation is extremely small. At this time, the wall is in the elastic working stage. With the continuous advancement of the loading process, the overturning moment caused by the horizontal load is also gradually increasing. Horizontal cracks appear in the middle and lower parts of the edge members of the specimen. The hysteresis curve is inclined to the horizontal axis. After unloading, there is residual deformation, and the area of the hysteresis loop is slightly increased. The energy dissipation capacity is limited. The shape of the hysteresis loop in specimen DW2 is closer to that of specimen DW1. Before the specimen cracks, the hysteresis curve is basically presented in the form of a straight line, and the area of the hysteresis curve is not large. As the loading progresses, horizontal cracks appear in the lower part of the edge member of the specimen, and the area of the hysteresis loop increases slightly.

From the perspective of the level of prefabricated building materials, the specific situation of DW1 and DW2 is shown in Figure 8.

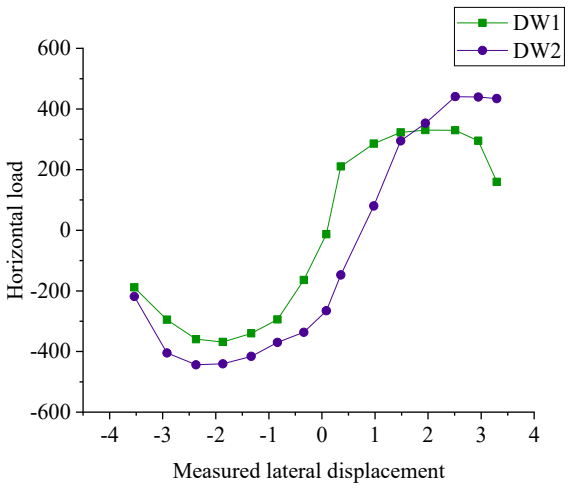


Figure 8. Horizontal stress of fabricated concrete material

Figure 8 expresses that in the initial stage of loading of the prefabricated building, the skeleton curves of all the specimens are basically straight lines, and the initial stiffness of the specimens is relatively large. With the deepening of the loading, the skeleton curve of each specimen begins to bend toward the horizontal axis, and the growth rate of horizontal load gradually decreases. Because the integrity of the cast-in-place specimen is better than that of the new prefabricated double-sided superimposed shear wall specimen, the peak bearing capacity is reached earlier, and the horizontal bearing capacity is the lowest, showing a certain brittleness. However, the new prefabricated double-sided composite shear wall specimen has a slightly higher horizontal bearing capacity than the full cast-in-place specimen due to the restraint effect of the prefabricated concrete wallboards on both sides of the internal cast-in-place concrete. The increase of the axial compression ratio increases the anti-overturning moment of the specimen, and the peak bearing capacity of the specimen increases significantly, but the ductility decreases significantly.

Finally, in terms of bearing capacity, the performance of prefabricated concrete for prefabricated buildings is shown in Figure 9.

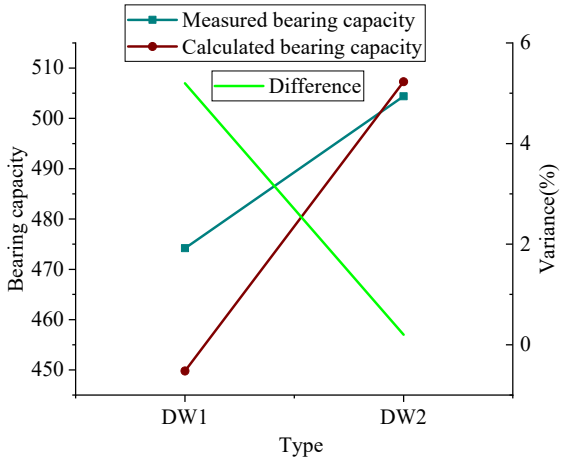


Figure 9. Bearing capacity of prefabricated concrete of prefabricated buildings

Figure 9 shows that the measured bearing capacity of each specimen with vertical force is not much different from the calculated bearing capacity, and the measured bearing capacity is greater than the theoretical calculation value. The reason is that the existence of vertical force delays the cracking of the shear wall, and the friction force on the crack surface also increases, which improves the bearing capacity of the specimen. Considering that there is a gap between the prefabricated concrete wallboard and the cast-in-place concrete, sliding between the two parts is easy to occur, which weakens the integrity of the specimen. It is suggested that the effect of axial pressure to improve the shear bearing capacity of the new prefabricated double-sided superimposed shear wall should not be considered in the design.

4. Conclusion

With the continuous improvement of science and technology, people pay more and more attention to the development of prefabricated buildings. Numerical analysis and finite element methods are used to analyze the stress of precast concrete materials in prefabricated buildings, and the following conclusions are drawn: The performance of precast wallboards, post-cast parts and the average strength is not much different to a certain extent. Compared with the three data, the performance data of precast wallboards is the highest. In the mechanical analysis of steel bars, among different steel bar diameters, the yield strength, ultimate strength, and elongation of steel bars with a diameter of 8 are the highest. In terms of bearing capacity, the measured bearing capacity of each specimen with vertical force is not much different from the calculated bearing capacity, and the measured bearing capacity is greater than the theoretical calculation value.

Due to the limited ability, there are certain limitations in data acquisition, resulting in some deviations in some tests of related data. There is also a numerical analysis-based study on the mechanical testing and analysis of precast concrete materials for prefabricated buildings, but the economic cost of investment has not been discussed. The subsequent benefit evaluation can be carried out according to specific conditions. In the future, the development of prefabricated buildings can bring the correct path to a certain extent

Acknowledgments

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