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# Establishing Connection Methods for Precast Concrete Shear Wall

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## Abstract:

Following rapid economic development, many countries have realized the necessity for the development of prefabricated construction. Therefore, it is predicted that the development of prefabricated concrete structure has become an increasingly important domain. In practical applications, the connection construction of precast components is complex, which is reflected in the need to pour concrete or grouting at the joint. Owning to that, the prefabricated concrete structure still belongs to the assembly monolithic structure to a large extent. Low assembly rate and high cost, both factors found to limit the prefabricated concrete structure, are important factors in widespread promotion. In addition, the prefabricated concrete shear wall structure is an important part of the prefabricated concrete structure, with good structural integrity and high rigidity at the joint region. However, for fabricated concrete shear wall structures, the wall structure is usually prefabricated in the factory, which not only resulted in transportation problems, and also difficulties pertaining to the construction standardization. Without doubt, it is imperative to study the prefabricated concrete structure with lower cost, simpler structure, convenient connection and good comprehensive performance, so as to promote the development of residential industrialization. Undoubtedly, reinforcement connection technology is one of the key technologies of prefabricated concrete structure. The joint is often the weakest link of the whole structure. The reliable connection between the prefabricated components can effectively guarantee the integrity and seismic performance of the structure. This paper shed some light on the precast concrete shear wall common connection methods.

*Keywords* — **Housing industrialization; Fabricated concrete structure; Shear wall; Connection methods**

## I. INTRODUCTION

The definition of prefabricated concrete structure is a concrete structure in which the structural components are prefabricated in the factory, and the prefabricated components are then installed on-site and cast-in-place at the joints [1]. Compared with traditional cast-in-place concrete structures, the advantages of prefabricated concrete structures are: less wet operation on site, less energy consumption, fast construction speed, easy quality control, clean construction environment, and fewer concrete shrinkage cracks [2]. Therefore, the popularization and application of prefabricated concrete structures are conducive to the promotion of residential industrialization and the development of building energy saving and emission reduction technologies. On top of that, it plays an important role in building a resource-saving and environment-friendly society. Developed countries such as Europe and the United States have gradually paid attention to the promotion of prefabricated buildings since the late 1940s. At present, these countries have also formed a relatively complete technical system and promulgated relevant technical regulations for prefabricated concrete structures. [3]

Rebar connection technology is one of the key technologies of precast concrete structures. The connection of the structure is often weak and the reliable connection between the prefabricated components can effectively ensure the integrity and seismic performance of the structure [4]. The connection methods of precast shear walls are predominantly divided into wet connection and dry connection. Wet connection is to first weld or mechanically connect the prefabricated steel bars, and then concrete is poured at the joints in order to connect the prefabricated components together.

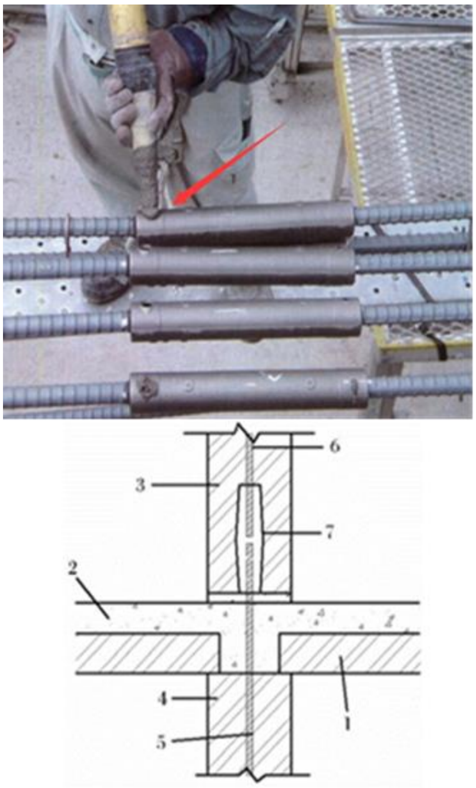
## II. CONNECTION METHODS

### WET CONNECTIONS

#### A. *Sleeve grouting connection*

The sleeve grouting connection technology is to insert prefabricated steel bars into a steel sleeve, and then pour high-strength grout into the sleeve. After the grouting material is hardened, the prefabricated steel bars at both ends and the steel sleeve are firmly connected together, thereby causing the stress of the steel bars to become effectively transferred through the bonding, friction and bite force between the steel bar and the grouting material. Tongue and groove in the sleeve and shear keys can effectively increase the adhesion between the grout and the cylinder wall, which is crucial with regards to slippage damage prevention. Sleeve grouting connection can be prefabricated in the factory to simplify the construction process, but the relatively high cost of the sleeve, high requirements for processing accuracy, and high processing difficulty have also restricted its usage spectrum in engineering [5].

The following figures demonstrate the sleeve grouting connection.




1-Precast slab; 2-Cast-in-place layer of the laminated slab; 3-Upper shear wall; 4-Lower shear wall; 5-Connected steel bar; 6-Embedded steel bars; 7-Sleeve

Fig. 1 Sleeve grouting connection

*B. Grouting-anchoring overlap connection*

The grout-anchor lap connection technology is a prefabricated hole in the shear wall with a rough surface. The embedded steel bars are located in the concrete outside of the hole wall. The insert connecting the shear wall is placed in the hole followed by pouring of high-strength grouting into the hole. The stress of the steel bar is transmitted through the bonding force and occlusion of the grout, the steel bar, and the hole made in the wall. Setting up spiral stirrups in the lap height range of steel bars can enhance the restraint on the cross-sectional deformation of concrete in order to prevent cracks in the concrete in the anchoring area, thereby improving the force performance of the nodes.

*C. Keyway connection*

Keyway connections are commonly used in fabricated slab structures [6]. The joints of prefabricated wall slabs are equipped with various keyways with uniform layout and regular keyways. The adjacent wall slabs are locked together by keyways, and concrete is poured during the occlusion. As shown in figure 2, the slab to beam connection, the steel reinforcing bars are inserted into the slab keyways to span the joint. The prefabricated components are connected as a whole, and the size and arrangement density of the keyway have a great influence on the reliability of the connection.

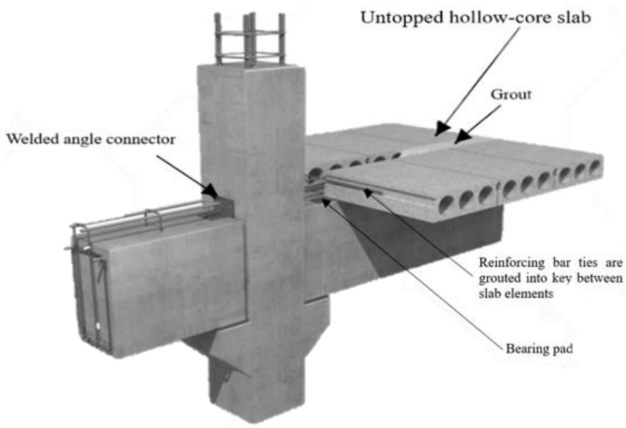



Fig. 2 Slab to beam connection

## DRY CONNECTIONS

*A. Mechanical Connection*

The mechanical connection technology works with the principle of steel bars connecting the upper and lower wall slabs, which are then connected by metal connectors, following that, the connectors can effectively transmit the stress of the steel bars through mechanical occlusion. Mechanical connection advantages are attributed to its short construction period and high industrialization precision, which causes it to be classified under wet connection.

Fig. 3 Mechanical Connection

*B. Unbonded post-tensioned prestressed connection*

The unbonded post-tensioned prestress connection technology is to connect the vertical wall slabs together through the unbonded post-tensioned pre-stressed bars. This connection method can concentrate the plastic deformation at the joints of the wall slabs, and the deformation of the rest of the structure is basically maintained within the elastic range, which is easier to repair compared to the traditional cast-in-place structure [7]. The prestressed tendons have self-healing properties, which can reduce the residual deformation of the structure after the earthquake.

*C. Tongue and groove connection*

The tongue-and-groove connection refers to the connection method of the beam and column in the fabricated concrete frame structure, which causes the steel plate to become embedded at the end of the shear wall, and ultimately resulting the shear wall panel with concave and convex notches to be welded together [8].

*D. Wall Shoes connection [9]*

The Wall Shoes connection technology is similar to the bolted connection. Firstly, insert the lower pre-embedded steel bars into the Wall Shoes connector of the upper prefabricated wall; secondly, anchor the bottom plate of the connector with bolts, and last but not least, pour concrete into the joints and connectors. In this way, the shear wall is connected as a whole. This connection method is convenient, quick to operate and easy to install.

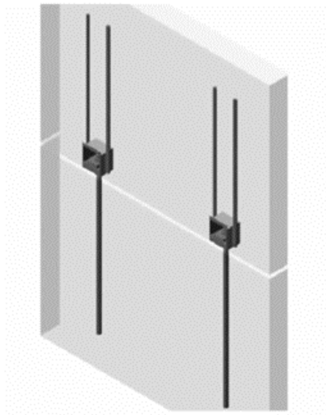


Fig. 4 Wall Shoe Connection

*E. Bolted connection*

Bolted connection refers to the method of connecting prefabricated walls as a whole by ordinary bolts or high-strength bolts. The bolted connection structure is convenient and easy to operate. Nonetheless, it requires high accuracy and has certain problems. For example, the bolts may become loose, rusty and corrode under the influence of long-term load and harsh environment, which is extremely detrimental to the overall structure. Therefore, it is necessary to solve the problems of bolted connection fastening, fire prevention and rust prevention to promote the application of this connection method in fabricated shear wall structures. Total bolt connection prefabricated concrete structure (BPC) consists of a roof system, a wall system, a floor slab system, and a cushion block system, as shown in Figure 5. The precast wall system plays the role of load-bearing and lateral force resistance. All prefabricated components form a standard series, which can be standardized in the factory, and then connected by bolts of different specifications at the construction site. The building is built like a "building block" method, which can adapt to the different area requirements of the building.

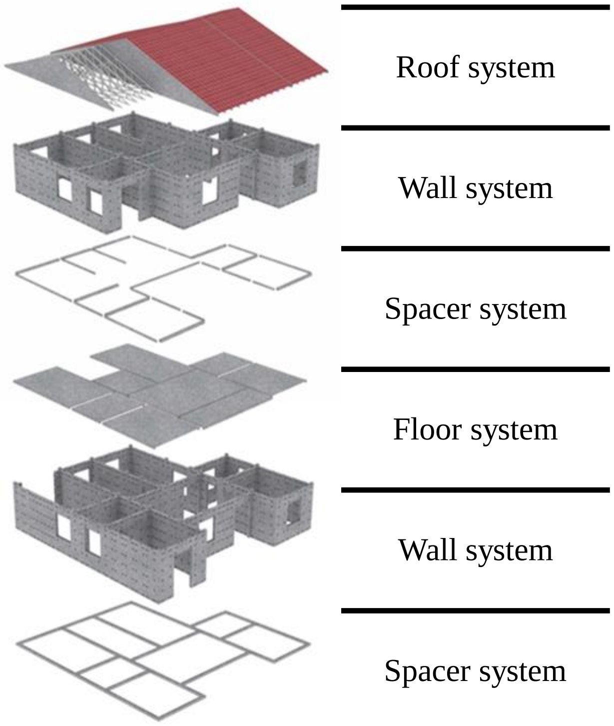
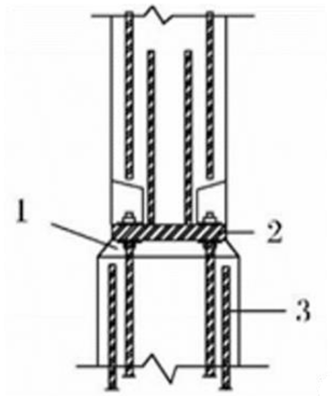



Fig. 5 BPC Structure

At present, there are few studies on bolted connection of precast concrete shear walls. A typical study is the connection structure of threaded rods proposed by Menetgotto et al. [10], as shown in Figure 6.




1-Pouring concrete; 2-Steel plate; 3-Inserting steel bar

Fig. 6 Connection Using Threaded Rod

## III. PRECAST CONCRETE SHEAR WALL STRUCTURE

Shemie M [11] proposed a slab structure system that connects precast concrete wall slabs and floor slabs through bolts. The prefabricated components are embedded with steel at specific angles at the ends of the components, and on top of that, backing plates are set. Moreover, friction-type high-strength bolts are used for connection. The bolt-connected slab structural system components are convenient for industrial production. The installation quality possesses highly controllable, and can be adapted to different building space requirements. The test results show that the bolted joints have good energy dissipation capacity, and the structural system exhibits sufficient ductility under earthquake action.

Soudki K A et al. [12-13] investigated the seismic performance of precast concrete shear walls with different connection methods for vertical steel bars. The connection methods include ordinary steel bar connection and post-tensioned prestressed compression connection. These two connection nodes also include other forms. Through the pseudo-static test, accompanied by justifications from a comprehensive perspective, the ductility and bearing capacity of the two types of nodes are analyzed. The test results show that, regardless of connection methods, the precast shear wall has sufficient bearing capacity and good ductility; for ordinary steel connection, the local unbonded steel can effectively improve the ductility performance, and the shear key can effectively improve the shear resistance and bearing capacity. As for the crimping of post-tensioned prestressing, local non-bonding of prestressed steel bars can increase the deformation capacity of the joints, which ensures that the prestressed tendons fall within its elasticity range.

Todut C and Dan D [14] carried out experimental research on precast concrete walls with openings. During the test, cracks, steel bar deformation, and concrete crushing appeared in the walls. The test results show that the shear force, which is generated during steel bar deformation, is evidently greater than the value calculated in the code, on the other hand, the actual shear force assumed by the concrete is smaller than the value calculated in the code. Furthermore, it is concluded that the smaller the opening area of the precast wall, the better the energy consumption and thus the greater the ductility. Besides, the finite element model established by the researcher is consistent with the experimental results, and the error of the results is within an acceptable range.

Tony Holden et al. [15] conducted a pseudo-static test of two precast concrete shear wall specimens. One specimen is designed to simulate the ductility behavior of cast-in-place concrete shear wall walls, whereas the other specimen is partially prestressed concrete shear wall, whose prestressing tendons utilize carbon fiber bundles. The concrete uses steel fiber concrete, and an energy dissipator is installed in the shear wall. The test results show that the prefabricated shear wall has better energy dissipation capacity than the prefabricated partial prestressed shear wall, but it will produce obvious residual deformation and cracks after unloading, while the prefabricated prestressed shear wall consumes energy through the energy dissipator. In this way, the residual deformation is small and the wall has self-recovery characteristics.

Zhu and Guo et al. [16] proposed a new hybrid precast wall (NHPW). A combination of prestressed compression technology, local non-bonded grout anchored steel indirect lap connection technology and buckle closed stirrup technology, are all required to connect the shear wall together as a whole.

Pouya Seifi [17] et al. conducted a cyclic load test on 7 full-scale precast concrete wall slabs connected by grouted metal pipes to study the influence of axial load, wall slab geometry, and wall slab splicing on the lateral bearing capacity of the wall slab. The results show that the damage to the wall slab of the double-layer steel reinforcement layer occurs at the connection, while the wall damage of the single-layer steel reinforcement layer occurs in the wall slab itself. For specimens with a long wall and a large axial load, the concrete at the bottom of the wall slab will peel off in a large area when it is damaged, which causes the metal conduit to fall off. Setting up stirrups near the metal conduit can effectively enhance the strength and ductility of the wall slab connection and prevent damage due to brittleness.

Felipe J. Perez et al. [18-20] conducted theoretical analysis and experimental research on unbonded post-tensioned pre-stressed precast concrete walls. The vertical joints of the precast concrete wall were connected by the vertical joints of ductile connectors, and the horizontal joints are unbonded tension prestressed tendon connection. The research results show that the precast concrete wall with vertical joints has good seismic resistance, and a performance-based seismic design method is proposed. Following that, the author discusses a fiber-based analysis model. The lateral load behavior of the wall under static and dynamic loads is then analyzed and obtained, and the rationality of the seismic design method is verified through parameter analysis; ultimately, a design-oriented analysis model is introduced, which uses a simple formula to estimate the nonlinear behavior of the wall subjected to vertical load. By comparing with the test results, the two analysis models have sufficient accuracy for the seismic design of unbonded post-tensioned pre-stressed concrete walls.

Sriram Aaleti et al. [21] proposed a simplified analysis method that introduced the neutral axis depth and the cross-sectional corner of the wall base based on the limitations of the existing analysis methods of unbonded post-tensioned pre-stressed precast concrete shear wall systems, and them verifies its accuracy through experimental data. The results show that the simplified method not only accurately predicts the monotonic load response of the unbonded post-tensioned pre-stressed precast concrete shear wall system as a function of lateral displacement, but also accurately quantifies the depth of the neutral axis, the elongation of the prestressed tendons, and the shear deformation at the vertical joints of the wall.

Brian J Smith et al. [22-23] proposed a seismic design method for hybrid fabricated shear walls, and verified the seismic performance of the wall and the feasibility of the design method through experiments. The vertical middle part of the wall is connected by unbonded post-tensioned prestressed bars, and the ordinary steel bars at the bottom layer are also arranged in the middle of the wall. The test focused on the lateral load, displacement, energy dissipation capacity of the shear wall, the behavior of the steel bars and the connection nodes. The results show that the wall behaves as a rigid body, and the horizontal deformation is mainly caused by the opening of the joints, and the unbonded prestressed tendons always maintain an elastic state, which reduces the residual deformation of the wall after the earthquake. In addition, the ordinary steel bar deforms when subjected to tension and compression, which improves the energy dissipation capacity of the wall; and the joints bear the shear force, which improves the hysteretic performance of the wall. Finally, before the test wall fails, the proposed seismic design method can accurately predict the mechanical performance of the wall.

Xue et al. [24] proposed a vertical bolt-sleeve hybrid connection for shear walls, and the vertical distribution steel bars and the edge member vertical steel bars were connected by single-row bolts and double-row sleeve grouting respectively. A low-cycle cyclic load test with 6 full-scale specimens of shear wall under high axial compression ratio with a value of 0.5 was carried out to systematically study the seismic performance of prefabricated shear walls with hybrid connections. The test results show that all specimens undergo bending failure. The bearing capacity of the precast shear wall is similar to that of the cast-in-situ shear wall, but the energy consumption is significantly better than that of the cast-in-situ shear wall, and the bolt-sleeve hybrid connection can effectively dissipate the stress of the steel bar. Furthermore, it was also pointed out that the shear wall has good seismic capacity.

Su-Min Kang et al. [25] used two vertical wall connection methods in order to prevent cracks and shear slippage at the joints of precast concrete walls and improve the seismic performance of precast concrete walls. One is a weakening strategy based on the concept of capacity design, that is, to reduce the area of vertical steel bars at the bottom of the wall, so that the plastic hinge area is formed in the wall instead of at the joint; the other is to use a RC-PC hybrid wall, which is the method of using cast-in-place concrete in the plastic hinge area at the bottom of the wall. The test results show that the new connection precast concrete wall and the cast-in-place concrete wall have considerable strength, rigidity, ductility and energy dissipation capacity, and therefore, further research is crucial.

Sri Sritharan et al. [26] developed a PreWEC seismic system consisting of precast concrete walls and the edge of columns, and verified its seismic performance through pseudo-static tests. In this system, both the wall and the edge of column are fixed on the foundation with unbonded post-tensioned prestressed tendons, the vertical joints of the wall and the edge of column are connected by low-carbon steel energy-consuming connectors. The test results show that, compared with the cast-in-place concrete wall, the PreWEC system has good seismic capacity, its elastic stiffness and bearing capacity are higher than the corresponding cast-in-place concrete wall, and the residual deformation and structural damage are smaller. The results of the simplified method and the finite element model analysis are highly consistent with the response of the PreWEC system subjected to lateral loads.

Ioannis N. Psycharis et al. [27] conducted an experimental study on precast concrete wall panels with integrated connections to investigate the impact of different connection methods on the seismic performance. The connection methods include steel bar connection, wall shoe connection, and steel plate connection. The test results show that the steel bar connection and wall shoe connection specimens have greater bearing capacity and ductility, while the steel plate connection specimens do not have ductility due to the brittle shear failure of the bolts before bending and yielding. According to the observed plastic deformation of the connecting rods during the test, which results in obvious slippage and damage at the connection, it is recommended to over-design the connection using the capacity design rules to ensure that the structure is in an elastic state during seismic loads.

## IV. CONCLUSIONS

There has been a relatively complete research on the structure of fabricated concrete shear walls with different connection methods, focusing on a large number of experiments and theoretical analysis on unbonded post-tensioned fabricated shear walls, and corresponding seismic design methods have been proposed；

Wet connection is currently the most frequently used connection method for fabricated concrete shear wall nodes. In actual engineering applications, it is not only a type of wet connection, but usually several connection methods are mixed together to fully make use of the advantages of various connection methods to ensure the reliability of the connection nodes of the concrete shear wall. Compared with wet connection, dry connection not only greatly reduce the wet work on the construction site, but also saves energy, confers some environmental protection, and improves overall assembly rate. Therefore, it is predicted that there will be a considerable application prospects in the future pertaining to prefabricated concrete structure.

Suffice to say, there are few studies on the seismic performance of bolted precast concrete shear walls. The bolted connection is a dry connection, which can effectively increase the assembly rate of prefabricated structures, thereby meeting the development requirements of building industrialization and residential industrialization. Above all, it is crucial that further research should be conducted in order to broaden its application scope in future.

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