Study on Bending-Shearing Separation Force of Reinforced Tenon Precast Shear Wall Joints

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Abstract: A new type of large-size reinforced tenon precast shear wall was proposed, which can effectively reduce the pin-key shear stress of the longitudinal connecting steel bars and improve the seismic performance of the precast shear wall. In order to study the bending-shear separation mechanism of the wall edge restraint member and the reinforcement-slotted shear, this paper first proposes the bending-shear separation mechanism of the wall edge restraint member. The concept of bending-shear separation degree was introduced, the mechanical analysis model of reinforced tenon was established, and the calculation method of horizontal relative slip of reinforced tenon interface was obtained by using Rayleigh-Ritz variational method. The relationship between horizontal relative slip of interface and shear stress of steel pin key was established, and the size of large-sized reinforced tenon to interface was studied.

1. Introduction

The joint connection of prefabricated shear wall is the weakest link in the whole prefabricated structure. Moreover, it plays a vital role in the seismic performance, integrity and stability of the fabricated shear wall structure. The provision of tenon at the joint of the fabricated shear wall can effectively improve its shear performance[1].

In recent years, domestic and foreign scholars have made some research on prefabricated tenon connections. Soudki et al.[2-3] performed loading tests on five different forms of horizontal seams. The experimental results show that the notch can significantly improve the shear slip capacity of the interface and the shear capacity when the notch interface reaches the maximum deformation, and the shear capacity when the notch interface reaches the ultimate deformation is 40% higher than that of the flat interface.

Based on the research of other domestic and foreign scholars on the tenon connection, it is proved that the tenon connection has good shear resistance, but the tenon connection is mostly plain concrete with small size, poor ductility, prone to shear brittle failure and complicated fabrication. In this paper, a large-scale reinforced tenon connection technology was proposed, it can effectively guarantee the shear resistance of prefabricated shear wall, reduce the shear stress of the pin key of the reinforcement, improve the yield strength of the reinforcement, enhance the energy consumption capacity of the prefabricated shear wall, and realize the bending-shear separation stress mode of joint bending and tenon shear resistance.

In this paper, a new type of large-size reinforcement tenon connection mode was proposed, and the bending shear separation stress mode is studied when the connection mode is affected by complex internal forces, the relationship between the horizontal relative slip of the interface and shear stress of
the bar pin key was established, and the calculation model and formula of the degree of bending shear separation were obtained.

2. The concept of a new type of reinforced tenon connection and the separation of Bending-Shearing

2.1 New connection mode of reinforced tenon

The fabricated shear wall has steel overlap, steel sleeves and strong restraining stirrups in the joint area of the steel bar, forming a steel bar strengthening zone, and the edges of the steel bar strengthening zone form two new weak surfaces [4]. The assembled joint on the weak surface at the bottom of reinforcement undergoes a large bending moment and forms a horizontal straight joint after the bond failure of the concrete, which was unfavorable to the stress of the connecting reinforcement. The yield strength of the steel bar at the joint will be significantly reduced after horizontal sliding [5]

\[ f_{y} = f_{y} - 3\tau \]  

(1)

in which \( f_{y} \) is the yield strength after shear of the reinforcement, \( f_{y} \) is the initial yield strength of the steel bar, \( \tau \) is the shear stress of the pin key of the reinforcement.

Therefore, in order to reduce the pin shear stress of the reinforcing bar at the joints, improve the yield strength after the reinforcement is sheared, and thereby improve the energy dissipation capacity and seismic performance of the integral fabricated shear wall member, a new type of reinforced tenon connection Mode, the specific connection mode as shown in figure 1.

(a) Component Sketch of Reinforced Tenon Shear Wall

(b) Detailed Drawing of Reinforced Tenon Joints

Figure 1. Structural Sketch of Reinforced Tenon Precast Shear Wall

2.2. The concept of bending-shear separation ratio

In this paper, in order to evaluate and control the new structural connection mode of joint bending tenon shear resistance, the concept of bending-shear separation degree is proposed: The ratio of the sum of the
shear forces offset by the static friction at the interface of the reinforced tenon and the joints to the total horizontal shear force of the large-scale reinforced coggled assembled shear wall member. When the bending shear separation ratio is 1, the static friction between the tooth slot and the joint completely offsets the shear force of the component, and the shear stress of the connecting steel bar without the pin key stress, which is the bending-shear complete separation stress mode; when the bending shear separation ratio is less than 1, which is the bending-shear partial separation stress mode.

The prefabricated shear wall tenon connection has complex shearing effects, and its shearing force is mainly composed of three parts, namely the friction at the joints, the shearing effect of the steel pin and diagonal compressive rod mechanism [6].

\[ V = V_s + V_c + V_t \]  
\[ \gamma = \frac{V_s + V_t}{V} = 1 - \frac{V_s}{V} \]  

In which \( V_s \) is the pin key shear force of the reinforcement, \( V_c \) is the friction force when the joint produces relative horizontal slip, \( V_t \) is the shearing force borne by the tooth slot of the reinforcement, and \( V \) is the total shear force borne by the horizontal joint.

It can be known from formula (3) that the ratio of the bending-shear separation is not greater than 1, and the closer the value is to 1, the smaller the pin shear force that the steel bar bears, the greater the yield strength, the better the energy consumption capacity and the better the degree of bending shear separation.

3. Theoretical analysis model for bending and shear separation of reinforced tenon assembled shear wall

When the prefabricated wall receives horizontal shear, there is a complex internal force interaction between the reinforced tenon and the fabricated wall, as shown in Figure 2.

![Figure 2. Diagram of Internal Force Action between Wall and Reinforcement Tenon in Precast Shear Wall Components](image)

3.1. Basic assumptions

According to the finite element simulation and theoretical analysis, the following basic assumptions are used in order to simplify the calculation of the bending-shear separation of the reinforced tenon assembled shear wall:
1) Reinforced tenon has sufficient strength to make the wall of the shear wall break before the reinforcement tenon is broken, so the reinforcing tenon is simplified as an elastic body;

2) The horizontal slip of each longitudinally connected reinforcing bar is equal, and is equal to the horizontal relative slip of the edge portion of the reinforced tenon, ignoring the vertical opening displacement of the joint in the tensile zone of the reinforcing bar;

3) The interaction force between the reinforced tenon and the contact surface of the prefabricated wall panel is uniform load;

3.2. Mechanical model

Taking the large-sized reinforced tenon as the research object, when the upper prefabricated wall is subjected to vertical axial force, horizontal shear force and bending moment, the right side of the tenon can be regarded as the fixed end. According to the basic assumptions above, a force diagram can be obtained. As shown in Figure 3.

4. Calculation process

4.1. Calculation of displacement under horizontal uniform load

Considering only the influence of laterally uniform load, the Rayleigh-Ritz variational method [7] is used to calculate the tenon displacement, and the displacement component is set as:

\[
\begin{align*}
  u &= u_0 + \sum_m A_m u_m, \\
  v &= v_0 + \sum_m B_m v_m 
\end{align*}
\]

(4)

Obtained the expression of deformation potential energy is:

\[
U = \frac{E}{2(1-\mu^2)} \left\{ \frac{1}{3} A_i^2 a b^3 + \frac{1}{3} B_i^2 a^3 b + \frac{(1-\mu)A_i^2 a^3 b}{4} + \frac{(1+\mu)A_i B_i a^2 b^2}{6} + \frac{(1-\mu)B_i^2 a b^3}{6} \right\}
\]

(5)

According to the displacement variational equation of \(A_m\) and \(B_m\), we only need to consider the partial boundary on the boundary of \(s_o\) where neither \(f_i\) nor \(v_i\) is equal to zero, and then we can get:

\[
\begin{align*}
  \frac{\partial U}{\partial A_i} &= \int_{s_o} \bar{f}_i u_m dy = -\frac{pab^2}{2} \\
  \frac{\partial U}{\partial B_i} &= 0
\end{align*}
\]

(6)

(7)
Simultaneously (5), (6) and (7), the expressions for solving \( A_i \) and \( B_i \) are:

\[
A_i = \frac{p b (\mu^2 - 1)}{E \left[ \frac{2a^2}{3} + \frac{1-\mu}{3} b^2 \right]} \left( \frac{2a^2}{3} + \frac{1-\mu}{3} b^2 \right) \left( \frac{2b^2}{3} + \frac{1-\mu}{3} a^2 \right) - \left( \frac{1+\mu}{4} \right)^2 a^2 b^2 \]  

(8)

\[
B_i = \frac{p a b^2 (1+\mu)(\mu^2 - 1)}{4E \left( \frac{1+\mu}{4} \right)^2 a^2 b^2 - \left( \frac{2a^2}{3} + \frac{1-\mu}{3} b^2 \right) \left( \frac{2b^2}{3} + \frac{1-\mu}{3} a^2 \right) - \left( \frac{1+\mu}{4} \right)^2 a^2 b^2 \]  

(9)

Where: \( p \) is the uniform load on the left section of the tenon, \( N/mm^2 \); \( \mu \) is the Poisson's ratio, and the Poisson's ratio of concrete is usually 0.2; \( E \) is the elastic modulus of concrete; \( a \) and \( b \) is the width and height of the tenon.

Formula (8) and formula (9) can be substituted into formula (4) to obtain the displacement calculation formula of reinforced tenon under the action of transverse local load, namely:

\[
u_i = A_{i,xy} = \frac{p b (\mu^2 - 1)}{E \left[ \frac{2a^2}{3} + \frac{1-\mu}{3} b^2 \right]} \left( \frac{2a^2}{3} + \frac{1-\mu}{3} b^2 \right) \left( \frac{2b^2}{3} + \frac{1-\mu}{3} a^2 \right) - \left( \frac{1+\mu}{4} \right)^2 a^2 b^2 \]  

(10)

4.2. Displacement calculation under vertical uniform load

Similarly, using the variational method used in Section 3.1, the calculation formula for displacement under longitudinal uniform load can be obtained.

Based on the superposition principle, the expression of the horizontal displacement of the corners of the reinforced tenon under external force can be obtained as:

\[ \delta = |u_i + u_j| = |A_i + A_j|ab \]  

(11)

4.3. The relationship between the shear stress and the interface displacement of the longitudinal connecting bar pin

According to the theoretical analysis in reference [8], the maximum shear stress of the pin key on the longitudinal connection reinforcement is obtained as follows:

\[
\tau = \frac{4E_{s} \xi_h}{11 \left( \frac{3\pi\eta}{4} \sqrt{\frac{\pi E_s}{2400f_{c}^{0.85}}} \right)^3} \]  

(12)

Where: \( \xi_h \) is the horizontal relative sliding value of the assembly joint interface and the diameter ratio of the longitudinal connecting reinforcement, which is referred to as the horizontal relative sliding ratio; \( \xi_v \) is the vertical opening displacement value of the assembly joint interface and the diameter ratio of the longitudinal connecting reinforcement, which is referred to as the vertical opening displacement ratio; \( f_c \) is the design value of the tensile strength of the reinforcement.

Therefore, the total pin key shear force on the longitudinal connection reinforcement is:

\[
V_s = \frac{npd\delta E_s}{11 \left( \frac{3\pi\eta}{4} \sqrt{\frac{\pi E_s}{22400f_{c}^{0.85}}} \right)^3} \]  

(13)

Where, \( n \) is the number of vertical connecting bars at the joint, and \( d \) is the section diameter of the vertical connecting bars.

Then, the calculation formula of bending shear separation degree can be obtained as follows:
\[ \gamma = \frac{n \pi d \delta E_s}{11V} \left( \frac{3 \pi \eta}{4} \sqrt{\frac{\pi E_s}{22400 f_i^{0.85}}} \right)^{-1} \]  

(14)

It is also pointed out in reference [8] that when the joint interface of the fabricated member is in the case of small slip, it can be considered that the pin key shear force of the longitudinal connection reinforcement increases with the increase of the relative slip. Therefore, the bending shear separation decreases with the increase of slip.

5. Conclusion

(1) In this paper, the concept of bending shear separation is put forward, the theoretical analysis model of bending shear separation is established and the theoretical calculation formula is derived. The formula of bending shear separation takes into account the relationship between the bending shear separation and the parameters such as the size of reinforcement slot, the performance of concrete material, the performance of longitudinal connection reinforcement material and the interaction between walls.

(2) The influence rule of the size of the reinforced tooth slot on the bending shear separation is analyzed, that is, the height of the tooth slot has more influence on the bending shear separation than the width of the tooth slot; when the height of the tooth slot is about 300-400mm, the bending shear separation first decreases and then increases with the increase of the width of the tooth slot; when the height of the tooth slot is more than 400mm, the bending shear separation decreases with the increase of the width of the tooth slot; when the width of the tooth slot is more than 400mm, the bending shear separation decreases when it is not changed, the separation degree of bending shear decreases with the increase of alveolar height.

References

[1] SAUSE R, FORSCH R, GHOSH S K, et al. Preview of PCI’s Japan earthquake reconnaissance team report [J]. PCI Journal, 2012, 57(1): 47-51.
[2] Soudki A Khaled, Rizkalla H Sami. Horizontal connection for precast concrete shear walls subjected to cyclic deformations part1: mild steel connections [J]. PCI Journal, 1995, 40(4): 78-96.
[3] Soudki A Khaled, Rizkalla H Sami, Bob Daiki W. Horizontal connection for precast concrete shear walls subjected to cyclic deformations part2: prestressed connections [J]. PCI Journal, 1995(5): 82-96.
[4] Wu Dongyue, Liang Shuting, Guo Zhengxing, Xiao Quandong. Calculation of bending capacity of modified reinforced mortar anchor assembled shear wall [J]. Journal of Harbin University of technology, 2015, (12): 112-116
[5] Masoud Soltani, Xuehui An, Koichi Maekawa. Computational model for post cracking analysis of RC membrane elements based on local stress–strain characteristics [J]. Engineering Structures, 25 (2003): 993–1007.
[6] KASSEM W, ELSHEIKH A. Estimation of shear strength of structural shear walls [J]. Journal of Structural Engineering, ASCE, 2010, 136: 1215-1224.
[7] Xu Zhilun. A concise course of elastic mechanics [M]. Higher education press, 2013
[8] Wu Dongyue. Aseismic performance evaluation of prefabricated shear wall structure with slurry anchor connection [D]. Southeast University, 2016