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Failure Characteristics and Seismic Performance Based on Artificial Intelligence and Precast Concrete Shear Walls

Yurong Zhang[1,*], Zhengqi Xu[2], Chenghao Xu[3], Jialu Xu[4]

[1]*SC Johnson College of Business, Cornell University, Ithaca, New York, USA*
[2]*St. George's Senior School, Vancouver, Canada*
[3]*Hangzhou Foreign Languages School, Cambridge-A Level Center, Hangzhou, China*
[4]*Watkinson School, Hartford, Connecticut, USA*
**Corresponding author Email: yz845@cornell.edu*

ABSTRACT. *In order to study the failure characteristics and seismic performance of precast concrete shear walls, the basic failure processes and phenomena of six shear walls were introduced. The length of the reinforcing bar of the prefabricated shear wall specimens with three confinement anchors was 1 times that of the anchorage length of the steel bar. Through analysis and observation, the failure forms of three prefabricated concrete shear walls of YZ12, YZ16 and YZ20 were bending shear composite failure. Because of the effect of the spiral stirrup, the collapse phenomenon was not found in the concrete core area of the compression zone. At the end of the test, the vertical steel bars were yielded. The results show that the most lateral longitudinal bar of YZ12 was broken at the connection between the ground beam and the prefabricated shear wall specimens. In the late test of three contrast cast-in-situ shear walls, the concrete compression zone was completely crushed and the edge longitudinal reinforcement exposed and showed obvious deformation. Therefore, the binding method of constrained pulp anchorage bar is safe and effective.*

KEYWORDS: *Precast concrete, Shear wall, Destructive properties, Shock resistance, artificial intelligence*

1. Introduction

The precast concrete structure has the advantages of standard, accurate, energy-saving and efficient construction design and construction (Behnam & Ronagh, 2014). In the external environment of energetically advocating energy saving and emission reduction, the precast concrete structure is suitable to be used in a large number of cities. The core technical problem of precast concrete structure is the site

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connection of prefabricated components, and the reliability of the connection of prefabricated components is the key technology (Bolhassani, Hamid & Moon, 2016). Through research and exploration, the relevant scholars independently develop the joint connection of the anchor bar and steel bar, and solve the problem of the connection of prefabricated components in the concrete structure (Chou, Chang & Hewes, 2013). This kind of reinforcing bar connection is used in precast concrete shear wall system, and good results have been obtained in practical engineering (Dominguez-Santos, Ballesteros-Perez & Mora-Melia, 2017).

The purpose of this test is to verify the horizontal bearing capacity of the precast shear wall components with anchored slurry anchorage connection, the overall energy dissipation capacity of the components and the safety capacity of the anchored slurry anchor connections. Therefore, the seismic performance of the prefabricated shear wall members with constrained pulp anchors is evaluated comprehensively.

2. Experimental design

The object of this test is 6 pieces of one-character type shear wall. The vertical longitudinal reinforcement diameter of three precast shear wall components is 12mm, 16mm, and 20mm respectively (Flindt Jørgensen, 2016). The diameter of the longitudinal bar of different dark columns corresponds to the different vertical axial pressure. The axial compression ratio is set to 0.1, 0.2 and 0.3 respectively to simulate the stress state of different positions in the actual high-rise shear wall structure. Each prefabricated shear wall component has a cast-in-situ shear wall member corresponding to it (Henin & Morcous, 2015).

The specific dimensions of the shear wall specimens in the test are: 2700 mm × 1500 mm × 200 mm. The top beam of prefabricated specimen is poured together with the wall, and the ground beam is poured alone. The cast-in-place specimens are cast together with the top beam, the wall and the ground beam. The type of steel bar is HRB335, and the strength of concrete is C30.

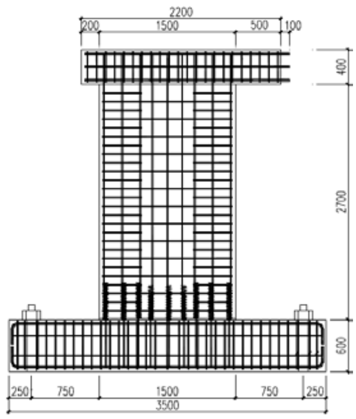

Figure 1. Positive facade reinforcement of precast concrete shear wall

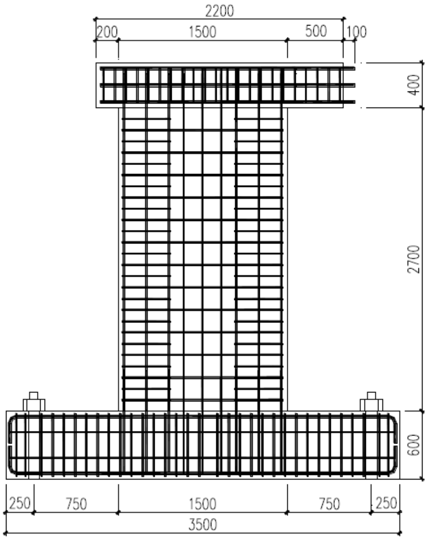

Figure 2. Positive facade reinforcement of cast in situ concrete shear wall

3. Test scheme and measurement content

3.1. Loading system

Figure 3 is a loading system diagram, which is loaded with force displacement control.

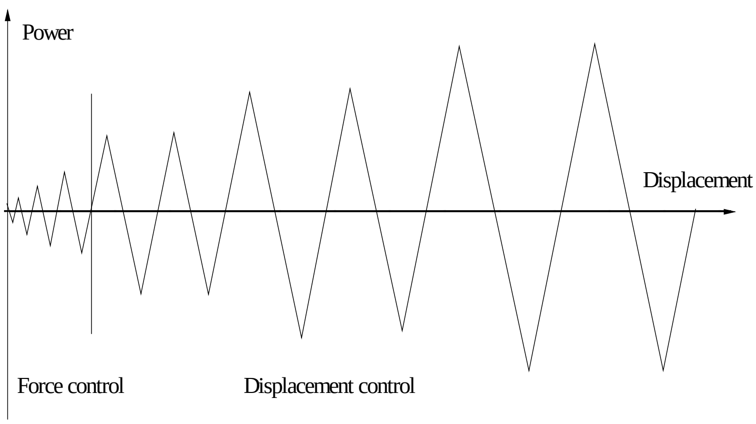

Figure 3. Loading system

During the test, the critical position of force control and displacement control is determined by observing the hysteresis curve in the actual test. According to the shear bearing capacity of the specimen, the load level is estimated at every step load. The specific value of load at each step is a pre-calculated yield load of 1/5 or 1/6. When performing the displacement control loading, the displacement of each step was taken as the yield displacement of 2.0-3.0 times, and the test was taken as 1.0 times.

3.2. Measurement content

(1) The content of displacement measurement

The high precision displacement meter LVDT is used to measure the horizontal displacement of the wall. The actual displacement of the wall is the difference between the displacement at LVDT 6 (the top of the shear wall) and the displacement at LVDT 1 (center of the earth beam).

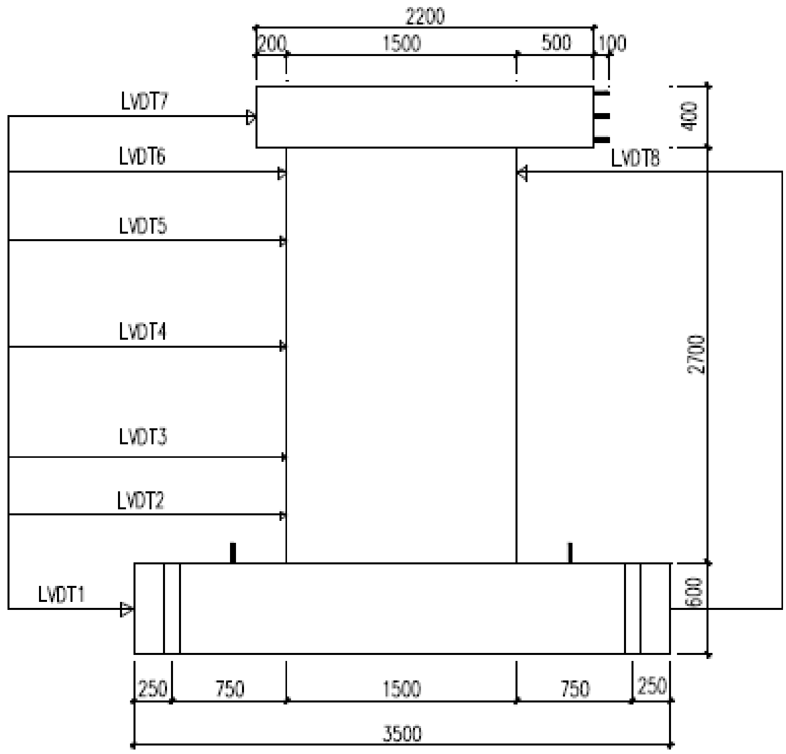

Figure 4. Experimental arrangement of the displacement meter

(2) Measurement of strain of steel bar

The strain of the steel bar was collected by the strain collector DH3816 in the laboratory. The sticker position of the strain gauge is shown in Figure 5 and Figure 6.

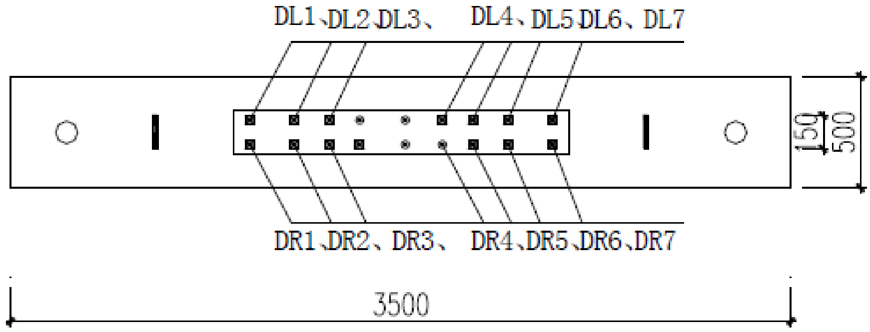

Figure 5. Pasting position of strained strain gage of prefabricated shear wall ground beam

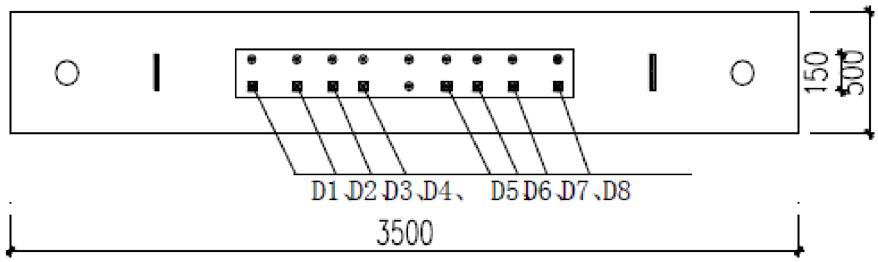

Figure 6. Stickup position of strained strain gage in cast - in - situ shear wall

3.3. Loading device

The 15.6m counterforce wall device of the power Hall of the aseismatic test room is used. The upper part of the top beam of the shear wall specimens is placed in the same distribution beam as the top beam (Kafle, Lam, Lumantarna, Gad & Wilson, 2015). Three rollers are placed on the upper part of the distribution beam, and the surface of the distribution beam is coated with lubricating oil to prevent the friction between the specimen and the rack under horizontal reciprocation, so that the top jack moves with the horizontal movement of the shear wall specimen. The distribution beam was placed on the top of the top beam. The vertical load is evenly transmitted to the top beam until it reaches the wall. The 3200kN oil jack is used as the main vertical loading device. At the top of the jack, the 5000kN sensor is added. The force values of the concrete vertical loading are controlled in real time by

YE2537, so that the vertical loading is stable (Maniatakis, Psycharis & Spyrakos, 2013). Lateral support is designed and installed on both sides of the top beam to prevent the specimen from producing plane deformation during the test.

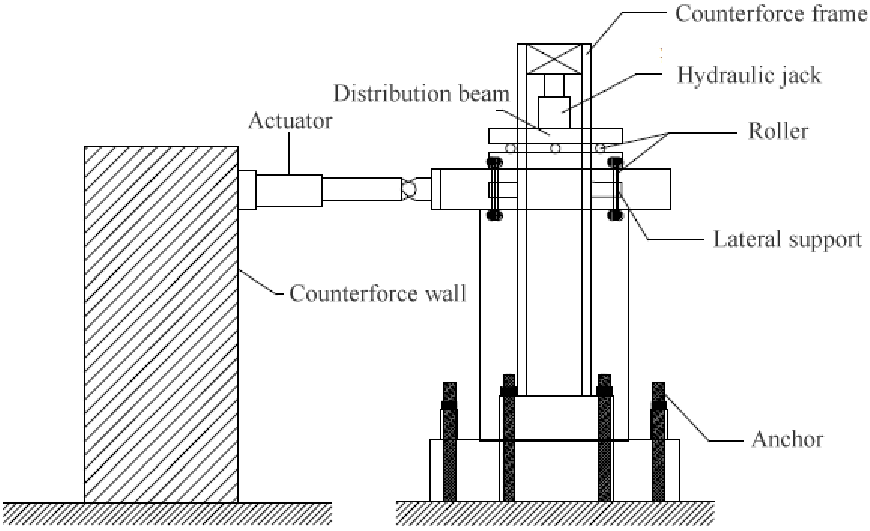

Figure 7. Test piece loading layout

4. Phenomenon of destruction

4.1. The destruction phenomenon of precast concrete shear wall

(1) The destruction phenomenon of YZ20 specimen

First, the elastic phase: the actuator on the top beam is negatively loaded with 300kN. The first horizontal crack appears at the bottom of the wall of the specimen far away from the edge of the actuator. The length of the crack is about 200mm. When the 300kN is loaded forward, the first horizontal crack appears at the bottom edge of the side of the actuator. The length of the crack is about 150mm. At this time, although both sides have curved horizontal cracks, there are no residual deformation when the horizontal load is returned to zero. It shows that the structure is still in a linear elastic phase (Nicolaides, Kanellopoulos, Savva & Petrou, 2015).

Second, elastic-plastic stage: when horizontal load is added to 350kN, horizontal cracks appear at 500mm at the bottom of the specimen, and gradually extend to the middle part of the wall. The horizontal cracks are found at the bottom of the wall. Its extension length is about 400mm. At this time, the cracks on both sides of the shear wall specimens begin to extend evenly. When the horizontal load is back to zero, the structure has the non-recoverable residual deformation, and it can be seen from the hysteresis curve that the curve appears in the curve. It is shown that the structure has entered the elastoplastic stage from the linear elastic phase (Olmati, Trasborg, Naito, Sgambi & Bontempi, 2016).

Third, the plasticity and softening stage: when the horizontal load is added to 450kN, horizontal cracks gradually appear around 800mm from the bottom of the test piece. Curved cracks in shear wall specimens are more obvious. In the process of further loading, the bending horizontal cracks constantly rise upwards along the wall height. A horizontal crack is formed at the bottom. The width of the crack is about 1mm. At the same time, the oblique shear slanting cracks in the middle of the center extend to the bottom of the wall. After the displacement control is loaded, the residual deformation of the structure is increasing, and the structure has basically entered the plastic stage. The crack extension speed is accelerated gradually, and the width of the crack increases gradually. The slight collapse was found at the concrete compression zone at the bottom of the specimen. However, the internal bonding of the spiral stirrup is still good, and the phenomenon of slipping or pulling out of the steel bar has not been found. The maximum horizontal load of the actuator in the test room is 1000kN. When the horizontal action is 960kN, the bearing capacity does not decrease obviously. When the load is stopped, the cracks almost fill the whole wall. As a whole, the development and distribution of A and B cracks are not very symmetrical. When interacting with each other, the actuator has an angle with the wall to force the specimen out of the plane. The concrete outside the spiral stirrup is shed, but the core area of the concrete in the compression zone is not damaged (Smith, 2013). However, the ductility coefficient of the specimen is more than 10 at this time, which shows good ductility.

Side A Side B

Figure 8. The overall diagram of the YZ20 test piece

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Figure 1 Figure 2

Figure 9. Concrete in the compression zone at the later stage of YZ20

(2) The destruction phenomenon of YZ16 specimen

First, the elastic phase: when the negative loading 240kN is loaded, the first horizontal crack appears at the bottom edge of the side of the actuator. The length of the crack is about 200mm. When the 240kN is loaded forward, the first horizontal crack appears near the bottom edge of the actuator. The length of the crack is about 200mm. At this point, there are already cracks on both sides. However, when the horizontal load is back to zero, the structure has no residual deformation. It shows that the structure is still in a linear elastic phase (Shubin, Tulin & Potseshkovskaya, 2017).

Second, elastic-plastic stage: when horizontal load is added to 320kN, horizontal cracks appear on the bottom of the specimen about 400mm, and gradually extend to the middle part of the wall. The horizontal crack appears at the bottom of the front of the wall, and its extension length is about 300mm. When the horizontal load is added to 400kN, horizontal cracks gradually appear around 600mm at the bottom of the specimen, and the horizontal crack width gradually increases to 6mm. Under the action of the actuator, the specimen is continuously pulled down and the cracks on both sides are continuously contracted and closed. The residual deformation of the specimen is increasing. At this point, it can be assumed that the structure has entered the elasto-plastic phase.

Third, the plastic and softening stage: a large number of bending cracks in shear wall specimens are produced (Szulc, 2014). In further loading, the bending horizontal cracks are constantly rising up the height of the wall, and a horizontal crack is formed at the bottom. At the same time, the oblique shear cracks in the middle of the center extend to the bottom of the wall, and there are cross slanting cracks on both sides. When the displacement control is loaded, the crack extension speed is accel-

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erated gradually, and the crack width is gradually increased. At a distance of 500 mm from the bottom, the main crack of the specimen appeared. With the gradual increase of horizontal load, the crack width becomes more obvious. The maximum crack width is 17mm. The concrete compression zone outside the spiral stirrups at the bottom of the specimen was crushed. When the main cracks through, the bearing capacity still did not decline. However, the width of the main crack is still increasing at this moment, so safety is considered and the test is stopped. The cracks are almost covered with 2/3 walls, and the concrete outside the compression zone is detached. The internal parts of the spiral stirrup have not been destroyed. It is still firmly "wrapped" in the force longitudinal tendons of the dark column. At this time, the ductility coefficient of the specimen is about 6 and the ductility is good.

Side A　　　　Side B

Figure 10. The overall diagram of the YZ16 test piece

Figure 1　　　　Figure 2

Figure 11. Concrete in the compression zone at the later stage of YZ16

(3) The destruction phenomenon of YZ12 specimen

First, the elastic phase: when the negative loading 60kN is loaded, the first horizontal crack appears at the bottom edge of the side of the actuator. The length of the crack is about 100mm. When 180kN is loaded in the forward direction, the horizontal cracks in the bottom of the wall begin to extend until the bottom has penetrated through the bottom of the wall. At this point, there are already cracks on both sides. When the horizontal load does not work, the structure has no residual deformation. In the hysteresis curve, there is no obvious bending phenomenon in the curve. It shows that the structure is still in the linear elastic phase.

Second, elastic-plastic stage: when horizontal load is added to 240kN, horizontal cracks appear on the bottom of the specimen about 500mm, and gradually extend to the middle part of the wall. When the horizontal load is added to 300kN, horizontal cracks will appear one after another around 600mm at the bottom of the specimen. The width of the horizontal crack increases gradually and the length is elongated. In the process of further loading, the bending horizontal cracks are constantly rising upward along the height of the wall, and the horizontal crack is formed at the bottom. At the same time, the oblique shear slanting cracks in the middle of the center extend to the bottom of the wall. The slight collapse was found on the outside of the spiral stirrup in the concrete compression zone at the bottom of the specimen.

Third, the stage of plastic and softening: after the loading of displacement control, the residual deformation of the structure increases continuously. The structure has entered the plastic stage. The crack extension speed is accelerated gradually, the width of the crack increases gradually, and the maximum width of the main crack is 10mm. When the test was made to the plastic stage, a "slamming" sound showed that the steel was broken. The bar breaking place is the connection between the wall and the ground beam, and there is no phenomenon of pulling out the steel bar inside the spiral stirrup. The crushing phenomenon was found in the concrete compression zone outside the spiral stirrups at the bottom of the specimen. When the main crack passes through in the later stage of the experiment, the bearing capacity tends to decrease (Zhang, Guo & Li, 2013). When the horizontal load drops to 85% of the ultimate load, a significant drop has occurred and the test is stopped. The cracks are almost covered with 2/3 walls, and the concrete outside the compression zone is detached. The most lateral vertical longitudinal tendons are broken and the other vertical longitudinal tendons have yielded. After the test, the most lateral vertical longitudinal tendons were broken at the root. The obvious damage was not found inside the spiral stirrup. The ductility coefficient of the specimen is about 8, and the specimen has a good ductility.

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Side A Side B

Figure 12. The overall diagram of the YZ12 test piece

Figure 1 Figure 2

Figure 13. Concrete in the compression zone at the later stage of YZ12

4.2. The destruction phenomenon of cast in situ concrete shear wall

(1) The destruction phenomenon of XJ20 specimen

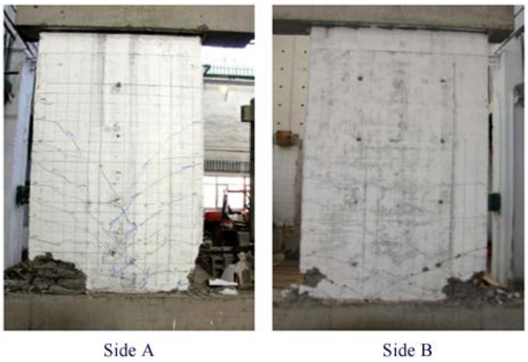

Figure 14. The overall diagram of the XJ20 test piece

First, the elastic phase: when the negative loading 300kN is loaded, the first horizontal crack appears at the bottom edge of the side of the actuator. The length of the crack is about 350mm. When the 300kN is loaded forward, the first horizontal crack appears at the bottom edge of the side of the actuator. The length of the crack is about 300mm. At this point, cracks have started to develop on both sides. When there is no horizontal load, the structure does not have residual deformation. Hysteresis curve is also no obvious bending phenomenon. It shows that the structure is still in a linear elastic stage.

Second, the elastic-plastic phase: when the horizontal load is added to 400kN, horizontal cracks gradually appear around 400mm from the bottom of the specimen, and there is a tendency to gradually extend to the middle of the wall. The horizontal crack is found at the bottom of the wall, and its extension length is about 30mm. When the horizontal load is added to 500kN, the horizontal cracks continue to spread along the height direction, and the height extends to the 800mm. The trend of the bending and shearing cracks has appeared. When the horizontal load reaches 600kN, the height of the horizontal crack is up to 1.5m, and the horizontal extension length is about 400mm.

Third, the stage of plastic and softening: in the process of further loading, the horizontal loading control form of the test is transferred from force control to displacement control. Bottom cracks become larger. At the same time, a diagonal shear oblique crack appears in the middle and it extends toward the bottom of the wall. After the displacement control is loaded, the residual deformation of the structure increases continuously and the structure has basically entered the plastic phase. The extension speed of the crack is accelerated gradually, and the width of the crack increases gradually. When the level is loaded to 690kN, a small amount of crisp is found at the bottom. The maximum crack has reached 7mm. Immediately, there was a collapse at the bottom. The steel bar is exposed and appears obvious bending phenomenon, but the plastic coefficient of the specimen is about 5, and the ductility is basically good.

(2) The destruction phenomenon of XJ16 specimen

First, the elastic stage: when a horizontal negative load is 240kN, a very small through crack is found on the bottom side, and it has the trend of extending horizontally and vertically. When the 320kN is loaded forward, two long horizontal slanting cracks appear at the bottom about 600mm of the specimen, and the length can reach about 500mm. At this point, cracks have started to develop on both sides. However, when the horizontal load is zero, there is no residual deformation in the structure. There is no obvious bending phenomenon in the hysteresis curve. It shows that the structure is still in the linear elastic phase.

Second, the elastic-plastic phase: when the horizontal load is added to 400 kN, a large number of horizontal cracks occur along the height at the horizontal level, and there is a tendency that the oblique shear cracks occur. The cracks spread very quickly, and the cracks below 1/2 at the bottom of the wall were basically full. When the horizontal load is 480kN, a large number of shear cracks are produced, and the level of the horizontal crack extends to 1.15m. The loading mode of the test load is transferred from force control to displacement control. The horizontal cracks in the bend constantly rise up along the height of the wall, and the horizontal cracks at the bottom have been formed. It can be seen from the hysteresis curve that the deformation of the specimen is not recoverable, indicating that the specimen is entered into the elastoplastic stage. At the same time, the oblique shear slanting cracks in the middle of the center extend to the bottom of the wall.

Third, plasticity and softening stage: after entering the displacement loading control, with the increase of horizontal load, the speed of crack extension gradually accelerates and the width of crack increases. When the level is loaded to 520kN, a small amount of crisp has been found at the bottom. The concrete protective layer on the outside of the steel bar is shedding. After the steel bars yield, the deformation is produced under the continuous overlying action, but the compression zone of the concrete is basically intact. When the level is loaded to 570kN, the maximum crack has reached 4.5mm at this time. Immediately, there was a collapse at the bottom. The steel is exposed. The obvious bending phenomenon was found. At this time, the plastic coefficient of the specimen is about 5, and the ductility is basically good.

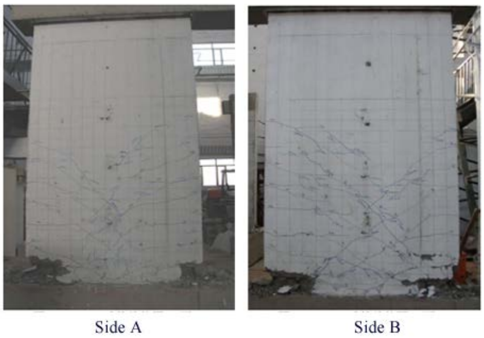

Figure 15. The overall diagram of the XJ16 test piece

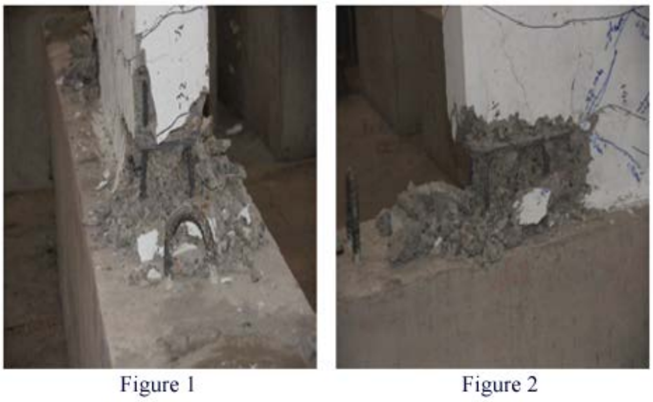

Figure 16. Concrete in the compression zone at the later stage of XJ16

(3) The destruction phenomenon of XJ12 specimen

First, the elastic phase: when the negative loading 60kN is loaded, a tiny crack appears on the bottom surface of the cast-in-place specimen and has an extension trend. At this time, the corresponding horizontal displacement is 1.22mm. When the 120kN is loaded forward, the horizontal crack extends at the bottom of the wall to the middle of the wall. The length of the crack is about 600mm. When the horizontal load is added to 180kN, diagonal cracks gradually appear around 400mm from the bottom of the specimen (the toe of the wall). It has a downward trend. At this point, the shear wall specimens along the width and length of the cracks have begun to produce. However, after several cycles of horizontal load on the specimen, the specimen did not show obvious residual deformation. From the hysteretic curve, it does not show that the curve has an obvious bending phenomenon. It shows that the structure is still in the linear elastic phase.

Second, the elastoplastic stage: when the horizontal load is added to 300kN, a large number of horizontal cracks appear along different heights. The horizontal crack is carried out in the syncline crack, and the length of the extension is about 800mm. In the process of further loading, the control form of the test is transferred from force control to displacement control. The horizontal cracks in the bend constantly rise up along the height of the wall, and the horizontal cracks at the bottom have been formed. At the same time, the oblique shear slanting cracks in the middle of the center extend to the bottom of the wall. When the horizontal load is back to zero, there is still more obvious residual deformation. There are obvious phenomena both on the surface of the specimen or from the hysteresis curve.

Third, plasticity and softening stage: after entering the displacement control load, the fracture extension speed gradually accelerates, the crack width increases gradually, and the main crack gradually forms. When the main cracks appear obviously, the cracks in the later specimens are mainly dominated by the main cracks. When the level is loaded to about 350kN, the bottom has a small amount of crisp phenomenon. At this point, the maximum crack has reached 4mm. Immediately, the phenomenon of crushing was found at the bottom. Reinforced steel is exposed, and it shows obvious bending. Later, the horizontal bearing capacity decreased rapidly. When it falls to 80% of the ultimate bearing capacity, there is an obvious downward trend and stiffness degradation trend in the hysteresis curve, and the test stops at this time. However, the plastic coefficient of the specimen is about 5 at this time, and the ductility is basically good.

Side A Side B

Figure 17. The overall diagram of the XJ12 test piece

Figure 1 Figure 2

Figure 18. Concrete in the compression zone at the later stage of XJ12

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4.3. Analysis of the destruction process of the test

The conclusion is obtained by observing the destruction process of the above shear wall specimens. Under the action of low cycle and reciprocating horizontal loads, the final characterization of the wall is that the longitudinal reinforcement is generally yielded or even broken. The concrete surface of the prefabricated shear wall specimens appears to be crushed. However, the interior of the spiral stirrup is basically intact, and the collapse of concrete in the compression zone of cast-in-situ shear wall is more serious. Finally, the horizontal bearing capacity of the shear wall specimens is reduced under the combined action of bending and shear, and the final failure mode of the specimens belongs to the ductile failure. The prefabricated shear wall test and the cast-in-situ shear wall specimen have significant difference in the degree of wall cracks and the damage degree of the compression zone due to the different connection modes.

(1) The confined zone of cast - in - situ concrete shear wall is confined only by rectangular stirrup. The precast concrete shear wall not only has the constraint of the rectangular stirrup, but also the internal spiral stirrup constraint. The test shows that the compression zone of precast concrete shear wall with spiral stirrup is only the phenomenon of crushing on the surface, and it is not destroyed inside.

Figure 19. The destruction phenomenon in the compression zone of shear wall

(2) The crack of precast concrete shear wall is more fully developed. For example, the YZ20 prefabricated shear wall specimens are reliable due to the lower connection. The wall is full of uniform cracks. The concrete compression zone in the middle and lower part of the XJ20 cast shear wall specimens is completely crushed. There are cracks in the wall below the height of 1/2. The crack does not extend to the upper part of the wall.

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Figure 20. Development of crack in shear wall

From the failure of shear wall, the failure process of shear wall specimen can be divided into four stages:

The first, elastic phase: the vertical load is added to the predetermined test value by using the hydraulic jack. In the first several stages of using force control to make the actuator, the hysteresis curve is basically a straight line. The obvious bending phenomenon is not produced. At this time, the bottom of the wall usually appears some slight bending horizontal cracks, but it is not obvious.

Second, the elastoplastic stage: the hysteresis curve has a bending phenomenon, and the specimen basically enters the elastoplastic stage. At this point, the extension of the hysteresis curve is not a straight line, and a closed graph is formed after a cycle of each stage load. With the increase of the first order of load, the area formed in each circle of hysteresis curve is also increasing. The horizontal bending cracks in the shear wall are produced in a large amount along the height in this stage. However, the length of each horizontal crack is not large, and a small number of slanting cracks are produced.

Third, the plastic stage: with the increasing of the horizontal load, the cycle is increasing, and the destruction of the wall is more serious. The horizontal cracks continue to extend. A large number of slanting cracks and the middle and lower parts of the wall specimens are produced. At this time, the value of the horizontal load no longer rises with the increase of the displacement, and it is basically in a stationary phase. Under the action of each periodic load, the hysteresis loop is full and the energy consumption becomes larger. At this stage, the main cracks have basically formed, the edge longitudinal reinforcement is yielded, and the concrete in the compression zone tends to crumble.

Fourth, the softening stage: the longitudinal reinforced bar in this stage has basically yielded. Among them, the longitudinal reinforcement of the YZ12 prefabricated shear wall specimens is broken at the most edge. The concrete of the prefabricated shear wall specimens is crushed by the lateral concrete of the spiral stirrup, and the concrete in the compression zone of the cast-in-place shear wall is crushed. The calculated area of the compression zone decreases, and the bearing capacity will decrease obviously at this time. When it falls to 85% of the ultimate bearing capacity, the specimen has been destroyed.

5. Conclusion

The basic failure process and phenomenon of six shear walls in the test are introduced. The length of the reinforcing bar of the prefabricated shear wall specimens with three confinement anchors is 1 times that of the anchorage length of the steel bar. Through analysis and observation, the failure forms of three prefabricated concrete shear walls of YZ12, YZ16 and YZ20 are bending shear composite failure. Because of the effect of the spiral stirrup, the collapse phenomenon is not found in the concrete core area of the compression zone. At the end of the test, the vertical steel bars are yielded. The most lateral longitudinal bar of YZ12 is broken at the connection between the ground beam and the prefabricated shear wall specimens. In the late test of three contrast cast-in-situ shear walls, the concrete compression zone was completely crushed. The edge longitudinal reinforcement is exposed and shows obvious deformation. By comparing the two kinds of walls, it is proved that the bonding method of the restrained pulp anchor bar is safe and effective.

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