Numerical Analysis on the Effect of Vital Design Parameters on the Seismic Performance of Shear Walls with Horizontal Ring Connection

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Abstract. Prefabricated shear walls are currently widely applied in mid-to-high-rise structures. As a new type of structural form of assembled shear walls, the ring connection assembled concrete shear wall has clear mechanical mechanism, easy construction and better performance and other significant advantages, which are gradually being applied in actual engineering. However, few systematic studies are carried on this new type of shear wall structure, and a complete theoretical system for guiding the design could not be given, especially in terms of mechanical mechanism and seismic performance, more detailed research work is needed. This paper uses numerical simulation as the main method to study the influence of different design variables such as shear span ratio, buckle size, axial compression ratio on the mechanical properties of the connection area in shear wall and the overall seismic performance of the structure. In this way, the theoretical basis for further optimizing the structural performance of the shear wall connection with ring connection.

Keywords. Precast building, shear wall, ring joint, numerical analysis, seismic performance.

1. Introduction

Prefabricated concrete shear wall, its main component are prefabricated wall panels, which are installed on site and partly connected by joints and cast in place. The main advantages of prefabricated shear wall concrete structures are production standardization, fast construction speed, energy saving and environmental protection, high construction quality, and conducive to the green and sustainable development of the society.

The current prefabricated concrete shear wall structure research focuses on the connection of horizontal wall panels and vertical wall panel steel bars. A reasonable connection method can transfer the force to other wall panel components reasonably, and meet the requirements on the basis of ensuring reliable connection the overall safety of the structure. Nodes are one of the important links in the design of fabricated shear walls. The steel bars at the nodes are required to be connected reliably, with clear force transmission, and easy to construct. Therefore, if you want to promote the overall seismic performance of fabricated shear walls and implement them in actual projects to promote the application, it is necessary to reasonably design and optimize the connection structure of the nodes. Researchers propose a ring connection [1-3], which is different from the traditional grouting sleeve and spiral stirrup grout anchor connection [4-7]. Research shows that the connection has good mechanical properties and the seismic performance of structural members is good. However, this
connection is applied to the horizontal joint connection of shear wall members, and its seismic performance needs further study. Therefore, based on experimental research, we carry out further research with the help of finite element software.

2. Design

2.1. Analysis Plan
To study the effect of key design factors on the seismic performance of shear walls and the mechanical mechanism of the ring connection, this chapter explores the effect of the design factors shown in Table 1 based on the ABAQUS finite element numerical simulation. The model design plan is shown in Table 1. The other parameter settings in the model are consistent with those in the literature [8, 9]. The design requirements of the ring connection size in the ring connection area meet the research results in the article, and other design requirements meet current specifications.

Table 1. Parameter list of numerical model.

| Specimens       | Parameter       | Wall size Height x Width (mm) | Axial ratio | Snap-in size of connection area (mm) | Thickness (mm) |
|-----------------|-----------------|------------------------------|-------------|------------------------------------|----------------|
| SWJ1F1K1W1      |                 | 3000×3000                    | 0.1         | 200                                | 200            |
| SWJ2F1K1W1      |                 | 3000×2000                    | 0.1         | 200                                | 200            |
| SWJ3F1K1W1      |                 | 3000×1500                    | 0.1         | 200                                | 200            |
| SWJ3F2K1W1      |                 | 3000×1500                    | 0.3         | 200                                | 200            |
| SWJ3F3K1W1      |                 | 3000×1500                    | 0.5         | 200                                | 200            |
| SWJ3F1K2W1      |                 | 3000×1500                    | 0.1         | 250                                | 200            |
| SWJ3F1K3W1      |                 | 3000×1500                    | 0.1         | 300                                | 200            |

2.2. Numerical Model
In the modeling process, the concrete material adopts the plastic damage concrete model and C3D8R unit, and the mesh size is 100 mm; the reinforcement material uses the damage model and T3D2 unit, and the mesh size is 50 mm.

The wall part and the foundation part are connected by vertical rebars. The research of this paper focuses on the study of seismic performance and mechanism of force, so the embedded connection method is selected. Figure 1 shows the model details.

Figure 1. The finite element model of the one-shaped shear wall specimen.
2.3. Model Verification

Based on the experiments in the literature [10], this paper establishes a quantitative model and carries out verification of numerical research methods, mainly including damage phenomena and bearing capacity performance.

The comparative analysis of finite element model and bearing capacity performance is shown in figures 2 and 3. According to the figure 4 it can be seen that the concrete cracking of the numerical model is basically consistent with the test results, mainly developing from the bottom up, all of which are bending failures.

![Figure 2](image1.png)

**Figure 2.** Overall schematic diagram of loading beam-shear wall

![Figure 3](image2.png)

**Figure 3.** Comparison and analysis of skeleton curve between numerical research and test results.

![Figure 4](image3.png)

(a) DAMAGET  (b) DAMAGEC  (d) PEEQ  (c) PEMAG

**Figure 4.** Cloud map of concrete damage.

In summary, the numerical research analysis results are relatively close to the experimental results, and this numerical method could be used for further performance research.

3. Results Analysis

3.1. Effect of Shear Span Ratio

In order to explore the effect of different shear span ratios on the buckling connection area of the ring reinforcement and the seismic performance of the specimens, models with shear span ratios of 1, 1.5 and 2 were established and numerical studies were carried out. The study found that the failure process and phenomenon of specimens are basically the same. Concrete failures are mainly the failure of the bottom and the horizontal cracks or diagonally downward shear cracks in the upper part, but the failure modes of the shear wall are different. Figure 5 shows the concrete cracking cloud diagrams. When the ratio is 1 and 1.5, the concrete damage at the bottom of the wall is serious and concentrated. The cracks on both sides of the wall first develop in the horizontal direction and then develop diagonally downward, which is a bending-shear failure mode. The cracks in the middle and upper part...
of the shear wall with a ratio of 2 are mainly horizontal cracks and develop step by step in parallel, which is a bending failure mode.

![Figure 5](image1.png)

**Figure 5.** Failure pattern of specimen.

According to figure 6 for the three specimens with different shear span ratios, the steel bars on both sides of the bottom have yielded, and the stress level of the steel bars in the buckling area of the ring rebars is low, and the steel rebars have not yielded or broken. When the ratio is 1, the stress of the outermost steel bar at the bottom is the largest, reaching the ultimate stress. The stress level of the steel bar inside the bottom is lower. At the middle of the wall, the stress is concentrated in the middle wall, and the stress on both sides is higher; when the ratio is 1.5 and 2, the stress distribution of the steel bar at the bottom is more uniform, reaching the maximum tensile stress almost at the same time and breaking, and the stress of steel shows a decreasing trend along the height of the wall. The ring-bar buckle connection under three shear span ratios is safe and reliable.

![Figure 6](image2.png)

**Figure 6.** Stress cloud diagram of shear wall with different shear span ratio.

As the shear wall shear span ratio gradually increased, its peak load decreased from 1649.9 kN to 554.836 kN, and the peak displacement increased significantly from 10.0 mm to 25.0 mm (figure 7 (a)); the ductility of the shear wall specimen The coefficient presents a trend of first increasing and then decreasing (figure 7 (b)); the stiffness of the shear wall decreases as the shear span ratio gradually increases by 55% (figure 7 (c)); Figure 7 (d) shows that the shear wall has a larger initial energy consumption capacity when the ratio is 1, but the total energy consumption is lower. The shear wall has the highest total energy consumption capacity while the shear-span ratio is 1.5, and the shear-span ratio when it is increased to 2, the energy consumption is reduced.
5

(a) Skeleton curve

(b) Ductility coefficient

(c) Stiffness degradation

(d) Energy consumption

Figure 7. Hysteretic analysis of shear wall specimens with different shear span ratios.

In summary, the shear-span ratio is an important design factor. The larger the shear-span ratio, the higher the mechanical performance requirements of the ring-bar fastening connection area. The ring-bar fastening connection can realize load transfer and is safe and reliable.

3.2. Effect of Axial Compression Ratio

In order to explore the effect of the axial compression ratio of the shear wall, three specimens with different the axial compression ratio were designed and numerical studies were carried out. The study found that the failure process is basically the same, but the failure phenomenon of shear wall concrete is different, mainly in the failure area and failure development form; through numerical research, the concrete failure stress cloud diagram in figure 8 is obtained.

Figure 8. Cloud diagrams of concrete crack pattern with different axial compression ratios.
Figure 8 shows that the distribution of cracks in the shear wall gradually changes from horizontal cracks to concentrated damage at the bottom end of the wall, and the development area of cracks gradually decreases with the increasing of the axial compression ratio. When the ratio is 0.5, the stress level in the middle of the bottom is lower, the concrete is not damaged, and the end stress level is higher, and the concrete cracks and fails. The distribution of cracks in the shear wall gradually changes from horizontal cracks to concentrated damage at the bottom end of the wall. When the ratio is 0.5, the stress level at the bottom 1/3 height of the wall is all very high, while the ratio reaches the design limit, the bottom of the shear wall will be crushed and damaged.

Figure 9. Rebar stress cloud diagram with different axial compression ratios.

Figure 10. Hysteretic analysis of shear wall specimens with different axial compression ratio.
The stress cloud of rebars with different axial compression ratios were shown in Figure 9. The stress of rebars is concentrated at the bottom and the end rebars have yielded. The stress of the outermost rebar at the bottom is the largest while the ratio is 0.1, reaching the ultimate stress and tensile failure, the stress level of the rebar inside the bottom is lower, and the rebars in the ring-reinforced area are not damaged. When the ratio is 0.3 and 0.5 respectively, the stress distribution of the rebars at the bottom is more uniform, and the stress of the rebars shows a decreasing trend along the height of the wall. As the ratio range from 0.1 to 0.5, the fracture cracks of the shear wall gradually change from horizontal cracks to concentrated crushing damage at the bottom end. The middle of the shear wall is damaged at the bottom and crushing damage were observed in the middle of the body. Comprehensive analysis shows that under the action of different axial compression ratios, the steel bars at the bottom are in an elastic working state, and the connection is safe and reliable.

The results of hysteresis performance analysis shown in figure 10 are obtained through numerical research. As the axial pressure of the shear wall increases step by step, when the ratio is 0.3 and 0.5, the yield load increases by 26% and 30%, respectively, compared with the axial compression ratio of 0.1, but the peak load increases by 33% and 45% respectively (figure 10 (a)). When the ratio is 0.3 and 0.5, the ductility coefficient of the shear wall is 28% and 43% lower respectively than that of 0.1 (figure 10(b)). The stiffness shows a decreasing trend with the gradual increase of the axial pressure, but its residual stiffness is basically the same (figure 10(c)). The total energy consumption of the shear wall decreases with the increase of the axial compression ratio (figure 10(d)).

In summary, increasing the axial compression ratio within a certain range could improve the seismic performance of the shear wall. With the increasing of ratio, the yield and ultimate load increase, and the rigidity increases, the strain value of the steel bar in the connection area shows a decreasing trend, and the connection is safe and reliable.

3.3. Effect of the Size of the Connection Area
In order to explore the effect of the connection size of the shear wall on the seismic performance of the shear wall, three specimens with different fastening sizes in the connection area were designed and carried out numerical research. The study found that the failure process of different shear walls is basically the same. The difference lies in the differences in the location of the failure cracks and the bearing capacity of the concrete. Figure 11 shows the tension failure cloud diagram of the shear wall with different fastening sizes in the ring reinforcement connection area. It can be seen from the figure that the shear wall cracks of the three different ring bar fastening sizes are all horizontal cracks, which are bending failures. The difference is that as the fastening size increases, the cracks gradually develop from the bottom to the top, and the cracks are distributed in the area, as the size of the buckle increases.

It can be seen from figure 12 that the stress level of rebars at the bottom end is relatively high, and yield failure occurs first, and the steel bars in the buckling area of the ring reinforcement have not yielded and are in an elastic working state, indicating that the connection is safe and reliable.

![Figure 11](image_url). Cloud diagrams of concrete tensile cracking of shear walls with different connection areas.
The hysteretic performance results shown in figure 13 are obtained through numerical research. As the buckling size of the shear wall increases step by step, the yield load and ultimate failure load of the shear wall do not change much; when the buckling size level is level 2 and level 3, the ductility coefficient is reduced by 9% compared with the level 1 (figure 13(b)). With the gradual increase in the size of the buckle, the rigidity is basically the same (figure 13(c)). As the size of the buckle increases step by step, the energy consumption of the shear wall is basically the same (figure 13(d)). The ring reinforcement buckle connection realizes the vertical load transfer and is safe and reliable. The change of the buckle size of the shear wall ring reinforcement increases the strain value of the steel bar in the connection area, but the increase in the elastic stage is small.

**Figure 12.** Rebar stress cloud diagram with different connection areas.

**Figure 13.** Hysteretic panalysis of shear wall specimens with different connection areas.
In summary, changing the size of the ring rebar has little effect on the seismic performance. With the increasing in the size of ring rebar, the yield and ultimate load are basically in the equal level, the ductility coefficient is slightly reduced, the stiffness is basically the same, and the energy consumption is basically the same. Importantly, the connection is safe and reliable.

4. Conclusion
This paper is based on the ring-reinforced connection technology and experimental research with the aid of numerical research methods, explores the effect of different design factors. The following conclusions:
- The numerical research method used in this paper could reflect the mechanical mechanism of ring connection, and could be used for subsequent seismic performance research.
- As the shear span ratio gradually increases, the failure mode changes from the shear failure mode to the bending failure mode. When the ratio is relatively small, the failure load is low. With the ratio increase, the tensile load of the vertical rebars at the two ends increases and the strain value of the ring rebars in the connection area increases step by step. As the ratio increases, the seismic performance is significantly affected. The larger the ratio, the higher the requirements for the mechanical properties of the ring connection area.
- As the axial compression load increases step by step, the peak load increases significantly, while the ductility coefficient also decreases. The stiffness tends to decrease with the axial pressure gradual increasing, but the residual stiffness is basically the same. The total energy consumption of the shear wall shows a decreasing trend while the ratio increase.
- Changing the connection size of the ring rebar has less impact. With the increase in the connection size of the ring rebar, the yield and ultimate load are basically in the same level, the ductility coefficient is slightly reduced, the stiffness is basically the same, and the energy dissipation capacity is basically the same.
- In summary, the ring connection could realize load transmission, the force transmission path is clear, and the connection is safe and reliable.

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