Stiffness Degradation of Shear Wall with Frame Column and its Influence to Structural Performance

Ming Wen, Zipeng Huang, Xinfang Wang, Baokui Chen, Yu Wan
School of Civil Engineering and Architecture, Nanchang University, Nanchang 330031, China
Email: 734525570@qq.com

Abstract. The shear wall with frame column has a wide application prospect in practical engineering for it has better ductility, bearing capacity and stiffness degradation than the shear wall with unframed column. In this paper, the finite element model of shear wall with frame column for an experiment was established in ABAQUS software firstly. Then on the base of proving the model’s precision, the axial compression ratio and the stiffness ratio of shear wall with frame column were adjusted, the influence of different axial compression ratio and stiffness ratio on the stiffness degradation coefficient was analyzed and the corresponding formulas were fitted. At last, by changing the axial compression ratio and the stiffness ratio of shear wall with frame column, The influence of stiffness degradation on the maximum displacement amplification coefficient and the bottom shear amplification coefficient were studied and the relevant formulas were fitted.

1. Introduction
With the development of science, technology and the improvement of people's living standard, the development and utilization of high-rise buildings with Shear walls are more and more extensive. Shear wall is generally divided into two types: shear wall with unframed column and shear wall with frame column. References [1] [2] show that the ductility, bearing capacity and stiffness degradation of shear wall with frame column for an experiment was established in ABAQUS software firstly. Then on the base of proving the model’s precision, the axial compression ratio and the stiffness ratio of shear wall with frame column were adjusted, the influence of different axial compression ratio and stiffness ratio on the stiffness degradation coefficient was analyzed and the corresponding formulas were fitted. At last, by changing the axial compression ratio and the stiffness ratio of shear wall with frame column, The influence of stiffness degradation on the maximum displacement amplification coefficient and the bottom shear amplification coefficient were studied and the relevant formulas were fitted.
degradation of shear wall is related to inter-layer displacement angle, axial compression ratio and shear-span ratio by Zhao Shifeng et Al [10].

From the studies that had been done, it can be found that the research on stiffness degradation of shear wall with frame column was mostly confined to experiment, and systematic analysis was seldom done. In this paper, the concept of stiffness ratio of shear wall with frame column was proposed firstly. Then a finite element model for an experiment was established in ABAQUS software, after proving the accuracy of the model, the influence of axial compression ratio and stiffness ratio on the stiffness degradation of shear wall with frame column was analyzed and the corresponding calculation formulas were fitted. At last, for an actual frame-shear wall with frame column structure, the axial compression ratio and the stiffness ratio of shear wall with frame column were changed, and the influence of stiffness degradation of shear wall with frame column on the magnification coefficient of maximum displacement and the magnification coefficient of bottom shear was studied. The conclusions have certain theoretical and practical value.

2. Establishment of Finite Element Model of Shear Wall with Frame Column

According to one of the experiments made by Sun Jinchi on shear wall with frame column [8], a finite element model was established in ABAQUS software. The parameters of the model were described as follows: the reinforcement ratio of frame column is 0.448% (4Ф4), the shear span ratio of shear wall is 3.37, and the reinforcement ratio of wall is 0.593% (3.5@35); the exact dimensions of the model were shown in figure 1.

The steel bar is grade 1 steel, the yield strength is 235 N/mm², Poisson’s ratio is 0.3, and the elastic modulus is 206 GPa. The concrete is C30, Poisson’s ratio is 0.2, the elastic modulus is 30 GPa. The concrete constitutive model is plastic damage model, and the steel constitutive model is two-fold line follow-up hardening model. The finite element model established in ABAQUS was shown in figure 2.

Let \( \beta = \frac{k_t}{k_0} \), Where \( \beta \) is stiffness Degradation coefficient; \( k_0 \) is initial stiffness of the shear wall with frame column; \( k_t \) is the secant stiffness of the shear wall with frame column.

Using the same loading mode as the experiment [8], the comparison of \( \beta \) got by calculation and got by experiment was shown in table 1.

From table 1, it can be concluded that the results are almost identical and the errors are within the allowable range, the finite element model established in ABAQUS software is effective.

3. Study on Influence Factors of Stiffness Degradation of Shear Wall with Frame Column

![Figure 1. Overall dimension of shear wall with frame column specimen.](image1)

![Figure 2. Loading model of shear wall with frame column structure.](image2)
Table 1. Comparison of β got by calculation and got by experiment.

| Inter-layer displacement angle | 1/3000 | 1/2000 | 1/1000 | 1/750 | 1/500 | 1/300 | 1/250 | 1/120 |
|-------------------------------|--------|--------|--------|-------|-------|-------|-------|-------|
| Experimental results          | 1.00   | 0.86   | 0.67   | 0.57  | 0.46  | 0.35  | 0.30  | 0.20  |
| Calculation result            | 0.996  | 0.855  | 0.657  | 0.554 | 0.453 | 0.342 | 0.289 | 0.188 |

The stiffness degradation performance of shear wall with unframed column is related to axial compression ratio and shear-span ratio, while the stiffness degradation performance of shear wall with frame column is related to the stiffness ratio of frame column and shear wall besides axial compression ratio. The stiffness ratio of frame column to shear wall is defined as

$$\frac{f_C}{\frac{EI}{w}}$$

where $f_C$ is the lateral stiffness of frame column; $H$ is the height of shear wall and $\frac{EI}{w}$ is the stiffness of shear wall. The effect of axial compression ratio and stiffness ratio on the stiffness degradation performance of shear wall with frame column was analyzed as follow in detail.

3.1. Influence of Axial Compression Ratio on Stiffness Degradation Performance of Shear Wall with Frame Column

The stiffness ratio $m$ remained unchanged at 1.4, the axial compression ratio $u$ was set as 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55 and 0.6 respectively. The corresponding models were established and calculated. Let $\alpha = \frac{\theta}{3000}$ ($\theta$ is inter-layer displacement angle). The relationship between inter-layer displacement angle and stiffness degradation coefficient under different axial compression ratio was shown in figure 3. As can be seen in figure 3

(1) The stiffness of shear wall with frame column decreases with the increasing of inter-layer displacement angle, and the degradation curve decreases obviously when $\alpha$ is in the range of 1.5-6.

(2) The axial compression ratio of shear wall has obvious influence on the stiffness degradation coefficient of shear wall with frame column. When the inter-layer displacement angle is the same, the stiffness degradation coefficient increases and the stiffness degradation degree decreases with the increasing of axial compression ratio.

(3) When the axial compression ratio changes between 0.1-0.25, the stiffness degradation coefficient of the shear wall changes greatly; and when the axial compression ratio changes between 0.25-0.5, the stiffness degradation coefficient of the shear wall changes little.

3.2. Influence of Stiffness Ratio on Stiffness Degradation Coefficient of Shear Wall with Frame Column

The axial compression ratio remained unchanged at 0.25, the stiffness ratio was set as 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 6.0 respectively. The corresponding models were established and calculated. Let $\alpha = \frac{\theta}{3000}$ ($\theta$ is inter-layer displacement angle). The relationship between inter-layer displacement angle and stiffness degradation coefficient under different stiffness ratio was shown in figure 4.

![Figure 3: Relationship curves between Inter-layer displacement angle and stiffness degradation coefficient under different axial compression ratio.](image)

![Figure 4: Relationship curves between Inter-layer displacement angle and stiffness degradation coefficient under different stiffness ratios.](image)
As can be seen in figure 4

(1) With the increasing of stiffness ratio between frame column and shear wall, the stiffness degradation degree of shear wall decreases when reaching the same inter-layer displacement angle.

(2) The stiffness degradation curve of shear wall decreases rapidly when $\alpha$ is in the range of 1-3, and the stiffness degradation coefficient is obviously affected by the inter-layer displacement angle. The stiffness degradation curve is relatively gentle when $\alpha$ is in the range of 3-10.

(3) With the increasing of the stiffness ratio between frame column and shear wall, the stiffness degradation velocity of shear wall decreases after elastic-plastic deformation. The stiffness ratio has an obvious effect on the stiffness degradation velocity when stiffness ratio is in the range of 1 - 2.8, and when the stiffness ratio is between 2.8 - 6.0, the stiffness degradation of shear wall is not obvious, the stiffness degradation performance of shear wall has been improved obviously.

3.3. Analysis of Stiffness Degradation of Shear Wall with Frame Column under Comprehensive Factors

The stiffness ratio was set as 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.5, 6.0 respectively; axial compression ratio was set as 0.25, 0.3, 0.35, 0.4 respectively, 52 sets of shear wall with frame column models were established, and the stiffness degradation performance of shear wall with frame column under different stiffness ratio and axial compression ratio was analyzed separately. Due to the limitation of space, the stiffness degradation coefficients were shown in table 2 only when the stiffness ratio is 1 and the axial compression ratio is 0.25.

| Inter-layer displacement angle | 1/3000 | 1/2000 | 1/1000 | 1/750 | 1/500 | 1/300 |
|--------------------------------|--------|--------|--------|-------|-------|-------|
| Stiffness Degradation Coefficient | 0.992  | 0.755  | 0.527  | 0.413 | 0.298 | 0.196 |

After fitting all the data of 52 models, the formula of stiffness degradation coefficient can be denoted as:

$$\beta = \sin \left[ \frac{1 + e^{p_1u} + e^{p_2u} + e^{p_3u}}{p_4 + e^{p_5u} + e^{p_6u} + e^{p_7u}} \right] \left( \frac{p_{10} - m}{p_{10} - m} \right)$$

Where $\beta$ is stiffness degradation coefficient, values range from 0-1; $m$ is stiffness ratio of frame column to shear wall, values range from 1-6; $u$ is axial compression ratio, values range from 0.25-0.4; $\theta$ is inter-layer displacement angle, values range from 1/3000-1/300; $p_1=0.17$; $p_2=137.54$; $p_3=-115.91$; $p_4=-2.99$; $p_5=0.00016$; $p_6=19.60$; $p_7=-0.0074$; $p_8=-1.0$; $p_9=0.66$; $p_{10}=-218.03$.

The comparison between data got from fitting formula and got by the finite element calculation (the target value) was shown in figure 5. It was shown that the fitting formula has higher precision.

4. Influence of Stiffness Degradation of Shear Wall with Frame Column on Seismic Behavior of Frame-Shear Wall Structure

For a frame-shear wall with frame column structure, the load on the structure was adjusted to change the axial compression ratio of the shear wall, and the section size of the frame-column was adjusted to
change the stiffness ratio of the frame-column to the shear wall, elastic time-history and elastic-plastic time-history analysis of structure with different axial compression ratio and stiffness ratio were carried out in SAP software.

The ratio between maximum floor displacement got in elastic-plastic time-history condition and that got in elastic time-history is defined as magnification coefficient of maximum displacement, and the ratio between the bottom shear got in elastic-plastic time-history condition and that got in elastic time-history is defined as magnification coefficient of bottom shear. The maximum inter-layer displacement angle got by elastic-plastic time-history analysis and the corresponding axial compression ratio and stiffness ratio of the shear wall with frame column were taken into formula (1) to obtain the stiffness degradation coefficient. The influence of stiffness degradation coefficient of shear wall with frame column on the displacement magnification coefficient and the bottom shear magnification coefficient were analyzed and the related formulas were fitted.

The structure is a 14-story frame-shear wall with frame-column structure. The height of bottom floor is 3.6 m, and the height of the other floors is 3.3 m. The layout of the structure is shown in figure 6. The seismic fortification intensity is 7 degree, the site type is II, the design earthquake grouping is the second group, the site characteristic period is 0.4 s.

The concrete strength of wall and column is C40 from 1 to 4 layers, and is C35 from 5 to 11 layers. The concrete strength of beam and plate is C30 from 1 to 11 layers. The concrete strength of each member from 12 layers to top layer is C25. The live load of floors is 2 kN/m². The reinforcement grade of column, beam and wall is HRB400, the size of frame column from 1-4 layers is 750×750, and is 600×600 from 5-14 layers, the thickness of shear wall is 200.

According to the norm, one artificial seismic wave RH1TG040 and two natural seismic waves TH003TG040 and TH005TG040 were selected for time history analysis. The bottom shear force calculated from each time history curve is more than 65% result calculated from the formation decomposition response spectrum method, the average value of the bottom shear force calculated by several time history curves is more than 80% result calculated from the formation decomposition response spectrum method, which means that the specifications are met. The formulas were fitted according to the seismic wave data with the largest amplification coefficient.

By adjusting the load value, the axial compression ratio can be adjusted to 0.28, 0.3, 0.32, 0.34, and by adjusting the frame column size to 600x600, 650x650, 600x700, 750x750, the stiffness ratio of shear wall with frame column can be adjusted to 1.965, 2.234, 2.469, 2.685. 16 groups of models were established and analyzed.

![Figure 6. Structural layout plan.](image)

4.1. The Influence of Axial Compression Ratio Variation on Structural Performance with Constant Stiffness Ratio

The stiffness ratio remained unchanged at 1.965, the axial compression ratio was set as 0.28, 0.3, 0.32, 0.34 respectively, the corresponding stiffness degradation coefficients of shear wall were 0.264, 0.303, 0.316 and 0.326. The relationship between the stiffness degradation coefficient and the bottom shear force magnification coefficient and the maximum displacement magnification coefficient was shown in figure 7.

As can be seen in figure 7

(1) When the stiffness ratio of frame column to shear wall is constant, the stiffness degradation coefficient of shear wall on the maximum displacement angle floor increases with the increasing of axial compression ratio in the limit range

(2) The maximum displacement amplification coefficient and bottom shear amplification coefficient of the structure decrease with the increasing of stiffness degradation coefficient of shear wall.
4.2. The Influence of Stiffness Ratio Variation on Structural Performance with Constant Axial Compression Ratio

The axial compression ratio remained unchanged at 0.28, the stiffness ratio was set as 1.965, 2.234, 2.469, 2.685 respectively, the corresponding stiffness degradation coefficients of shear wall were 0.264, 0.273, 0.279 and 0.285. The relationship between the stiffness degradation coefficient and the bottom shear force magnification coefficient and the maximum displacement magnification coefficient was shown in figure 8. As can be seen in figure 8:

1) When the axial compression ratio of shear wall remains constant, the stiffness degradation coefficient of shear wall increases with the increasing of the stiffness ratio of frame column to shear wall.

2) The maximum displacement magnification coefficient and bottom shear magnification coefficient decrease with the increasing of stiffness degradation coefficient of shear wall.

4.3. Influence to Structural Performance with Change of Axial Compression Ratio and Stiffness Ratio

Due to space limitation, the stiffness degradation coefficients of the layer with the maximum inter-layer displacement angle, the maximum displacement magnification coefficient and the bottom shear magnification coefficient were listed in table 3 only when the stiffness ratio was 1.965 and the axial compression ratio was 0.32.

Table 3. Elastoplastic analysis results when m = 1.965, μ=0.32.

| Analysis category        | Elastoplastic time-history analysis |
|--------------------------|------------------------------------|
| Coefficient of stiffness degradation | 0.316                              |
| Displacement magnification coefficient | 3.48                               |
| Bottom Shear magnification coefficient | 3.05                               |

From calculation data of 16 models, the relationship between the stiffness degradation coefficient and the maximum displacement magnification coefficient can be fitted into formulas (2), and the relationship between the stiffness degradation coefficient and the bottom shear magnification coefficient can be fitted into formulas (3).

\[
X_d = \cos(p_1u) + \frac{1}{p_2 + u} - \frac{1 + p_3\beta + p_4 + p_5m}{p_4 + p_5u + p_6m} + \frac{p_7}{(1 - \beta)^2}
\]  \(2\)

Where \(X_d\) is maximum displacement magnification coefficient; \(m\) is stiffness ratio of frame column to shear wall, Values range from 1.965~2.685; \(u\) is axial compression ratio, values range from 0.28~0.34; \(\beta\) is stiffness degradation coefficient of shear wall, \(p_1=0.043; \ p_2=-0.23; \ p_3=190.39; \ p_4=-64.87; \ p_5=-7.22; \ p_6=-11.793; \ p_7=15.30; \ p_8=36.82; \ p_9=-0.60; \ p_{10}=-0.34; \)

\[
X_v = p_1 + p_2mu + p_3m\beta + p_4u\beta + p_5m + p_6u + p_7m^2 + p_8u^2
\]  \(3\)
Where $X_v$ is bottom shear magnification coefficient; $m$ is stiffness ratio of frame column to shear Wall, values range from 1.965–2.685; $u$ is axial compression ratio, values range from 0.28–0.34; $\beta$ is stiffness degradation coefficient; $p_1=28.48$; $p_2=-19.42$; $p_3=21.11$; $p_4=-134.33$; $p_5=1.11$; $p_6=-149.72$.

The comparison between the result calculated by fitting formula and the result calculated by finite element (target value in figure) were shown in figure 9, which shows that the fitting formulas have enough precision.

(a) Error of maximum displacement magnification coefficient between formula and target value
(b) Error of bottom shear magnification coefficient between formula and target value

Figure 9. Comparison between fitting formula calculation results and finite element calculation results.

5. Conclusion
The following conclusions can be drawn from previous analysis

(1) When the stiffness ratio remains constant, the stiffness degradation of the shear wall with frame column under the same displacement angle is more obvious with the decreasing of the axial compression ratio; and when the axial compression ratio remains constant, the stiffness degradation of the shear wall with frame column under the same displacement angle is more obvious with the decreasing of the stiffness ratio.

(2) The relationship between axial compression ratio, the stiffness ratio of the frame column to the shear wall, the displacement angle and the stiffness degradation coefficient can be fitted as formula (1), the formula has high precision.

(3) When the stiffness ratio of frame column to shear wall is constant, the shear wall stiffness degradation coefficient of the layer with the maximum inter-layer displacement angle increases with the increasing of axial compression ratio in the limit range, and the displacement magnification coefficient and bottom shear magnification coefficient decreases with the increasing of stiffness degradation coefficient.

(4) When the axial compression ratio is constant, the shear wall stiffness degradation coefficient of the floor with the maximum inter-floor displacement angle increases with the increasing of stiffness ratio of the frame column to the shear wall, and the displacement magnification coefficient and bottom shear magnification coefficient decrease with the increasing of stiffness degradation coefficient.

(5) The relationship between axial compression ratio, the stiffness ratio, stiffness degradation coefficient and the maximum displacement magnification coefficient can be fitted as formula (2), the relationship between axial compression ratio, the stiffness ratio, stiffness degradation coefficient and the bottom shear magnification coefficient can be fitted as formula (3), the formulas have high precision.

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