Analysis of the Effect of Column-to-Beam Strength Ratio on Seismic Performance of RC Frame Structure

Hao Zhang¹, Zhanxuan Zuo¹*, Maosheng Gong¹*, and Lili Xie¹

¹Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration, Harbin 150080, China)  
²E-mail: zuozhanxuan@sina.com; gmshiem@163.com

Abstract. Strong column-weak beam is one of the important concepts in seismic design of RC frame structure. The experience of earthquake damage shows that the structure designed according to the existing codes cannot achieve the expected failure mode of strong column-weak beam due to the effects of factors such as axial compression ratio, slab and so on. In this paper, the RC frame structures are designed with column-to-beam strength ratio of 1.2, 1.4, 1.6, 1.8 and 2.0, and the structural responses are obtained using Push-over analysis. The effect of column-to-beam strength ratio on failure modes of RC frame structure is studied. The results show that the existence of slab affects the yield mechanism of steel bars in beams and columns, and further affects the possible failure modes of structures. In case of considering slab, increasing column-to-beam strength ratio can effectively enhance structural seismic capacity. The failure mode of strong column and weak beam can be achieved when the column-to-beam strength ratio is 1.8.

1. Introduction
RC frame structure is widely used all over the world. According to the seismic design code of buildings, the deformability of frame structures is closely related to the failure mechanism of structures [1]. Studies show that the strong column-weak beam failure mode can make the whole structure have better internal force redistribution and energy consumption capacity and increase the ultimate inter-story displacement [2]. However, in post-earthquakes, a large number of plastic hinges appear at the end of columns in RC frame structures, which cannot achieve the design expectation of strong column-weak beam in seismic design code. The main reason is the effect of the slab. Ehsani and Wight has conducted six full-scale joint tests with floor slabs, and suggested how to consider the effect of slab in calculating the flexural strength of the beam [3]. Kara and Dooley analyzed the three-story and six-story frame structures respectively, and suggested that the minimum column-to-beam strength ratio (η) should be 2.0 to meet the needs of strong columns and weak beams[4]. The above study shows that the effect of slab on seismic performance of structures cannot be ignored and further research is needed.

In view of the problem that the frame structure fails to achieve the failure mechanism of strong column-weak beam under earthquake, this paper analyzes the effect of slab and column-to-beam strength ratio on failure mode, and suggests the reasonable values of the ratio[5].

2. Structural model and analysis
A 3-story RC frame structure was designed according to seismic design code[1]. The sketch of frame structure is shown in Fig.1. The concrete strength of the structure is C30. HRB335 for longitudinal...
reinforcement of beams and columns, HPB300 for stirrups and slab bars. The section of column and beam are 400mm×400mm and 250mm×400mm respectively. In the analysis, the column-to-beam strength ratio is adopted as 1.2, 1.4, 1.6, 1.8 and 2.0 by adjusting column reinforcement. The pushover analysis of the structures is performed based on OpenSees[6], and the responses are obtained and analyzed.

Figure 1. Sketch of frame structure

3. Effect of slab on frame structure

3.1. Structural capability curve
The inverted triangle inertial force distribution is used to control the vertex displacement of the structure to 180 mm, and relationship between the base shear force and the vertex displacement of the structure is calculated as shown in Fig. 2.

From Fig. 2, it can be seen that the shapes of their capacity curves are similar. When the vertex displacement is equal, the base shear force of frame with slab is larger than that of frame without slab. The maximum base shear force of frame without slab is 7.76% higher than frame with slab. When the reinforcement of column is same, the greater the base shear force is, the greater the stress of the longitudinal reinforcement of the column will be, and the corresponding column reinforcement will yield first. Therefore, the plastic deformation capacity of frame without slab is stronger than structure with slab.

Figure 2. Relationship between base shear and vertex displacement of structure
3.2. Stress change of reinforcement
During the Push over analysis, the stress of steel bar varies with the increase of the displacement of the vertex. In this paper, taking the middle node 9 (Fig. 1) of the bottom story of the structure as an example, the effect of the slab on the seismic behavior of the frame structure is analyzed by comparing the changes of the stress of the beam between the frames with and without slab.

![Figure 3. Relationship between stress and vertex displacement of beam-column reinforced steel](image)

It can be seen from Fig. 3, when the vertex displacement is same, the tension stress of the frame beam with slab is less than the frame without slab. On the section 2 (Fig. 1), the slab frame and the frame with slab are yielded at the same time. The reason is that both the longitudinal bars of the bottom of the beam participate in the tension, and the existence of the slab has little effect on the stress of the steel bar at the bottom of the beam. In section 1 (Fig. 1), the steel bars with slab structure have never yielded, but the section 2 of the frame without slab yielded earlier. The reason is that the steel bars of section 1 participate in the bending action at the beam and slow down the yield speed of the steel bars on the top of the beam, thus changing the yield order of the steel bars in the beam of frame structure.

4. Effect of different column-to-beam strength ratio on RC frame structure

4.1. Structural capability curve
Pushover analysis was carried out on five models with different value of η. The vertex displacement and base shear of each model were recorded and the relationship curves were drawn as shown in Fig. 4.

![Figure 4. Base shear-vertex displacement curve](image)
It can be seen that the capacity curves of structures with different values of $\eta$ are relatively close in the elastic range. With the increase of $\eta$, the bearing capacity of the structure increases gradually. When $\eta$ is adopted as 1.2, 1.4, 1.6, 1.8 and 2.0, the maximum base shear force of the structure is 19.5%, 37.7%, 54.6%, 72% higher than that of $\eta=1.2$.

4.2. Realization of strong column weak beam performance

Taking node 9 as an example, Fig. 5 shows the variation of tension steel bar with vertex displacement of beam-column joints under different $\eta$. It can be seen that with the increase of $\eta$, the structure transits from column hinge failure to beam hinge failure. When $\eta=1.6$, the tension bar of column and beam almost yield at the same time. When $\eta=1.8$, the tension bar of beam will yield before the column section. The stress of the compressive steel in section 2 and slab is small, which is not affected by the value of $\eta$. The reason is that the compressive stress is afford by the concrete.

Figure 5. Relationship between stress and displacement of steel bar in beam and column
5. Conclusion
Pushover analysis is carried out for 3-story RC frame structures with different value of $\eta$. By comparing the structural capacity curve, the effects of slab and the value of $\eta$ on beam-column failure modes are studied. The following conclusions are drawn:

1. In pushover analysis under the lateral force distribution of inverted triangle, the frame structure with slab has a certain improvement in the bearing capacity compared with the frame without slab. The slab changes the yield order of steel bar in frame structure.
2. Considering the effect of slab, the seismic capacity of RC frame structure is gradually enhanced with the increase of $\eta$, and the failure mode is transited from column hinge to beam hinge. When the value of $\eta$ increases to 1.8, the failure mode of strong column weak beam can be achieved.

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