Static Pushover Analysis of Beam-Column Joints in Frame Structures

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Abstract. There are many factors influencing the yield mechanism of "strong column and weak beam", which is not required by the current seismic design of frame structures in earthquakes. In this paper, pushover analysis is done by creating ETABS framework model. Firstly, this paper analyses that cast-in-place floor will increase the stiffness and bearing capacity of frame beams. Then, this paper analyses the amplification factor of frame beam stiffness under combined loads. Finally, this paper achieves the effect of "strong column and weak beam" by controlling the reinforcement at the end of the beam.

Keywords: Strong Column and Weak Beam, Beam Stiffness Amplification Factor, Pushover Analysis

1. Introduction
In building structure, reinforced concrete frame structure system is a kind of structure system which is commonly used at present. In previous earthquakes, most of the frame structures show a kind of damage, which is "strong beam and weak column". Architectural structure that meets the requirements of "strong column and weak beam" is an important research problem to be solved urgently. The collapse modes of frame structures are beam hinge type and column hinge type under earthquake action. If a plastic hinge is formed in the frame column, it will be accompanied by a huge interlayer lateral displacement. This will not only cause instability problems, but also endanger the structure ability to withstand vertical loads. Therefore, in the seismic design of structures, we require frame structures to achieve "strong columns and weak beams" under earthquake action, which will present a beam hinge ductile structure. However, in several earthquakes, plastic hinges will appear at the end of columns rather than at the end of beams, which greatly reduces the ductility of the whole structure.

2. Study on stiffness amplification factor of beam
When calculating and analyzing, the stiffness of beam and column will directly affect the stress state of frame structure. The stiffness of frame columns and beams are mainly related to the elastic modulus of
materials, section size and column height. However, the stiffness of frame beams is also related to the thickness of cast-in-place slabs. In practical engineering, cast-in-place floor will cast frame beam and slab as a whole. The joint working ability of the two will be greatly enhanced, so the stiffness of the plate has a great influence on the calculated stiffness of the beam \(^{[1]}\). A large number of studies have also shown that cast-in-situ slabs can increase the flexural capacity of frame beams by 20\%-30\%, and in some cases even nearly double\(^{[2-7]}\). In today's stiffness design of slab-to-beam structures, we usually multiply the flexural stiffness of beams by a stiffness amplification factor. Because this method does not consider the thickness and span of the plate, we can not fully consider the contribution of the plate to the beam stiffness. Furthermore, it will affect the analysis results of beams and columns. This will lead to a large deviation between the calculated and actual structural forces, which is unreasonable in structural design. Therefore, the rationality of the beam stiffness magnification factor is of great significance to the frame structures design.

In today's general design software, we set the beam stiffness amplification factor under vertical load conditions. But in the design process, besides the vertical load on the frame structure, we also need to apply wind load and seismic load. Multilayer frame structure engineering is mainly affected by seismic load on structure design. The beam stiffness enlargement will increase the bending moment at the end of the beam under horizontal load. In the whole design process, what we need is the stiffness amplification factor of the beam under combined loads.

Through large-scale finite element software ANSYS and ETABS, we can carry out elastic analysis of a large number of frames. Then we can calculate and select the finite element model which can reflect the joint work of beam and plate more. Next, we can calculate the influence of beam stiffness amplification factor on beam end section bending moment under different load conditions, and finally get the combined load.

The reasonable values of the beams stiffness amplification increasing factor are as follows.

\[
\alpha_m = 1.9040 + 1.5481 \frac{h_f}{h}
\]

According to the code, the stiffness amplification factor of the side beam is as follows.

\[
\alpha = \frac{(\alpha_m + 1)}{2}
\]

3. Static pushover analysis of frame structures

3.1. Engineering example
The project is a unit dormitory, built in 2008, with a cast-in-situ reinforced concrete frame and a total of seven floors. The building height is 20.2m, the first floor elevation is -1.000m, the floor height is 3.2m, and the rest is 3.0m. The first column is made of concrete with strength grade C30 and elastic modulus of 3.0 \(10^7\) KN/m². The rest are concrete with strength grade C25 and elastic modulus 2.8 \(10^7\) KN/m². HRB335 reinforcing bar is selected as the main force reinforcement of beam-column section, and its strength is 300N/mm². HPB235 reinforcing bar is used as stirrup, and its strength is 210 N/mm². The floor slab is cast-
in-place with 110mm. The type of building seismic fortification is C, and the intensity of seismic fortification in the area is 7 degrees. The design earthquakes are grouped into the first group, the site type is two, the site characteristic period $T_g = 0.35$sec, and the aseismic grade is three.

According to the current specifications, the internal forces of the structure under various load combinations are calculated by using PKPM structural design software. We will get the reinforcement of each frame beam and column. The reinforcement results are input into ETABS model for Pushover analysis.

| Table 1. Main Section Dimensions of Frame Beams and Columns (mm) |
|---------------------------------------------------------------|
| Frame beam | 250×600 | 250×400 |
| Frame column | 450×550 | 450×500 | 400×500 | 400×400 |

The plane, elevation and 3D drawings of the frame structure are as follows.

**Figure 1.** The plane diagram of finite element model on the seven-story frame
In the design process, the reinforcement value calculated after the stiffness of the beam is amplified will be distributed to the beam and plate. However, designers usually allocate this amount of reinforcement to the beam section, but the floor will be reinforced separately. In this way, there are too many reinforcements in the beam section. Many researchers have also studied that the steel bar in a certain range on both sides of the beam section is subjected to the joint force of the beam section. The reinforcement of the beam section calculated by this design method will be increased, and the actual bending capacity will be greatly improved. It has been pointed out in literature that the reinforcement of frame beam bearings can generally be reduced by about 30%[8].

Three modeling schemes are analyzed in this paper. Firstly, the original design structure model. Secondly, the structural model of beam stiffness amplification factor design. Thirdly, the structural model is obtained by reducing the reinforcement of the beam end section by 30%.

3.2. Relation between displacement and base shear
Default-M3 (Default-M3) is defined at both ends of the beam in this paper. The frame column mainly bears the combined action of axial force and bending moment, so the Default-PMM (9-10) is set at both ends of the column.

Pushover analysis was carried out using the following analysis conditions: gravity load + mode1. Firstly, it is controlled by force, and then we calculate the internal force and deformation of the structure under gravity load. Then the displacement control is used to analyze the elastic-plastic behavior of the structure under the action of horizontal force.

It can be seen from the comparative analysis results. There is little difference between the original design structure and the structure designed in this paper, but the performance of the structure designed in this paper will be better, such as the displacement of the yielding vertex, the shear of the yielding base, the displacement of the ultimate vertex, the ultimate base shear and the absorbed energy, etc. The base shear force of the modified beam end section is smaller than that of the former two, but the ultimate displacement of the top is larger and the ductility is the best.

3.3. Distribution of plastic hinges under failure
Six-axis frame is selected for analysis.
Comparisons can draw the following conclusions. The number of plastic hinges appearing at the end of column in the modified design structure is relatively small. It can be seen from the ability level of plastic hinge in the figure that the damage degree of plastic hinges in the modified design structure is slight. For example, the original design and the bottom side columns of the frame designed in this paper exceed the ultimate load-carrying collapse limit, but the revised design structure does not.

In addition, the results can be obtained from the analysis of the plastic hinges during large earthquakes occurrence. Both the designed structure and the original structure appear plastic hinge at the end of the column, which belongs to the "column hinge" failure mechanism. However, the first plastic hinges of the modified design structure appear less and develop slowly\(^{[9-10]}\). The number of plastic hinges at the end of the column decreases greatly, which delays the plastic development of the structure.

4. Conclusion
In this paper, the stiffness contribution of cast-in-place slabs to beams is fully considered, and then the stiffness of beams is amplified. It plays a limited role in realizing the design structure. The structure designed in this paper is better than the original one in some aspects, such as ultimate vertex displacement, ultimate base shear and seismic ductility. Compared with the original design, the damage degree of plastic hinge is lighter. Reducing the reinforcement of beam section can greatly improve the ductility of the whole structure, which is an important reason for realizing the seismic fortification requirements of "strong column and weak beam". The ductility of the modified design structure is improved, for example, the ultimate vertex displacement and ultimate base shear are greater. Both the designed structure and the original structure appear plastic hinge at the end of the column, which belongs to the "column hinge" failure mechanism. However, the first plastic hinges of the modified design structure appear less and develop slowly. The number of plastic hinges at the end of the column decreases greatly, which delays the plastic development of the structure.
There are many key problems to be solved in this research, such as concrete strength grade. In fact, the strength grade of concrete will change the mutual stiffness of frame members, thus affecting the magnification factor of beam stiffness. In this paper, a 30% reduction in the reinforcement of beam section is proposed based on the previous research conclusions. In fact, the determination of this value needs more detailed study.

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