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Finite element analysis of steel-bonded reinforcement for cast-in-place beamless floor

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Abstract: *In recent years, there have been a lot of accidents in the beamless building, the most serious of which is the shear damage of the column cap of the beamless building, and the column head rushes out of the plate, causing the collapse of the beamless building. In addition, cracks are easily generated at the location of the column cap of the beamless floor, which affects the durability and safety of the structure. In this paper, ABAQUS finite element software is used to model the beamless floor cap and to compare and analyze the stresses of the beamless floor cap before and after reinforcement. The results of the study show that: the adhesive steel reinforcement can effectively inhibit the development of cracks at the location of the column cap of the beamless floor; the shear resistance of the column cap of the beamless floor can be improved after the adhesive steel reinforcement.*

Keywords: *Abaqus, Cast-in-place beamless floor, Reinforced with bonded steel, Crack analysis*

1. Introduction

On June 24, 2021, at least 97 people were killed in the collapse of the Champlain Tower South Apartment in Miami-Dade County, Florida. An engineer's report in 2018 showed that the Champlain Building had "major structural damage" and "major errors" during the construction process.[1]In recent years, there have also been many incidents of beamless floor coverings in China [2]-[4]. On August 1, 2019, Building 5 and 10 of Zhongjun Yongjingwan Project south of Huiren Avenue, Dongxin Township, Nanchang County The roof of the basement garage between #buildings partially collapsed.On November 12, 2018, a partial collapse of the basement roof occurred in the second bid section of the first phase of Shenghai Hao Ting, Gu Town, Zhongshan City. The total area of the collapse was about 3,500 square meters.On August 19, 2017, the roof on the northeast side of the underground garage of the A-E block in Xihuang Village, Shijingshan District, Beijing, partially collapsed.

The beamless floor structure is mostly used in basement garages. In the underground garage, there is no sunlight, good ventilation, and high humidity. Beamless floor structure will be due to the thinner steel protection layer; the spacing of the steel bars does not meet the design requirements; the actual cover thickness is greater than the design cover thickness; the concentrated operation of construction machinery and the concentrated stacking of construction materials; the shrinkage of concrete; the concrete is not compacted and cracks .The above reasons will cause cracks in the column cap of the beamless floor under the action of unbalanced bending moment or concentrated vertical pressure, which will have a certain impact on the safety and durability of the beamless floor. In order to prevent the cracks from expanding and structural damage, the suggestion is to strengthen the column cap by sticking steel.

Due to the difficulty of collecting traditional test data, the internal stress status of the beamless floor slab cannot be measured by the traditional test, but the finite element analysis can make up for the shortcomings of the traditional test. This paper is based on the finite element software ABAQUS for modeling, and simulates the sticking steel reinforcement at the position of the column cap of the beamless floor. The thickness of the steel plate is 3cm, 2cm, 1cm, and the shape is roughly L-shaped. To prevent cracks from expanding and structural damage, the advice given is to strengthen the column caps by sticking steel.

2. Overview of a beamless floor project

The underground garage of a project in Chongqing has a beamless floor structure. The underground garage of this project adopts a beamless floor structure. The column is equipped with a cone-shaped column cap of 2600mm×2600mm as a support. The column section size is 500mm×500mm. The beam floor slab thickness is 400mm.The design strength grade of column and column cap concrete is C35, and the design strength grade of beamless floor slab concrete is C30.

After field survey, the main structure of the underground garage has been completed, and the roof of the garage is covered with soil. Horizontal cracks (Figure 1) and vertical cracks (Figure 2) appeared in the column caps of beamless floors in the garage inspection area, and most of the cracks were straight.

Figure 1: Photograph of lateral cracks in column cap

Figure 2: Photos of vertical cracks in column caps

A steel tape measure and a crack width observer were used to detect the crack width of the column cap of the beamless floor in the garage inspection area. The cracks in the column cap of the three-zone garage are mostly vertical, and the cracks extend from the top of the column cap to the bottom of the column cap. There are horizontal cracks and longitudinal cracks in the column cap of a garage. The horizontal cracks are located at the junction of the column cap and the slab or within the range of 100-300mm from the top of the column cap. The vertical cracks mostly cross the horizontal cracks and extend along the lower end of the column cap.

On-site investigations were carried out on the construction conditions of the beamless floor caps and the upper load conditions in the inspection area of the three-zone garage, and the design thickness of the slab cover in the inspection area was 1.2m after consulting the design drawings. According to the introduction of the relevant unit: this area is a green belt, and there is concentrated pile of soil during the construction process, and the thickness of the covering soil is close to 2.0m. At the same time, heavy vehicles such as muck trucks and excavators pass through the area. The construction unit self-examined after construction and found that the column caps and slabs in the inspection area were cracked.

On-site investigations were carried out on the construction conditions and upper load conditions of the column caps of the beamless floors in the inspection area of the garage in the first area. The upper part of the roof of the inspection area of the garage is the arc-shaped steel structure corridor and the green belt. There are independent foundations of steel structure steel columns and structural components such as steel columns. At the same time, heavy vehicles such as concentrated soil and muck trucks and excavators pass through the area.

In the detection range, the reinforced concrete protective layer is generally thin, which does not meet the requirements of the design and acceptance specifications, and the local roof load is overloaded. There are two types of horizontal cracks in the column cap. The first type of crack is the crack at the junction of the column cap and the slab of the non-beam floor. The construction cold joint caused by the lack of compactness in construction or the untimely supply of concrete, plus the slab The surface load causes the crack to expand further. The crack is a structural crack, but the width of the crack is generally larger, which has a certain impact on safety. Another type of crack is located in the middle

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and lower part of the column cap. According to the force analysis, it is a tension crack caused by unbalanced bending moment (the generation of unbalanced bending moment is related to the unequal column span, uneven load, and overload). Security has a greater impact.

The vertical cracks on the side of the column cap are also stress cracks. They are produced under the combined action of horizontal tensile stress and vertical compressive stress caused by unbalanced bending moments, and have a relatively large impact on the safety of the structure. The safety of column caps that produce horizontal and vertical cracks has been significantly reduced, and should be reinforced. It is recommended to use steel-bonded reinforcement.

3. Finite element analysis of cast-in-place beamless floor

This paper simulates the reinforcement of column caps for beamless floors. There are 9 columns in the model, and only the column caps of the middle columns are reinforced and analyzed. The non-beam floor slab adopts symmetrical restraint on all sides, and the column foot adopts completely fixed restraint. The model is reinforced with three steel plate thicknesses, 3cm, 2cm, and 1cm respectively. The column cap of the beamless floor is reinforced with full section, and the reinforced steel plate extends 500mm in the direction of the column, as shown in Figure 3, Figure 4 and Figure 5.

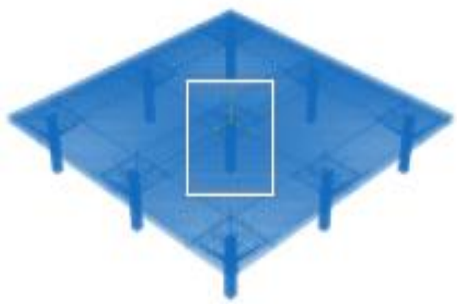

Figure 3: Computing unit

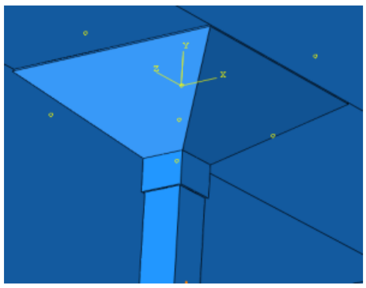

Figure 4: Reinforcement of column caps for beamless floors

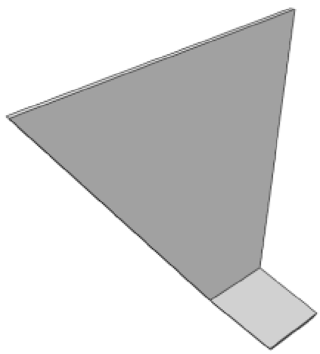

Figure 5: Reinforced steel plate

3.1. Constitutive relationship

This paper adopts the "Concrete Damage Plasticity Model"[5] To simulate concrete performance.

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The ultimate compressive strain of concrete $\varepsilon_{cu} = 0.0033$, the compressive constitutive curve of concrete is determined by the following formulas (1)～(5), The constitutive relationship curve of concrete is shown in figure 6.[6]

$$\sigma = (1 - \mathrm{d}_c)\mathrm{E}_c\varepsilon \quad (1)$$

$$d_c = \begin{cases} 1 - \frac{\rho_c n}{n-1+x^n} & x \le 1 \\ 1 - \frac{\rho_c n}{\alpha_c(x-1)^2+x} & x > 1 \end{cases} \quad (2)$$

$$\rho_c = \frac{f_{c,r}}{E_c \varepsilon_{c,,r}} \quad (3)$$

$$\mathrm{n} = \frac{E_c \varepsilon_{c,,r}}{E_c \varepsilon_{c,,r} - f_{c,r}} \quad (4)$$

$$\mathrm{x} = \frac{\varepsilon}{\varepsilon_{c,,r}} \quad (5)$$

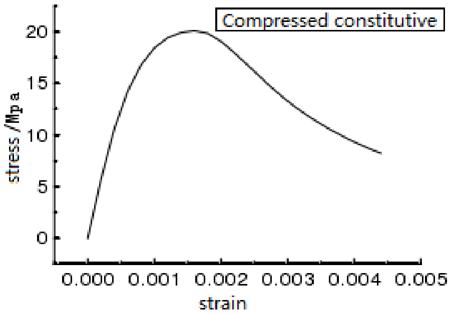

Figure 6: The constitutive relationship of concrete under compression

The constitutive model of the steel bar is determined by the following formula, and the monotonic tensile stress-strain curve of the steel bar is shown in Figure 7.[6]

$$\sigma_s = \begin{cases} E_s \varepsilon_s & \varepsilon_s \le \varepsilon_y \\ f_{y,r} & \varepsilon_y < \varepsilon_s \le \varepsilon_{uy} \\ f_{y,r} + k(\varepsilon_s - \varepsilon_{uy}) & \varepsilon_{uy} < \varepsilon_s \le \varepsilon_u \\ 0 & \varepsilon_s > \varepsilon_u \end{cases} \quad (6)$$

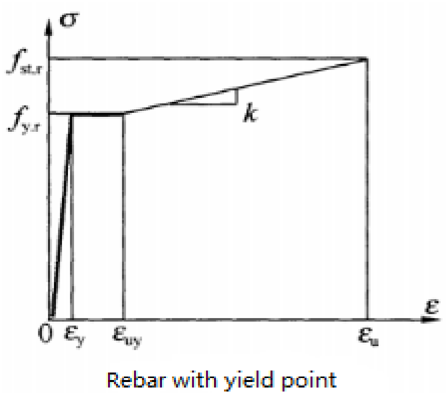

Figure 7: Rebar constitutive relationship

3.2. ABAQUS calculation results and analysis

ABAQUS is divided into pre-processing and post-processing. The pre-processing module can create a variety of solid elements (hexahedral elements, tetrahedral elements, first-order elements, second-order elements, etc.), which can solve stress and displacement problems. ABAQUS software analysis steps: (1) Part; (2) Property; (3) Assembly; (4) Step; (5) Interaction; (6) Load; (7) Mesh; (8) Job; (9 Visualization.

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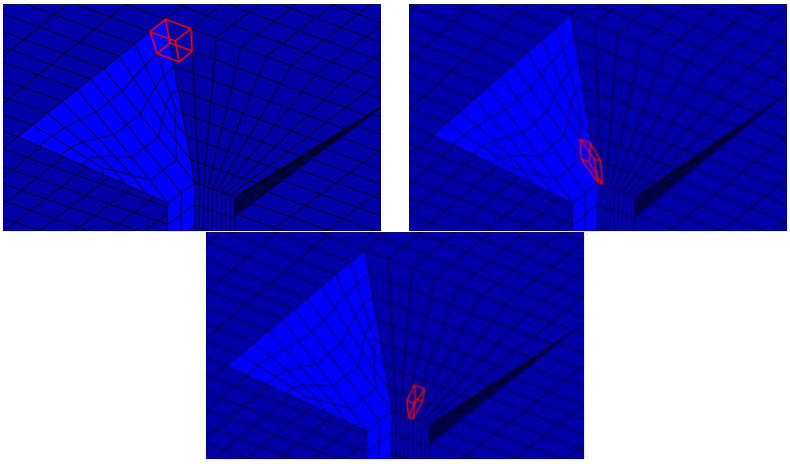
3.3. ABAQUS calculation results and analysis

Under the action of 0.04Mpa compressive stress, the stress cloud diagram at the reinforced position of the beamless floor is shown in Figure 8. The comparison results are shown in Table 1.



(1) Unit 1 *(2) Unit 2* *(3) Unit 3*

Figure 8: Unit number and unit position at the column cap

Table 1: Column cap element stress (MPa)

Unit number / Steel plate thickness	1	Stress ratio	2	Stress ratio	3	Stress ratio
3cm	9.60	59%	1.88	41%	2.59	32%
2cm	9.60	59%	1.88	41%	2.59	32%
1cm	12.85	44%	2.86	10%	2.80	26%
0	23.14		3.18		3.79	

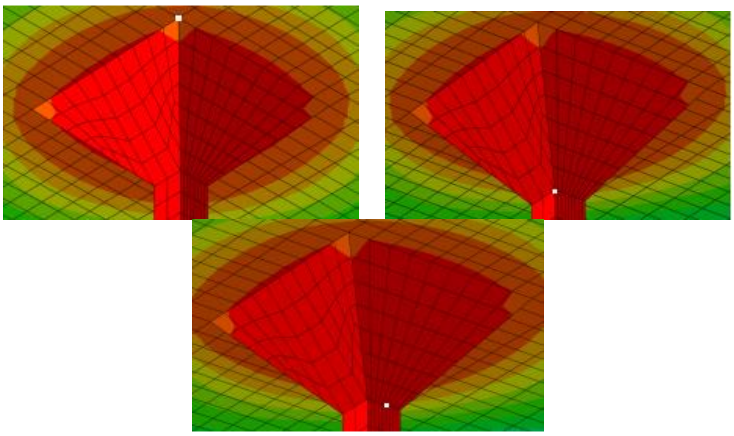
Note: Stress ratio = (stress of the element before strengthening-stress of the element after strengthening) / stress of the element before strengthening × 100%

When the thickness of the reinforced steel plate is 3cm and 2cm, the stress of unit 1 is reduced by 59%; the stress of unit 2 is reduced by 41%; the stress of unit 3 is reduced by 32%.

When the thickness of the reinforced steel plate is 1cm, the stress of unit 1 is reduced by 44%; the stress of unit 2 is reduced by 10%; the stress of unit 3 is reduced by 26%.

3.4. Analysis of Displacement Cloud Diagram of Column Cap of Non-beam Floor

Under the action of 0.04Mpa compressive stress, the vertical displacement cloud diagram at the reinforced position of the beamless floor is shown in Figure 9 below. The comparison results are shown in Table 2.



(1) Node 1 *(2) Node 2* *(3) Node 3*

Figure 9: Node number and node position at the column cap

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Table 2: Vertical displacement of column cap node (mm)

Node number / Steel plate thickness	1	Displacement ratio	2	Displacement ratio	3	Displacement ratio
3cm	1.09	34%	0.76	10%	0.75	9%
2cm	1.09	34%	0.76	10%	0.75	9%
1cm	1.31	20%	0.80	5%	0.79	4%
0	1.64		0.84		0.82	

Note: Displacement ratio = (vertical displacement of the node before reinforcement-vertical displacement of the node after reinforcement)/vertical displacement of the node before reinforcement × 100%

When the thickness of the reinforced steel plate is 3cm and 2cm, the vertical displacement of node 1 is reduced by 34%; the vertical displacement of node 2 is reduced by 10%; the vertical displacement of node 3 is reduced by 9%.

When the thickness of the reinforced steel plate is 1cm, the vertical displacement of node 1 is reduced by 20%; the vertical displacement of node 2 is reduced by 5%; the vertical displacement of node 3 is reduced by 4%.

4. Conclusions

Through ABAQUS simulation and analysis of the stress cloud diagram and displacement cloud diagram of the column cap of the beamless floor, the following conclusions can be drawn:

(1) Pasting steel plates on the column caps and surrounding columns of beamless floors can effectively reduce the stress value of the upper part of the column caps, and can restrain the horizontal and vertical cracks on the upper part of the column caps and inhibit the development of cracks.

(2) Reduce the vertical displacement of the upper part of the column cap of the beamless floor.

(3) The steel plate with a thickness of 3cm and a thickness of 2cm have the same reinforcement effect on the column caps of beamless floors, and both are better than the steel plate with a thickness of 1cm. The thickness of the reinforced steel plate is preferably 2cm.

Acknowledgments

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