Investigation of Hollow Slab-Column Structure under Lateral Cyclic Loading

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Abstract: To investigate the seismic performance of the hollow slab-column structure, the lateral low-period cyclic loading tests on a single span 2-storey frame were carried out. The crack distribution, hysteresis properties, strength degradation and stiffness degradation, ductility, energy dissipation capacity and destruction mode were analyzed. The experimental results indicate that: the hollow slab-column structure under lateral low-period cyclic horizontal loading is very similar to equivalent beam with imperfect failure mechanism of hinges. At the beginning of the experiment, the stiffness of the component degrades rapidly, and the equivalent viscous damping coefficient also decreases rapidly. During the loading process, the horizontal displacement of the first floor is twice as much as that of the second floor. The degradation of the component stiffness and the equivalent viscous damping coefficient tend to be stable in the end. The hollow slab-column structure has good ductility and the decrease of the strength is not obvious. But the hysteresis curve indicates obvious slip pinching phenomenon, and the energy dissipation capacity is limited.

1. Introduction

In recent years, China is in a period of rapid urbanization and industrialization. In order to improve the efficiency of construction material for new buildings, the development of a conservation-oriented structure is an inevitable direction [1]. In reinforced concrete high-rise buildings, the floor weight accounts for 50%~60% of the total weight of the structure [2]. In a large span structure with a span of more than 9m, the floor weight accounts for about 60%~80% of the total weight of the structure [3]. Cast-in-place concrete hollow-core slab column structure system introduces hollow core slab into cast-in-place concrete slab column composite structure. The hollow slab enduring vertical and lateral load was directly supported on the columns. It has advantages of using less material which provides substantial economic benefits, reducing the weight of the structure, and good for large span applications, etc. For these practical reasons, it is very important to have a comprehensive study of this type of structure and promote its adoption in new constructions.

Hollow floor originated from Leopold Muller proposed a honeycomb hollow concrete floor structure [4], L.A.CLARK [5] and R.P. Pama [6] proposed a method for calculating the torsional stiffness of tubular hollow slab bridges through tests. E.I Behai et al. [7] conducted a nonlinear finite element analysis on the hollow plate. At present, all countries generally adopt the same calculation...
method as the solid beamless floor slab with the same rigidity to design the hollow beamless floor structure. [8] Research on hollow beamless plates in China mainly focuses on the analysis of elastic and elastoplastic behaviors under vertical loads [9-11], However, the study of the mechanical properties of the structural system under lateral loads is not sufficient.

In this paper, the cast-in-place reinforced concrete hollow-core slab column structure with one-way arrangement of circular tube as inner formwork is taken as the research object. The hysteretic properties, energy dissipation capacity, strength and stiffness degradation, and ductility properties of the test specimen under low-period cyclic loading were analyzed to provide basis for engineering application and theoretical research of this type of structural system.

2. Test Overview

2.1. Specimen design

The prototype structure of the specimen is a five-storey composite structure. The column grid is 7200 mm × 6000 mm with floor height 3000 mm. Column section is 600 mm × 600 mm. Slab thickness is 300 mm. Hollow pipe diameter is 150 mm. In order to avoid the destruction of the column prior to the hollow slab in the test, the column section was increased to 300 mm × 300 mm. The test model is a two-storey cast-in-place concrete hollow-core slab column structure. The second floor is one span of column grid while the first floor is one and a half. In order to anchor the column longitudinal reinforcement, second floor columns extend above the second floor 300 mm. Both floor models are 2000 mm wide. Each floor is 1000 mm high with slab thickness of 100 mm. The first floor design length is 4100 mm with 400mm wide hidden beam. The design length of the second floor model is 3400 mm.

All the hollow pipes used in the test are ordinary PVC pipes. Diameter of the pipes is 50 mm. The hollow tubes are 25 mm from top and bottom of the slab. 25 mm spacing is also provided between each hollow tube to form a rib beam in the slab. The test columns are connected with the ground beam and the ground beam is fixed on the laboratory floor to form a fixed bearing. Girder section is 300 mm × 300 mm. The horizontal length is 4000 mm. In the test piece production, PVC tubes with a diameter of 50 mm are embedded into the ground beam to facilitate laboratory anchorage, See Fig. 1 for details. Specimen reinforcement is according to specifications with minimum reinforcement ratio. The reinforcement for hidden beams, columns and ground beams are arranged according to the requirement of the structure [12], as shown in Fig. 2.

![Fig. 1 Component Section](image-url)
2.2. Material property test

The test uses commercial concrete with concrete strength class C30. The reserved cubic test block adopts the same maintenance method as the test piece. The measured results are shown in Table 1. Tests use two types of steel bars, HRB400 and HPB235 with a total of four diameters, 16mm, 8mm, 6mm and 4mm, respectively. Three components were randomly selected from the entire batch of steel bars during the production of the components for mechanical testing of the materials. The test results are shown in Table 2.

![Specimen size and reinforcement](image_url)

**Fig. 2** Specimen size and reinforcement

| Specimen number | $f_{cu,k}$/MPa | $f_{ck}$/MPa | $f_{tk}$/MPa | $E_c/10^4$/MPa |
|-----------------|----------------|--------------|--------------|-----------------|
| S1              | 34.22          | 22.89        | 2.16         | 3.11            |
| S2              | 30.04          | 20.09        | 2.01         | 2.98            |
| S3              | 32.40          | 21.67        | 2.09         | 3.05            |
| Average value   | 32.22          | 21.55        | 2.09         | 3.05            |

**Tab. 1** Concrete material test results

| Rebar specifications | Yield Strength /MPa | Yield strain /με | Tensile strength /MPa | Elongation after fracture % |
|----------------------|---------------------|------------------|------------------------|----------------------------|
| B4                   | 550.80              | 2622.86          | 662.43                 | 11.27                      |
| B6                   | 537.47              | 2559.38          | 598.80                 | 9.90                       |
| B8                   | 432.47              | 2059.38          | 507.13                 | 14.13                      |
| B16                  | 438.20              | 2191.00          | 583.20                 | 18.27                      |

**Tab. 2** Steel bar test results
2.3. Test device

The experiment was completed at the Jiulong Lake Laboratory of Southeast University. Jacks on the top of the test specimens apply axial pressure. Side column axial pressure ratio design value is 0.2, the axial column pressure ratio design value is 0.3. The vertical loading device is composed of reaction force rack, hydraulic jack, force sensor and ground anchor screw. The lateral loading device is composed of a reaction wall, an electro-hydraulic servo loading system, a steel plate and a tension bar. Lateral low-period cyclic loading is applied by horizontal actuator MTS. MTS acts on the height of the second floor, that is, at the centroid of the slab section. Experimental loading device schematic and real-time diagram are shown in Fig. 3 and Fig. 4.

Fig. 3 Test loading device real view
Fig. 4 Test loading device schematic

2.4. Loading plan and measurement content

The loading system shall be implemented in accordance with the requirements of "Building Seismic Test Regulations" (JGJ/T 101-2015). Before the formal loading, the specimen is preloaded and the vertical load is added to the predetermined load for a period of time. Apply a 10kN low-cycle repeated load to confirm that all instruments are working properly. At the time of formal loading, the vertical load is first applied to the predetermined axial pressure and remains unchanged; Then add the lateral load and the force loading control of the specimen before yielding. When the strain on the tension side of the column reaches the yield strain the load displacement is 85% of peak load with displacement loading control and the specimen is destroyed. That completes the entire test. The test is carried out for 5 minutes after loading to observe and describe the cracks.

A total of 7 displacement sensors are arranged according to the features of the model structure (The range is ±100mm). The lateral displacement of the test piece is measured by a displacement sensor arranged on the axis of each beam. And access X-Y function recorder to draw the hysteresis curve of the specimen under the effect of low level of repeated cycles: A displacement sensor is set at half height of each floor of the test piece used to measure the displacement of the column along the column height to analyze column performance. A displacement gauge is installed at the end of the ground beam to measure the overall horizontal slip of the specimen. Steel strain gauges are mainly arranged at the top and the bottom of the hollow slab to measure the deformation of steel. Concrete strain gauges are mainly arranged in quarter of the slab, in the other parts of the slab, the other concrete strain gauges are used to check the data.

3. Experimental phenomenon

3.1. Destructive form

In order to describe the test phenomenon conveniently, we assign number for each column. The position of the actuator is on the west side, and the west side column number is Z₁. East column number is Z₂. The loading process of test pieces can be divided into force control stage and displacement control stage. The detailed destruction pattern is as follows:
Force control stage: When the load is added to +30kN, slits appear on the west side of a column which is about 100 mm in length; When the load increases to -40kN, micro-cracks appear on the floor near the 1st column of a floor slab. There is no crack in the 2nd floor column and floor slab; When the load increases to -60kN, the second column at the bottom of the second floor slab, approximately 300mm from the west side of the second column, cracks become visible with approximately 400mm in length. The first column floor slab surface, the cracks on the second floor slab are not obvious. There is a large amount of micro-cracks in the cross section of the 1st column and the 2nd column; When the load is increased to -80kN, the cracks at the bottom of the slab are more obvious. Taking a second column floor as an example, the cracks develop along the west side of the column and the inverted figure eight forms the northwest and southwest directions; When the load is increased to -105kN, cracks on the surface of the slab split into Eight-Shaped character on the top of column, and the distance from the column edge is about 600mm. Some cracks have a crossover trend and the width of cracks also increases. There are several cracks that extend to the edge of the slab. Through stitches appear at the lower middle of the first column and the second column; When the load is increased to +115kN to +120kN, the yield phenomenon begins to appear on the outer longitudinal bars of the 1st column observed in the collection box. Hydraulic Servo Actuator also monitors Head Load displacement. That is, it is determined that the specimen begins to enter the yield phase. At this point the yield displacement is 12.28mm, and then the displacement loading is used.

Displacement control stage: When the control displacement reaches +2\(\Delta y\) in the first cycle, there are more new cracks in the components. In the first and second floor panels around the column cross section eight-shaped cracks with length of about 700mm; When the displacement is increased to -2\(\Delta y\), a new crack appears on the side of the column and the bottom of the slab at the first cycle. The original crack continues to develop and widen. Part of the crack extends to the slab edge. The cracks in the column continue to grow high, and cracks appear through the column section. There is a small amount of concrete spalling at the column base; When the horizontal displacement is added to the second cycle of +4\(\Delta y\), a crack with a large width appears on the surface of the slab and throughout the entire slab section. The development of structural cracks at this time has been more comprehensive and full. The structure is clearly observed with large horizontal displacements. Some steel strain gauges have overflowed and failed; When loading to the first cycle of -6\(\Delta y\), the crack width increases and deepens along the slab column junction and through the slab. Concrete pressure and peeling in the height range of 0~100mm at the bottom of the column. The second column slab joint junction large area cracking. As the test continues, the column strain gradually decreases. The test piece load gradually drops to 85% of the peak load. At the end of the three-cycle test, the test specimen crack distribution is shown in Fig. 5.
3.2. Load-displacement curve

Before the specimen cracks, the area of the hysteresis curve is very small and the loading curve is approximately a straight line. Displacement is mainly caused by the elastic deformation of the material. Under the effect of the reciprocating load, the stiffness degradation is not obvious. Residual distortion is small. The structure is basically in a flexible working state. After the specimen cracks, the residual deformation increases as the load increases gradually. The unloading section of the hysteresis curve clearly starts to tilt toward the displacement axis. The hysteresis curve gradually increases in area and gradually becomes full. With the repeated action of the load, the stiffness of the hollow slab column structure is degraded. The test piece begins to enter the nonlinear working phase. After the specimen yields, the hysteresis curve is anti-S. This is mainly due to the original defects of the components: the bottom bearing design is too small and it is difficult to form a consolidation constraint on the hollow slab column structure, resulting in a certain degree of structural slip. As the test piece enters the elasto-plastic working stage, the load value under the second displacement magnitude in the load-displacement hysteresis curve in the cycle of the same displacement magnitude is slightly lower than the first time and the hysteresis loop contains a smaller area in the same displacement magnitude. It shows that the energy consumption capacity of the hollow shell structure has declined. This phenomena reflects the cumulative effect of structural material damage. Hysteresis curve has obvious "pinching" effect against S-shape at this time, and its stiffness is deteriorating obviously. When the component enters the plastic stage, with the increase of the amount of slip of the column base in the concrete, and the cracking of the joints, etc, Hysteresis curve develops from anti-S-shaped to Z-shaped. Energy consumption is further reduced. The hysteresis curve of the test specimen is shown in Fig. 6. The load and displacement characteristics are shown in Table 3.

Fig. 6 Hollow slab column structure hysteresis curve  
Fig. 7 Skeleton curve of hollow slab column structure
**Tab. 3** specimen load, displacement characteristic value and displacement ductility coefficient

| Load direction | $P_{cr}$/kN | $P_{cr}$/mm | $P_{y}$/kN | $P_{y}$/mm | $P_{m}$/kN | $P_{m}$/mm |
|----------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Forward        | 30          | 4.58        | 115         | 12.28       | 264.84      | 80.09       |
| Reverse        | -35         | -2.26       | -105        | -13.16      | -207.15     | -65.61      |

| Load direction | $P_u$/kN | $P_u$/mm | $P_y/P_{cr}$ | $P_y/P_{cr}$ | $P_m/P_y$ | $P=P_u/P_{cr}$ |
|----------------|----------|----------|---------------|---------------|------------|----------------|
| Forward        | 225.13   | 96.39    | 3.83          | 3.17          | 2.3        | 7.85           |
| Reverse        | -176.07  | -97.67   | 3             | 4.5           | 1.97       | 7.42           |

The skeleton curve of hollow slab column model is shown in Fig. 7. The initial stage of loading is in the elastic stage and the skeleton curve is approximated by a straight line. As the load increases, the components crack and residual deformation begins to accumulate. When loading continues, the skeletal curve clearly shows an inflection point and the test piece is believed to have reached its yield. After entering the displacement control stage, the slope further decreased, bearing capacity increased, and it was in the stage of yield strengthening. After reaching the peak load point, the bearing capacity rapidly drops and the stiffness of the component continues to decrease until the bearing capacity falls below 85% of the peak load.

4. Analysis of test results

4.1. Intensity degradation

The degraded nature of a structure (or component) reflects the effect of structural cumulative damage and is an important component of the seismic performance of a structural member. Under the cyclic load of constant displacement amplitude, the characteristic that the bearing capacity of the members decreases with the increase of the number of cycles is called strength degradation. The strength degradation of components can be represented by the load-carrying degradation coefficient $\lambda_{i}$ in each cycle of the same loading stage:

$$\lambda_{i} = \frac{P_{i-1}^j}{P_{j}}$$

In the formula, $P_{i}^j$ is the peak load value of the i-th cycle when the displacement ductility coefficient is j; $P_{i-1}^j$ is the peak load value of the i-1th cycle when the transfer coefficient is j.

In order to reflect the gradual decrease of the bearing capacity of the specimen with the number of cyclic loadings, the peak load after the first cycle of the specimen is taken as $P_{i}^j$. It can be seen from Fig. 8. For positive loading, when the displacement has reached 40 mm, the bearing capacities of the first and third cycle specimens are 250.5 kN and 220.0 kN, respectively. $\lambda_{i}$ minimum is 0.878; For reverse loading, when the displacement has reached 80 mm, the bearing capacities of the first and third cycle specimens are 207.1kN and 177.3kN, respectively. The minimum is 0.856. In summary, the strength degradation coefficient of the specimen is controlled between 0.85 and 1.0. Intensity degradation is not serious.

![Fig. 8 Intensity degradation](a) Positive loading  (b) Reverse loading
4.2. **Stiffness degradation**

Stiffness is the ability of a structure (or component) to resist deformation. The stiffness is expressed as the slope of the line connecting the positive and negative peak points at the same strength level (displacement magnitude) to indicate the stiffness of the structure or component under low-period cyclic loading. The specific formula is as follows:

\[
K_i = \frac{+[P_+]+[P_-]}{+[\Delta_+]+[-\Delta_-]}
\]  

In the formula \(K_i\): The displacement ductility coefficient is the secant stiffness of the component; \(+[P_+], -[P_-]\): The displacement ductility coefficient is the load value corresponding to the positive and negative peak points; \(+[\Delta_+], -[\Delta_-]\): The displacement ductility coefficient is the displacement value corresponding to the positive and negative peak points. Defined as the slope of the positive (negative) peak point load and the origin of the coordinates at the strength level (displacement magnitude) to indicate the positive and negative stiffness of the structure or component under low-period cyclic loading (specified that the MTS thrust is positive and the tension force is negative).

As shown in Fig. 9, the specimens have undergone cracking, yielding, reaching peak load, and eventually failure. The stiffness has deteriorated significantly and mainly focused on the post-column reinforcement yield and the appearance of large area hollow cracks. Before 30KN the component is in the elastic stage, the stiffness is less degraded, and the component deformation is very small. After the load is greater than 110KN, the rigidity decreases due to the yield of the component; In the displacement control stage, the stiffness degradation under the same displacement magnitude is not obvious, but the stiffness degradation is significant in the next displacement magnitude; Due to the initial defect of the component, the forward stiffness is slightly less than the negative stiffness, which is consistent with the expectations before the start of the test. However, in the late stage of loading, the positive and negative stiffness tend to be consistent, indicating that the initial defects affect the bearing capacity of the components within an acceptable range; When the specimen is damaged, the positive and negative residual stiffness is only 10.7% and 13.2% of the initial stiffness of the component, indicating that the test model has been severely damaged.

![Fig. 9 Stiffness degradation](image)

4.3. **Ductile performance**

Ductility is the ability of the structure to undergo non-elastic deformation under the premise of no significant reduction in the bearing capacity of the structure. The indicator that is “not significantly reduced” here is more agreeable, which is no less than 85% of its ultimate bearing capacity. Displacement ductility factor \(\mu\) is expressed as:

\[
\mu = \frac{\Delta}{\Delta_y}
\]  

(3)
In the formula $\Delta_u$ is the limit displacement when the structure or component is broken. Take the displacement when the bearing capacity drops to 85% of ultimate load; $\Delta_y$ is the yield displacement when the structure or member yields.

as shown in Table 3. The time delay coefficients of the test specimens for forward loading and reverse loading are 7.85 and 7.42, respectively, which are far greater than the ductility ratio of the structural anti-seismic requirements. This is caused by artificially increasing the column section and its reinforcement: Inconsistent coefficient of time delay between forward loading and reverse loading of test piece. The reason is that the loading pressure cannot be completely symmetrical during loading, as well as the dispersion of concrete materials and the asymmetry of the loading device.

4.4. Energy dissipation

The area enclosed by the load-displacement curve in the hysteresis loop curve can reflect the amount of energy absorbed by the structure (i.e., the strain energy produced by the structure). The energy dissipation performance of the structure is evaluated using the equivalent viscous damping coefficient, $h$. The calculation method is as shown in Equation 3:

$$h = \frac{1}{2\pi} \frac{S(ABC + CDA)}{S(oBE + oDF)}$$

In the formula $S_{ABC}$ and $S_{CDA}$ are the area of the hysteresis loop and the amount of reactive plastic energy consumed; $S_{oBE}$ and $S_{oDF}$ Responsive elastic strain energy. As shown in Fig. 10.

Take the hysteresis loop area E under the same force/displacement loading level as the energy consumption at this loading level. See Fig. 11 for details. Before the sign is the force control phase hysteresis loop area. After the number is the displacement control phase area. The overall energy consumption of the test specimen is shown in Fig. 12. The abscissa indicates the load (displacement) of the specimen during loading of the specimen. The ordinate indicates the equivalent viscous damping coefficient of the test piece.

In the force control phase, the hysteresis loop area shows an approximately linear growth trend; As the lateral load increases, the member gradually enters the yield state. The equivalent viscous damping coefficient is continuously reduced, and the energy consumption of the test piece is continuously reduced; After entering the yield phase, the energy consumption of the test piece has increased. This is mainly due to the deformation of the steel bars in the hollow slab column structure and the crushing of the concrete. This has increased the energy dissipation capacity of the components to some extent; In the displacement control stage, three cycles of each stage are loaded due to displacement loading. It can be observed that the area of the hysteresis loop decreases with each displacement magnitude. With the increase of horizontal displacement at each level, the equivalent viscous damping coefficient shows a decreasing trend. Note that the hollow slab structure has limited energy consumption and tends to be stable at the end of loading. The equivalent viscous damping coefficient of the hollow slab column structure shows a decreasing trend during the whole loading process, which indicates that the energy dissipation capacity of the system is limited and should be paid attention to when designing.
4.5. Horizontal displacement analysis

The deformation of the first floor slab and the second floor slab of the test specimens were collected using the No. 4 displacement meter and the MTS, respectively. The displacements of the two were compared as shown in Fig. 13.

When the lateral load is small, the component is in the elastic stage, the displacement changes linearly and the horizontal displacement of the first floor is approximately 2 times of the second floor. With the increase of the lateral load, the component enters the yield state and it can be observed that the MTS displacement data has become significantly larger. This is mainly due to the fact that after the component reaches its yield, its horizontal displacement will be larger than before yielding under a certain lateral force. This results in disengagement of the MTS loading head from the component and a large displacement of the MTS. After the yield of the component, the yield displacement control is used instead, and the horizontal displacement of the loading point gradually increases. On the other hand, the displacement at the displacement gauge 4 (ie, the first floor) increases as the displacement of the top floor increases, but there is no increase in the loading point displacement. This is mainly due to the articulation of the side slab supported on the right side of the column. This will constrain the horizontal displacement and the support does not achieve the ideal sliding effect; it can be found that the positive horizontal displacement of MTS is larger than that of negative horizontal displacement. This may be due to the initial defects of the component. The positive lateral stiffness is slightly smaller than the negative stiffness. It can be found that the forward horizontal displacement of MTS is larger than the negative horizontal displacement, which may be due to the initial defects of the component. The positive side stiffness is slightly less than the negative stiffness. The first floor positive horizontal displacement is smaller than negative horizontal displacement. This is because when the component is subjected to thrust, there is a bearing on the edge of the first floor will limit its displacement. When the tension is reversed, there is no bearing restraint and it is an ideal sliding bearing.

![Fig.13](image-url) Comparison curves of horizontal and vertical displacements in first floor and second floor

5. Conclusions

1) Under the effect of low-period cyclic loading, the hollow-core slab column structure first appears cracks transverse to the column edge and across the full slab to the through-slit. The width of the cracks is large and the damage is severe. The column base also collapse subsequently. The test specimen belongs to the equivalent beam hinge destruction mechanism and is not an ideal destruction mechanism.

2) Hollow slab column structure shows better ductility. The strength degradation coefficient is between 0.856 and 1, and the intensity degradation is not obvious. However, the hysteresis curve shows a clear phenomenon of slipping and pinching, and the energy dissipation capacity is limited. Therefore, we need to pay attention to this during design.

3) In the initial stage of loading, the stiffness of the specimen degenerates quickly and the equivalent viscous damping coefficient decreases rapidly; In the late stage of loading, the stiffness
degradation and equivalent viscous damping coefficient of the specimen tend to be stable. When the specimen is damaged, the residual stiffness is only 12% of the initial stiffness of the component.

4) From the early stage of loading to the late stage of loading, the horizontal displacement of the first floor is approximately 2 times the horizontal displacement of the second floor; In the late stage of loading, the difference between the lateral displacements of the first and second floor has increased to 2.32 times due to the horizontal displacement of the slab supported on the right side of the column.

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References
[1] Xu Youlin, Feng Dabin. Promotion of Cast-in-situ Hollow Floor Covers and Development of Economical Concrete Structures [C]. National In-situ Concrete Hollow Floor Structure Technical Conference Proceedings. Shanghai: China Construction Standardization Association Concrete Structure Professional Committee, 2005, 1-5
[2] Cheng Wenyu, Li Aiqun editor. Concrete floor design [M]. Beijing: China Building Industry Press, 1998.1
[3] Gao Zhiqiang. Research on Analysis and Design Method of Cast-in-Place Concrete Hollow Floor [D]: [Master Thesis]. Shanghai: School of Civil Engineering, Tongji University, 2007
[4] Fertigteil-Vertrieb Gmbh, B-Z Reinforced Concrete Cellular plate for one-Way and Tow-Way Stress Directions for High Loads and Large Spans [J]. Engineering Design Brochure, 1965
[5] Clark L A. Comparisons of Various Methods of Calculating the Torsional Inertia of Right Voided Slab Bridges [R]. Cement and Concrete Association, 1975. 6
[6] Pama R P, Imsom-Somboon S, Lee S L. Elastic rigidities of circularly voided slabs [J]. Building Science, 1975, V10(3): 207-212.
[7] Behairy E I, Soliman A S, Essawy M I, Foud N A. Nonlinear Finite Element Analysis Of Voided Reinforced Concrete Slabs [J]. Annual Conference and 1st Biennial Environmental Speciality Conference, 1990, V4pt 1: 214
[8] Franz G. Test Report Extract on a Mode of the Cellular Flat Plate [J]. Engineering Design Brochure, Mar. 9, 1965
[9] Chen Jingru. Analysis and research on cast-in-place reinforced concrete hollow slab beamless floor system [D]: [Master Thesis]. Wuhan: School of Civil Engineering and Architecture, Wuhan University of Technology, 2002.
[10] Wang Zhiyuan. Research on the performance of cast-in-situ reinforced concrete hollow slab and its application [D]: [Doctoral Dissertation]. Nanjing: School of Civil Engineering, Southeast University, 2004
[11] Jianjun Yang, Qingjie Cheng, Jin Wang, et al. Experimental study on cast-in-place hollow concrete floor [J]. Building Structure, 2006, (03): 71-74.
[12] China Academy of Building Research. Design Specification for Concrete Structures [S] GB50010-2010. Beijing: China Building Industry Press, 2011.