Experiment on Punching Shear Capacity of Hollow Slab-column Connection under Unbalanced Bending Moment

Zhu Qiang1,2 Liang Shuting1 Zhu Xiaojun1 Dang Longji1 Wang Jie3 Xu Cheng3
(1School of Civil Engineering, Southeast University, Nanjing 210096, China)
(2Nanjing Censor Center of Construction Drawing Design, Nanjing 210005, China)
(3Nanjing Yangtze River Urban Architectural Design Co. Ltd., Nanjing 210002, China)
Zhu Qiang (1973-), male, PhD, senior engineer, 32828975@qq.com.

Abstract: Through the punching shear test of six hollow slab-column connection specimens, the mechanic parameters of the hollow slab-column connection were collected, including the cracking load, the ultimate load, the displacement of the slab bottom and the strain data of steel and concrete under the influence of the unbalanced bending moment. Afterward the effect of the hollow ratio and the bending direction on the ultimate punching shear capacity of hollow slab-column connection was studied. The test results show that the capacity of hollow slab-column connection decreases with the increase of hollow ratio, but only within a narrow range. When the unbalanced moment is low, both the horizontal unbalanced moment and the along pipe unbalanced moment create almost the same impact on the punching connection. The punching capacity of the hollow slab-column connection under two-way unbalanced moment is lower than that under one-way unbalanced moment, but the final displacement is larger and the deformation ability is better. Finally the relationship between the unbalanced moment and the ultimate bearing capacity of hollow slab-column connection was proposed.

1. Information
Cast-in-situ reinforced concrete hollow slab floor, also known as the cast-in-situ hollow slab, generally by adopting the buried core pore forming process technology, and by placing the circular (or special-shaped, square, et, al) GBF in the slab with a certain distance, forms the thick slab floor structure. Compared with general beam slab structure, the economic and technical effect of the new structure is more significant due to its prominent advantages, such as larger span, lower weight, sound insulation, heat insulation, and good heat preservation behavior[1-4]. Domestic researches of the slab-column structure were more focused on the solid slab column connection shear resistance[5-13]. However, few studies on punching shear behavior of hollow slab-column connection and no specified design theory or mechanical performance have been published.

The slab-column connection is a critical part of any new structure. For instance, under the seismic load, the repeated punching of unbalanced moment will seriously weaken the punching shear capacity of the connections. Therefore, the slab-columns connection in hollow slab-column system is a crucial component, and the destruction of the connection is usually the main cause of the structure damage or even leading to the collapse of the structure. In this paper, experimental investigation on the hollow slab-column connections under the unbalanced bending moment and punching was carried out, and the punching damage mode of the hollow slab-column structure connection had been realized. Then
2. The slab-columns connection specimens experiment

2.1 Specimens design
The hollow slab-column structure interior connection was selected as the research object, which was isolated, with a reverse bent line as the boundary, from the intermediate zone in a real project. Considering the laboratory condition, six specimens were designed by 1/2 scale. Fig.1(a) is the hollow tube layout, while Fig.1(b) is the finished specimens. The height and the size of the column are 700 mm and 300mm×300mm respectively. The longitudinal reinforcements in the column are four steel bars with the diameter of Φ12mm. The span of the slab is 1400mm. The concrete strength grade is C30. The compressive strength of the concrete cube were tested as 32.2MPa. The elastic modulus of concrete is $30.5 \times 10^3$MPa. The tensile strength of the 8mm diameter steel is 520MPa. Tab. 1 shows the parameters of the specimens.

![The hollow tube layout](image1)
![The finished specimens](image2)

**Fig. 1 The specimens**

| Specimen number | Thickness (mm) | Pipe diameter (mm) | Hollow ratio (%) | Reinforcement (Two-direction) | Load direction | Spacing (mm) |
|-----------------|----------------|--------------------|-----------------|-------------------------------|----------------|--------------|
| UM1             | 100            | 50                 | 26.2            | 8@100                         | Along the pipe | 25           |
| UM2             | 100            | 50                 | 26.2            | 8@100                         | Transverse pipe| 25           |
| UM3             | 100            | 50                 | 26.2            | 8@100                         | Cross the pipe | 25           |
| UM4             | 125            | 75                 | 35.3            | 8@100                         | Along the pipe | 25           |
| UM5             | 125            | 75                 | 35.3            | 8@100                         | Transverse pipe| 25           |
| UM6             | 125            | 75                 | 35.3            | 8@100                         | Cross the pipe | 25           |

2.2 Experiment loading device
The specimen constraint condition is four-edges simply supported. The reaction frame is fixed by steel supports of 1m high connected with the laboratory rigid ground. The specimens are supported in order to easily observe the crack propagation of the slab bottom. The manual jack is placed in the
center of the column top, and the hydraulic jack provides the horizontal force. All of the vertical load and the horizontal load are finally applied by the reaction frame.

![Reaction frame](image)

**Fig.2 The loading device**

### 2.3 The loading and measuring solutions

The test loading program is divided into two stages: preloading and formal loading. The preloading has 3 levels and the load of each level is 10 kN. Before the formal loading, 10 kN of horizontal force is applied per level until the horizontal force reaches 40 kN. Then 10 kN of vertical force is applied per level. Wait for 10 minutes after each level, and then keep loading the next step until the column is completely damaged. During the pause of each step, the crack propagation process and its corresponding position on slab is observed and marked. In the loading process, the horizontal load value is calculated according to 21 kN·m of the bending moment on the hollow slab nodes in the normal using.

At each of the four angles of the slab bottom, a displacement measure is installed to measure the buckling changes of the hollow slab angles; At the center of the slab bottom, another displacement measure is installed to measure the displacement change of the center of the slab bottom. Reinforcing steel bar strain of the top and bottom of the slab are measured using strain gauge. At the top of the hollow slab, the concrete strain gauges are laid around the column. The distance between the gauge center and the edge of the column equals to the thickness of the slab.

### 3. Test results

#### 3.1 Failure pattern

All specimens' failure is the punching shear failure. The typical shear failure of the specimens is shown in Fig.3. UM1 is taken for a case to describe the failure, and the failures of the rest specimens are similar to it. The first slender crack appeared at the slab bottom and the column edge, with 45°to the edge of the slab. The cracks on both sides of the oblique edge developed with the increase of vertical load. At the same time, more cracks came into existence along the pipe and the circumferential cracks significantly developed with the sound of concrete cracking. When the vertical load was increased to 80 kN, the slab bottom gradually showed radial cracks which centered around the edge on one side of the column and radiated to the slab edge. Cracks originally appeared in piping direction also turned wider constantly. When vertical load was increased to 120 kN and then decreased, the side of the column sank and soon the specimen was damaged.
According to the experiment result, the specimen punching shear cone is obvious asymmetry for the effect of the monotonic horizontal load, and the specimen damage is the brittle punched shear damage. Tab. 2 lists all the specimen's fracture load.

| Specimen number | Fracture load $F_{\text{max}}$ (kN) | Failure pattern         |
|-----------------|-------------------------------|------------------------|
| UM1             | 120                           | Brittle failure        |
| UM2             | 110                           | Brittle failure        |
| UM3             | 80                            | Brittle failure        |
| UM4             | 100                           | Brittle failure        |
| UM5             | 100                           | Brittle failure        |
| UM6             | 90                            | Brittle failure        |

3.2 The load-displacement curve
According to the load-displacement curve in Fig. 4 of UM1, it can be found that when the load is low, the specimen is in a flexible stage. After the slab cracks, the curve slope changes drastically which means the stiffness of the specimen decreases. The slope of curve before cracking is greater than that after crack, which is due to the decrease of the effective sectional inertia moment of the slab caused by the crack. The load-displacement curve of punching shear damage in slab shows that the load has a sudden decreasing, and when the slab punching shear cone is formed, the capacity decreases and the displacement of the slab bottom increases rapidly.

4. Test results analysis

4.1 The influence of hollow ratio and thickness
The thickness of specimen UM1, UM4 is 100mm. The thickness of specimen UM2, UM5 is 125mm. The thickness of the upper and lower layers of the solid zone is 25mm and the hollow ratio is 26.2% and 35.3% respectively. All other factors are the same. It can be seen from the test results of the two groups of specimens that the punching shear capacity of hollow slab decreases with the increase of hollow ratio, while the amplitude of the decreasing is 16.7% and 9.1% respectively. Comparison of the load-displacement curve of the four components is in Fig.5 and Fig.6 respectively. It can be found from the figure that with the increase of the thickness, the maximal displacement at the bottom of the slab reduces when the hollow slab is damaged; the deformation ability is good when the thickness and hollow ratio are both low. The ultimate displacement of UM1 is about 2 times of that of UM4, and the ultimate displacement of UM2 is about 1.3 times of that of UM5. The stiffness of the thicker slab is larger.

4.2 The influence of the bending direction

The parameters of specimen UM1 and UM2 are the same except the horizontal load direction: the horizontal load direction of UM1 is along tube, while that of UM2 is horizontal to tube; Similarly, UM4 and UM5 are another group of specimens with same parameters, horizontal load of UM4 is along tube, while that of UM5 is horizontal to tube. The comparison of the load displacement curve of the four specimens is shown in Fig7 and Fig.8. As shown in the chart, the development trends of the 2 groups are similar. For UM1 and UM2 of which the hollow ratio are lower, the punching shear capacity of the specimen of which the bending direction is along the pipe, is greater than that of which the bending direction is horizontal to tube, and the magnitude of the increase is about 9.1%; Because the hollow ratio of UM4 and UM5 is relatively larger, the punching shear capacities are similar when
bending moment is in two directions respectively. As a result, when the unbalanced moment is small, the horizontal load direction of the hollow slab-column connection have little effect on the punching shear bearing capacity, no matter the direction is horizontal to or along the pipe.

4.3 The influence of bi-directional unbalanced moment

Fig.9 Load-displacement curve of specimen UM1, UM2, UM3

Fig.10 Load-displacement curve of specimen UM4, UM5, UM6

In this paper, the hollow slabs UM1, UM2, UM3 have the same parameters. Among them, one-directional unbalanced moment is applied on UM1 and UM2, and bi-directional unbalanced moment is applied on UM3. The hollow slabs UM4, UM5, UM6 have the same parameters. Among them, one-directional unbalanced moment is applied on UM4 and UM5, and bi-directional unbalanced moment is applied on UM6. Comparisons of load-displacement curve among the specimens are in Fig.9 and Fig. 10. It can be found from the diagram that the punching shear capacity of hollow slab-column connection bearing bi-directional unbalanced moment is reduced by 27.3%~33.3% than those of which bearing one-directional unbalanced moment. However the displacement is larger in the final condition and the deformation ability increases by 32%~70% compared to the specimen bearing one-directional unbalanced moment.

5. Finite element analysis and formula fitting

In order to study the effect of the unbalanced moment on punching shear capacity of the hollow slab-column connection, specimen UM1 was selected as a prototype in finite element analysis and different unbalanced moments were applied on it. Six models were established using finite element software.

Fig.11 Load-displacement curve of nodes under different unbalanced moment

Fig.12 Load-moment curve of nodes under the different unbalanced moment

Fig.11 shows the load-displacement curve of punching shear in hollow slab-column connection under different unbalanced moment. It can be found from the diagram that, when the specimen is only applied vertical load, the destroying displacement is very small when the punching shear damage
happened. While the unbalanced moment is applied to the specimen, the displacement is larger, the deformation ability of the connection is stronger, and the curve has the characteristics of bending failure. The final displacement of the specimen under unbalanced moment is 150% larger than that of pure punching failure. It can be seen from the Fig.12 that, the punching shear capacity of hollow slab-column connection decreases while the unbalanced moment increases. Comparing the results of the pure punching failure models, the punching shear capacity of the model decreases by 19.1%, 20.7%, and 27.0%, 32.0% and 38.5% respectively. The transmission of the unbalanced moment makes the distribution of shear stress around the column of hollow slab domain uneven, and the plate cutting critical section near the cavity exacerbates this effect, resulting in the lower punching shear capacity.

After analyzing the results using the least squares method for data fitting, we concluded the relationship between punching shear capacity and unbalanced bending moment of the hollow slab-column connection can be written as:

\[
\frac{V}{V_0} = -0.85 \left( \frac{M}{M_0} \right)^2 + 0.0324 \frac{M}{M_0} + 0.8742
\]

In formula 1, \(M_0\) is the unbalanced moment of the hollow slab-column connection without vertical force; \(V_0\) is the vertical shear of hollow slab-column connection without unbalanced moment; \(M\) and \(V\) is the real unbalanced moment and vertical shear of hollow slab-column connection, respectively.

Fig.13 shows the correlation between unbalanced bending moment and punching shear bearing capacity of hollow slab-column connection.

![Fig.13 The correlation between unbalanced bending moment and punching shear bearing capacity of hollow slab-column connection](image_url)

6. Conclusions
The punching failure of hollow slab is brittle failure. Before the failure happened, with the increase of load, the top of column suddenly move down and cause the decrease of bearing capacity. The top of the column moves down to punch a certain depth, then the punching shear rupture cracks appear within a certain distance between slab bottom and the load center. The punched down concrete of the topside slab and the concrete in the dislocation cracks of the underside slab form a punching cone. The failure pattern is similar to that of the solid one. But with the influence of the unbalanced moment, most of the specimens have the punching cone in only one side.

The initial cracks appear outside the loaded column bottom area, and the bottom of the plate has gathered cracks which are along the pipe and vertical to it before damaged.

Capacity of the hollow slab column node decrease while the hollow ratio increases, but not much.

When the unbalanced moment is low, the punching shear capacity of the hollow slab-column is only marginally affected by the load direction, whether it is the horizontal direction or the along pipe direction.

The punching shear capacity of hollow slab-column punching node under two-way unbalanced moment is lower than that under one-way unbalanced moment, but the displacement is larger after it is damaged, and the deformation is smaller.

The correlation between the unbalanced moment and the punching shear bearing capacity of hollow slab-column node was studied by using finite element software.
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