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State of the art of research on punching shear behavior of reinforced concrete slab-dege column connections

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Abstract

At the beginning of the 20th century, American engineer Turner proposed a new type of building structure - plate and column structure, and confirmed the feasibility of the structural form through the load test, and built the world's first plate and column structure. Its advantages such as beautiful appearance, simple construction and flexible spatial arrangement have made plate-column structures at home and abroad rise and are widely used in practical projects, and caused a large number of researchers to study the properties of plate-column joints. However, plate-column structures are prone to brittle local punching failure during use. Once punching failure occurs at individual nodes within the structure, The original load will be redistributed to the adjacent nodes, which will cause the continuous collapse of the structure. Domestic and foreign scholars have conducted a large number of experimental studies on the punching resistance of plate-column joints, and have made remarkable progress. The research shows that the measures to improve the punching resistance of joints generally include: configuring punching elements, improving the strength and reinforcement ratio of the flexural longitudinal reinforcement of plates, applying fiber high-strength concrete materials, setting column caps or trays, etc.

Keywords

Reinforced concrete slab-edge column connections, punching behaviors, punching capacity.

1. Introduction

Slab-column structure is a housing structure that consists of floor slabs and columns to form a load-bearing system (Figure 1). Tracing back, the American engineer Turner in 1906 in the design program and constructed the world's first beamless floor structure Bovey-Johnson building, and through the load test confirmed the feasibility of the structural form of the building's floor directly through the increase of the column head of the column support, the formation of a new structural form of the slab-column structure [1]. It is characterized by the absence of beams under the indoor floor slab, smooth and concise space, flexible layout, and can reduce the height of the building, so it is suitable for multi-storey factories, warehouses, halls of public buildings, and can also be used for office buildings and residences.

Fig. 1 Slab-column structure

Although the slab-column structure has good social and economic benefits as mentioned above, it is very easy for sudden localized punching damage to occur at the floor slab and column joints without taking effective measures so that the nodes reach sufficient bearing capacity, and once brittle punching damage occurs at individual nodes of the structure, the original loads borne by the structure will be redistributed to adjacent nodes, which will lead to continuous structural collapse. On August 19, 2017, a localized collapse occurred at the northeast side of the basement roof slab during the construction of the underground garage project of Block E in Xihuangcun, Shijingshan District, Beijing. At the Xihuangcun A-E Lot underground garage project in Shijingshan District, Beijing, on-site construction workers were using a forklift to carry out soil cladding construction on the top slab of the basement when the top slab on the northeastern side of the first basement floor partially collapsed. Fortunately, no one was under the basement, and only 2 people were injured.2021 On June 24, 2021, a 12-story residential building in Florida, U.S., partially collapsed, killing at least 3 people and injuring 12 others. For a long time, engineering accidents of continuous collapse have occurred in slab-column structures both in the construction stage and in the use stage [2-4], which have not been completely solved so far. In this paper, we summarize the research contents of domestic and foreign scholars, and make some suggestions and opinions on future research.

2. Research significance

Along with the deepening of research and the gradual maturation of technology, the emergence of steel-concrete composite slab-column structure makes up for some of its shortcomings and expands its scope of application, and the problem of punching damage of slab-column nodes has been a classic research topic in the field of structural engineering. However, most of these studies focus on the middle node of the plate-column, and there are fewer studies on the edge node, which are more inclined to the study of its seismic performance, and the experimental study on the resistance to punching and shearing performance is still relatively blank. In order to further investigate the force performance, force transfer mechanism and failure mode of plate-column edge nodes, it is necessary and significant to conduct an in-depth study on the punching resistance of slab-column edge joints.

3. Analysis of research status and development dynamics of slab-column edge connections

Slab column structure in the process of use, the plate column node connection area force situation is complex, in addition to bearing a large impulsive force, but also bears a large unbalanced bending moment, the edge of the plate column node and the node of the plate column node due to its structure is not completely symmetrical and has the essential difference, in the case of not subjected to horizontal load, the edge of the plate column node continues to be in the unbalanced bending moment of the state of force.

3.1. Research status

El-Gendy [5] et al. investigated the performance of full-size glass fiber reinforced polymer (GFRP-RC) plate-column edge nodes (Fig.2), which showed that the members without shear-resistant elements (bolts) suffered from sudden punching shear damage and that members configured with shear GFRP bolts were able to control the diagonal shear cracks and increase the node punching-shear load carrying capacity, and proposed that the spacing of 0.5d (effective plate thickness) was the optimum distance to increase the punching-shear performance. effective thickness) is proposed as the optimum distance to improve the improvement of edge node punching performance.

Mostafa [6] et al. conducted an experimental analysis of the factors affecting the shear bearing capacity of column-edge nodes of glass fiber reinforced polymer (GFRP-RC) slabs with respect to parameters such as bending longitudinal reinforcement reinforcement ratio and type of shear-resisting elements, and the results showed that the use of 8 rows of shear-resisting GFRP reinforcement with both stigma-like and corrugated rod-like shear-resisting GFRP reinforcement (Fig. 3) was able to control the development of shear cracking and could effectively prevent the nodes from punching shear damage, while using 6 rows of shear resistant GFRP reinforcement, only the column head-like shear resistant GFRP reinforcement can make the nodes have better bearing capacity and ductility to reach the bending damage, and suggests the minimum shear reinforcement ratio of 0.4%.

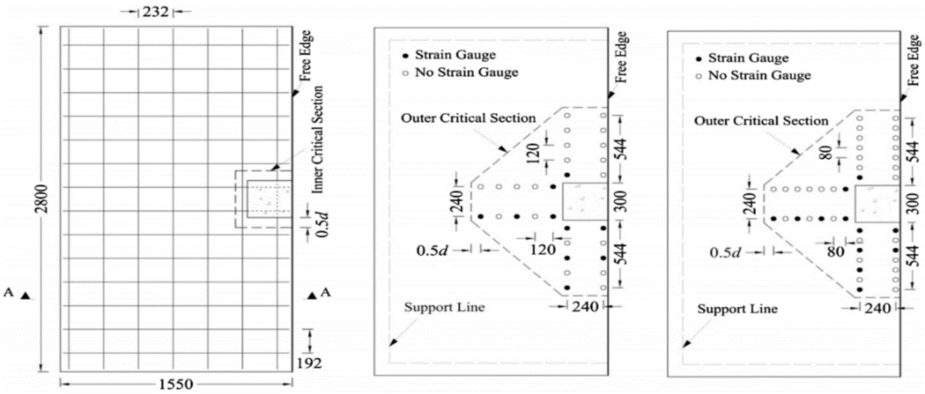

Fig.2 The dimension of test specimen and The arrangement of shear-heads

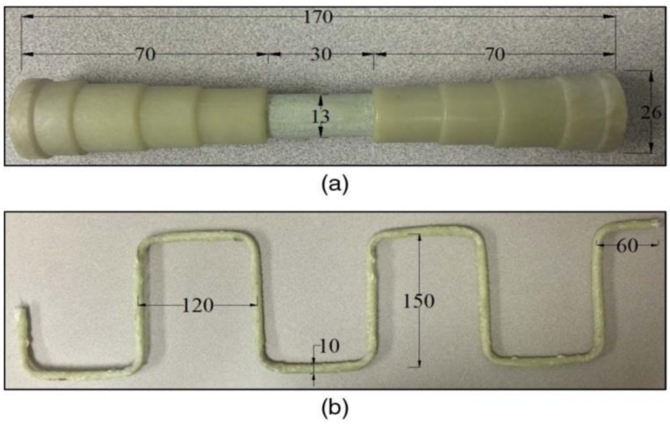

Fig.3 GFRP Shear reinforcement (a) headed studs,(b)corrugated bars

Salama [7] et al. conducted an experimental study on the performance of concrete slab-column edge node joints incorporating glass fiber reinforced polymer (GFRP). The results showed that the configuration of closed or spiral GFRP hoops around the column perimeter improved the punching and shearing resistance of the specimen joints, and the use of spiral hoops was preferred over closed hoops. When the length of GFRP shear element extends to 1.75~4.25d (the effective thickness of the plate), the plates all show the form of bending damage with better ductility.

Nivea [8] et al. conducted 13 tests to investigate the effect of external eccentricity on the punching shear resistance of flat plate edge column nodes. The results showed that the rotational stiffness and punching shear strength of plate edge column nodes decreased with the increase of eccentricity, the rotational stiffness could be improved by increasing the reinforcement ratio of plate bending reinforcement, while the addition of closed shear hoops at the edges of the plate increased the punching shear strength of the nodes, but could not increase their rotational stiffness. Figure. 4 shows the cracking pattern of the specimen.

Mohammed G. [9] et al. conducted experimental tests on the seismic performance of full-scale RC slab-column nodes using GFRP shear bolts, GFRP corrugated rods, and no shear reinforcement, and the test results showed that the forms of reinforcement using GFRP shear spirals and corrugated rods increased the node's horizontal load capacity by 47% and 44%, respectively, and enabled the node to undergo inelastic deformation, with an interstory displacement The ratios were 3.5% and 2.5%, and no punching damage occurred.

Farshad J [10] et al. investigated the effect of type and arrangement of shear reinforcement on the performance of plate-column nodes through finite element analysis, which showed that both ways of arranging the encrypted zones significantly increased the ductility of the plate-column nodes but the encrypted zones were located perpendicular to the free edges of the plate as compared to the encrypted zones located parallel to the free edges of the plate and the increase in the performance of the resistance to punch shear was more significant

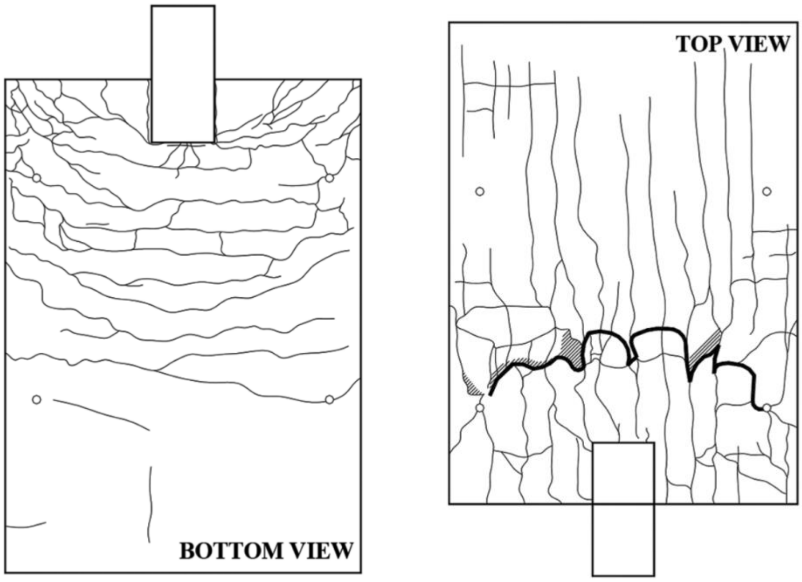

Fig.4 The cracking pattern of the test specimen

Abu-Salma D [11] et al. investigated the modeling of punching shear damage of flat plate edge columns without shear reinforcement. Nonlinear finite element analysis (NLFEA) was used to investigate the effect of parameters such as column aspect ratio and load eccentricity on punching resistance and incorporate the failure criterion of critical shear crack theory (CSCT). Both experimental and NLFEA analysis results show that the design value of punching shear resistance based on elastic load eccentricity is conservative.

Cao Ming [12] et al. investigated the occurrence of damage pattern and resistance to punching and shearing in the connection zone of plate-column by testing the plate-column node loaded by a single static load, deduced the upper limit value of b for the occurrence of bending damage in the connection zone of plate-column with a better ductility ρ_b and gave the expression of ρ_b in the following equations (1) and (2).

$$\rho_b = \frac{f_c\left(\eta_1 - \sqrt{\eta_1^2 - 4\eta_2}\right)}{2f_y} \tag{1}$$

$$\begin{cases} \eta_1 = 2.2 - 0.204\left(2a + \pi h\right)\lambda / l_0 \\ \eta_2 = 0.068\left(2a + \pi h / 2\right)\lambda / l_0 \\ \lambda = \left(l_0 - a\right) / 2h_0 \end{cases} \tag{2}$$

Lu Xilin [13] and others, after determining the intrinsic relationship of the material, deduced the equations related to the punching and shearing strength of the plate-column edge nodes by analyzing the plastic limit theory, and compared the calculation results with the test results to arrive at the way with a high degree of accuracy. An important contribution is made to the design method of plate-column system. Yang Zhen [14] and others through the test of the edge node, concluded that the bending and punching composite damage is the correct damage pattern of the node damage, and at the same time verified that in the verification of the plate column node, can be used in the bending damage, shear damage in the ultimate load of the smallest value of prevail has a certain degree of reliability.

Li Lin [15] set up three plate-column edge node specimens, the configuration of the anti-impact cut reinforcement comparative experimental research and simulation analysis, it is concluded that the configuration of the anti-impact cut anchor bolts, can greatly improve the performance of the plate-column edge node, it is concluded that the configuration of the anchor bolts can improve the structural deformation capacity of the interstorey, ductility, and energy-consuming capacity, etc., in a certain range, for the seismic performance of the seismic performance of China's "Code for the Design of Concrete Structures" draft for approval (GB50010-201X) [16] within the formulae bias security, the simulation results of the stress cloud map and the actual damage morphology is more in line with the (Fig. 5).

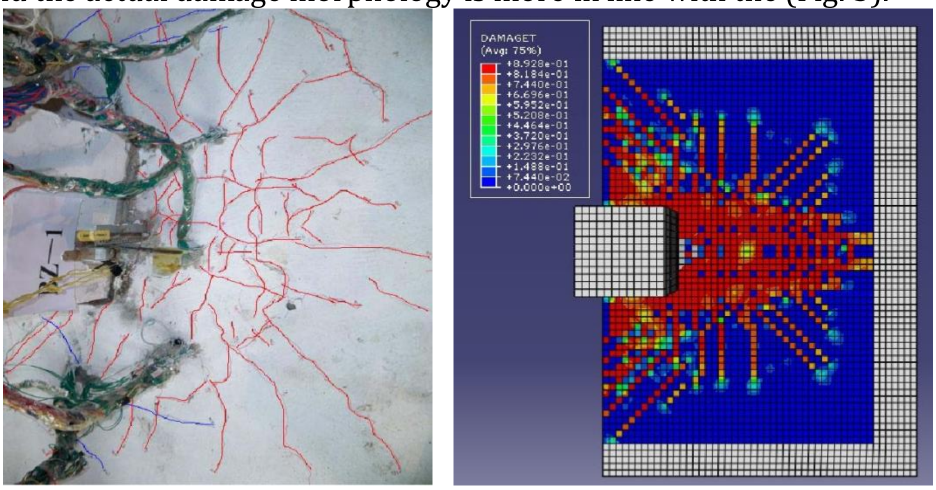

Fig.5 Comparison diagram of specimen BZ-1 test and simulation

Zhang Lei [17] et al. set up three specimens for testing under low-cycle repeated loading, and the results of the test data show that the configuration of a certain amount of impact cut-resistant elements can achieve a certain level of seismic performance, and at the same time, encrypted hoops can also better inhibit outward buckling of the edge plate, which is safer and more reliable than the tension bar.

Huang, Wenjun, and Li, Yi [18] carried out static loading tests on plate-column structures with continuous line collapse, in the initial loading until the collapse of the structure, the side column nodes were involved in bearing a larger percentage of the load, and in the collapse process was as high as 50 percent. In the assessment of load-carrying capacity, it was concluded that the compressive film effect contributes to the load-carrying capacity of the slab-column nodes at different levels of deformation in the event of damage.

Yang Tao, Yi Weijian [19], etc. conducted tests on the continuity collapse performance of beamless building cover after the failure of side columns, and the test results showed that the configuration of diagonal structural reinforcement at the bottom of the slab would increase the cracking load of the node by 78.3%, the peak load by 32.3%, and the ultimate collapse resistance capacity by 50.7%, and it was also concluded that the value of the DIF (Dynamic Increment Factors of Loading) of the slab-column structure should be taken between 1.16 and 2.0.

Zhang Junhua [20] completed the punching test of two nodes with concealed beams and side columns using longitudinal bar reinforcement rate as the test variable. The experimental results showed that the provision of concealed beams and the increase of reinforcement rate can effectively improve the performance of the nodes to see punching, but the specimens with higher reinforcement rate showed relatively poor ductility, and the yield region of the reinforcement became smaller accordingly, and brittle bending and punching damage phenomenon occurred. At the same time, it is concluded that it is more effective to strengthen the punching resistance measures within the range of 2h (effective height of slab) from the column edge.

4. Conclusion

After systematically reading a large number of literature on plate-column structures by scholars at home and abroad, we have gained a more in-depth understanding of the force-transfer mechanism of the nodes of plate-column structures, and have gained an accurate position on the current research status of plate-column structures. At present, the research on the punching and cutting resistance of edge nodes of plate-column structure needs to be carried out continuously, and scholars still do not have a unified understanding of the force mechanism and the prediction criteria for the damage type of the nodes. As scholars from all walks of life continue to promote the research, nowadays the development of high-strength materials and more reasonable construction technology has been replaced, using the original calculation model has been unable to accurately predict the node punching bearing capacity, many provisions need to be revised, and the specification should also be updated.

Acknowledgements

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