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Strength and Behavior of Bolted Ultra-High Performance Concrete Panel Joint with Geometric Parameter

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Abstract

One of the most reasonable ways to connect thin ultra-high performance concrete (UHPC) facades to building structures is bolted joints. To design the joints for the facades economically and safely, a clear investigation of the structural behavior is needed. In this study, the joint strength, failure modes and strain concentration phenomena of the bolted UHPC panels are investigated by direct tensile test. The main experimental variables are the geometric parameters, which are the width of the specimen, its thickness, and the distance from the center of the hole to the edge. Experimental results show that ductility of the joint depends on the failure mode. In addition, it is shown that the increase in the material cost of the panel, such as size and thickness, does not necessarily lead to an increase in the joint strength.

Keywords: Ultra-High Performance Concrete (UHPC); Facade; Panel; Bolted joint; Cleavage failure; Net-tension failure

Introduction

The development of information technology has led to the development of freeform design technology in the field of architecture, which is attracting much public attention. Metal or concrete has been used as the most suitable material for manufacturing such a preform facade. However, fabricating the preform facades using these materials can lead to some problems such as design complexity and high cost.

UHPC can be a reasonable alternative to the freeform facade, because it has outstanding mechanical performance, self-compacting property and durability [1,2]. Although the material cost of UHPC itself is much higher than that of normal concrete [2,3], the UHPC facade manufactured by precast method can be assembled by bolt fastening, so the construction cost can be reduced and the whole construction cost can be reduced. Nevertheless, the study on the bolt joints of UHPC panels is still lacking. Therefore, this study was conducted to investigate the structural performance of the bolt joint for connecting UHPC panels.

Experimental Procedure

Test parameters

The experimental program was designed to investigate the effect of panel geometry on the behavior of the panel. Based on this, three basic geometric variables, which can affect the strength and failure mode of the joint, were considered. These parameters are shown in Figure 1 and also can be summarized as follows.

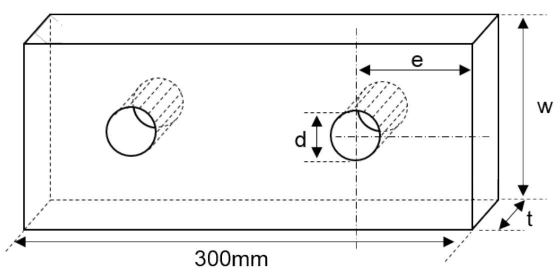

Figure 1: Geometric parameters of specimen.

Cement	Silica fume	Quartz sand	Silica flour	Water	Super-plasticizer	Steel fiber*
1	0.25	1.1	0.35	0.22	0.03	2%

* Volumetric ratio of UHPC

Table 1: Mix proportion of ultra-high performance concrete (by wt% of cement).

In Figure 1, e/d is the ratio between the end distances (e) to the hole diameter (d). The three ratios were considered as e/d=2, 3 and 4 or e=48 mm, 72 mm and 96 mm at d=24 mm, respectively. In addition, w/d is the ratio between the plate width (w) and the hole diameter (d). The three ratios were planned as w/d=4, 6 and 8 when the plate width is 96 mm, 144 mm and 192 mm, respectively. Lastly, to investigate the effect of panel thickness on the behavior of the joint, it was divided into two types of 20 mm and 30 mm.

Preparation of specimens

Total 18 UHPC panels were fabricated according to the raw materials, mix proportion (Table 1) and procedures of our previous studies [4-6]. When all the mixing was completed, the prepared mold which was placed on a flat table was filled with fresh UHPC by the self-compacting property. After 24 hrs, the mold was demolded and the UHPC was cured at a temperature of 90°C and 95% for 48 hrs. Then, the specimen was cured at a room temperature of 20°C and 60% until the test.

Test setup and instrumentation

Figure 2 shows an experiment prepared to investigate the force and strain transmitted to the hole of a UHPC panel through a bolt and its behavior. The panel and the loading device, universal testing machine

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(UTM) was fixed by bolts inserted into the holes. The tensile force was applied to the fixed specimen by the displacement control method at a speed of 0.005 ± 0.0015 mm/sec.

Linear variable differential transducers (LVDTs) were installed on both sides of UTM to measure the relative displacement between the panel and the UTM, and the load was measured by the load cell. A total of six strain gauges were attached to estimate the stress distribution around the hole in the panel. Its arrangement is shown in Figure 3.

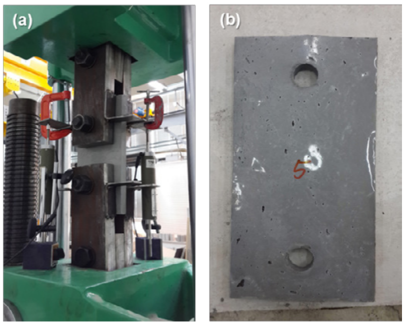

Figure 2: Test setup (a) and prepared UHPC panel (b).

Specimen number	d [mm]	e/d	w/d	t [mm]	Max. load [kN]	Failure mode
1	24	2	4	20	8.3	Cleavage
2	24	2	4	30	11.6	Cleavage
3	24	2	6	20	9.3	Cleavage
4	24	2	6	30	13.5	Cleavage
5	24	2	8	20	10.8	Cleavage
6	24	2	8	30	11.7	Cleavage
7	24	3	4	20	10.7	Net tension
8	24	3	4	30	16.7	Net tension
9	24	3	6	20	13.3	Cleavage
10	24	3	6	30	25.0	Cleavage
11	24	3	8	20	16.5	Cleavage
12	24	3	8	30	23.6	Cleavage
13	24	4	4	20	13.1	Net tension
14	24	4	4	30	15.5	Net tension
15	24	4	6	20	18.6	Net tension
16	24	4	6	30	29.5	Net tension
17	24	4	8	20	19.9	Cleavage
18	24	4	8	30	29.1	Cleavage

Table 2: Test results.

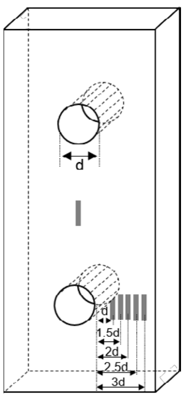

Figure 3: Arrangement of strain gauge.

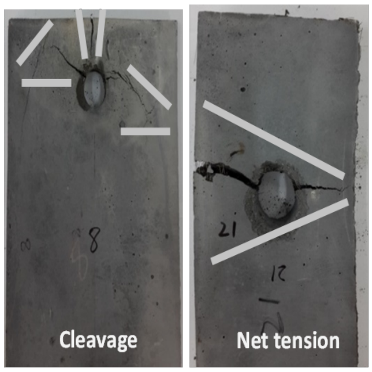

Figure 4: Failure modes.

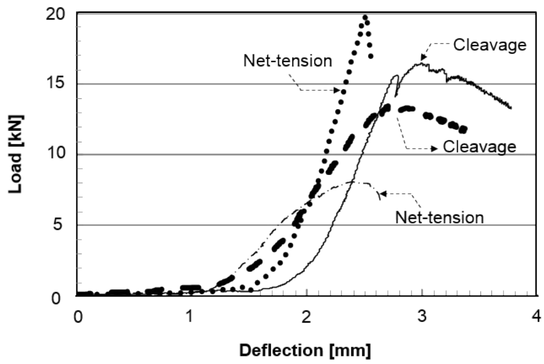

Figure 5: Load-displacement relationships.

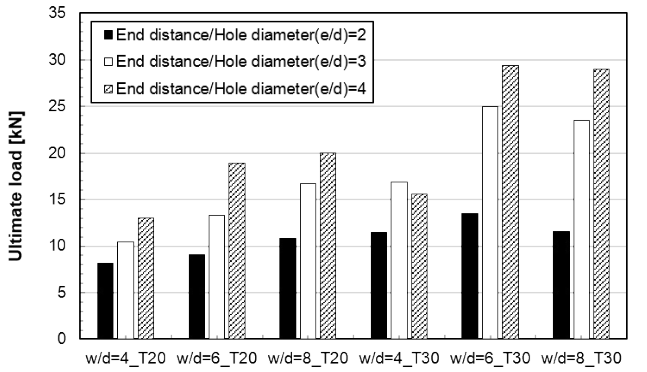

Figure 6: Effect of end distance to hole diameter ratio (e/d) on maximum load.

Results and Discussion

The specimen information and test results are summarized in Table 2. The test results are analyzed by divide into three categories, failure modes, load-displacement characteristics, and Strain concentration factor.

Failure modes

UHPC panels with bolted connections were found to exhibit two modes of failure, such as cleavage and net-tension failures, due to the tensile loading (Figure 4). The cleavage failure was characterized by large cracks from the hole to the nearest side of the panel; then two additional cracks occur in parallel, which improve the ductility of the panel. The widths and lengths of these cracks increase until the maximum load is reached. On the other hand, the net-tension failure was caused by cracks occurring perpendicular to the loading direction through the hole.

Load-displacement characteristics

Figure 5 shows typical load displacement relationships of this study. The displacement of each panel was determined as the average values measured from the two LVDTs. The initial displacement (about 0 mm to 1-1.5 mm) occurred without load resistance because the load was not transferred to the panel through the bolt, where the bolt slipped off the plates. Compared with net-tension failure, cleavage failure showed more ductile behavior, i.e., the load decreased more slowly after the peak load. On the other hand, in the case of net-tension failure, the load suddenly dropped, which means the brittle failure. To quantitatively evaluate the load redistribution capability of each failure mode, the ductility ratio was estimated. This was determined as the displacement at 80% of the maximum load in the post peak state to the displacement at the maximum load. Based on this, it was found that the ductility ratio is higher when the UHPC panel shows cleavage failure than when it shows net-tension failure; especially, in the case of net-tension failure, this ratio is less sensitive depending on specimen geometry compared with cleavage failure.

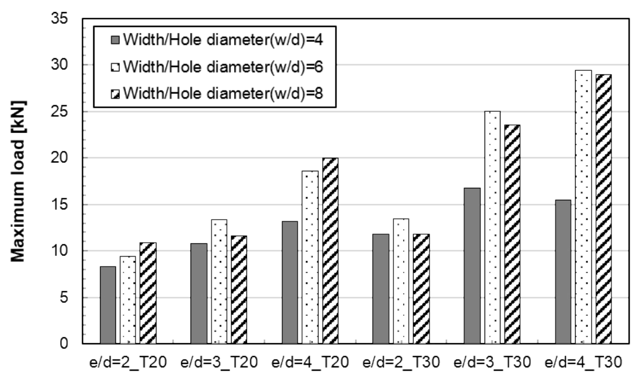

Figure 7: Effect of panel width to hole diameter ratio (w/d) on maximum load.

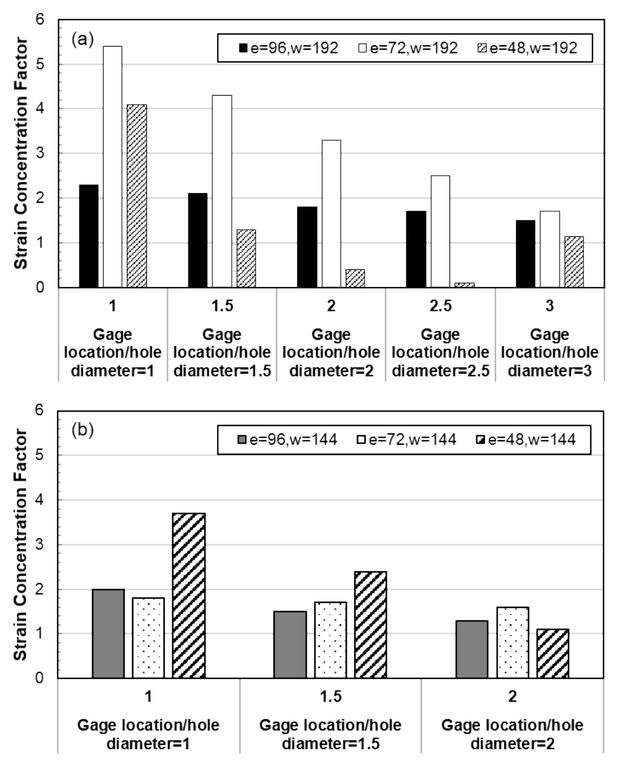

Figure 8: Effect of end distance to hole diameter ratio (e/d) on strain concentration factor.

Strength of panel joint based on geometric parameter

Figure 6 shows the effect of e/d on the maximum load of the connection of bolted UHPC panels. Only results for the same width and thickness were presented in this figure. As expected, e/d was found to be a factor affecting failure mode. One notable result is that when w/d was 4 at t=30 mm, the failure mode was changed from cleavage failure to net-tension failure as e/d increases. This change in failure mode was also directly related to the sudden change in the maximum load and the strength. Without change of the failure mode, the strength was increased with increasing e/d.

The maximum load as a function of w/d is shown in Figure 7 which includes only the results of the specimens with the same end distance. Changes in panel width at the bolted joints were found to be the factors that affect the failure mode as well as its structural performance. It is confirmed that the final load increases as w/d ratio increases. In addition, it is also confirmed that as the e/d increases, the failure mode changes from net-tension fracture to cleavage fracture when the end distance is short (w/d=4 at t=20).

Based on Figures 6 and 7, it is confirmed that increasing the panel thickness in the selected thickness range (20-30 mm) is not directly linked to the increase in joint strength of the UHPC facade. In practice, this result is especially important because the structural performance of a facade is often determined by its connections. In other words, the method of increasing the panel thickness for a conservative design is not always guaranteed to increase its structural performance, but rather it is desirable to change the geometrical parameters, as presented in this study. These experimental results can help to design the joints of UHPC facades economically and efficiently.

Strain concentration around hole

The strain distribution of the selected six panels subjected to tension was analyzed. The purpose was to verify the strain concentration around the bolt hole. The results are presented in Figures 8 and 9 on the basis of geometric parameters which were set in this study. In these figures, the strain concentration factor is defined as the ratio of the strain near the hole to the strain at a distance where the concentration does not occur. In all specimens, actually the concentration phenomenon was found, i.e., the closer location from the hole, the higher the strain concentration factor is.

It is also confirmed that this factor increases when the width of the panel increases (compare Figures 8a and 8b). The change in edge distance also affected the strain concentration factor (compare Figures 9a and 9b). However, the degree of the change was not as critical as the case of panel width. Overall, by analyzing the strain distribution as a function of the geometric parameters, it was confirmed that the strain distribution and thus stress concentration of the connection of UHPC panel depend on sensitively the panel width.

Conclusion

The strength and failure mode characteristics of the bolted joint

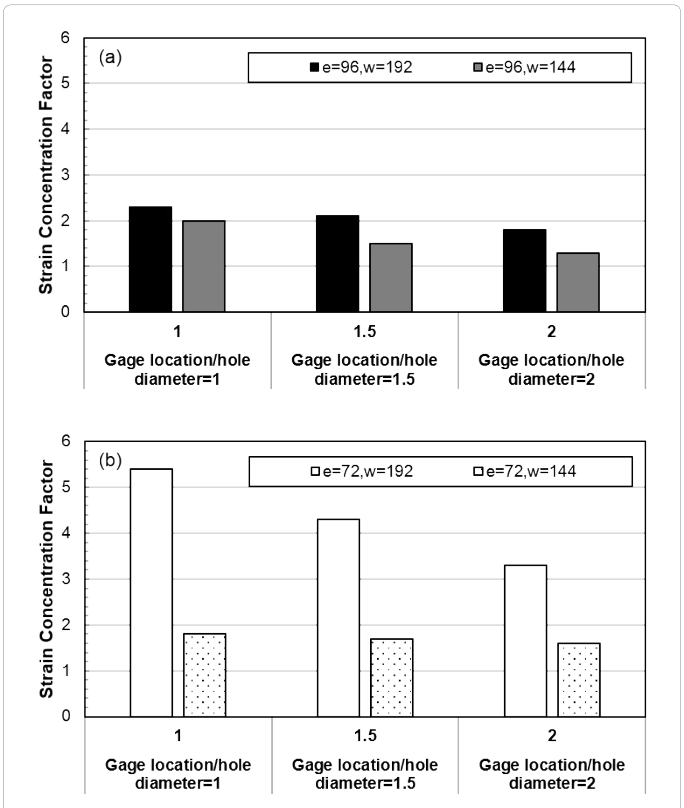

Figure 9: Effect of panel width to hole diameter ratio (w/d) on strain concentration factor.

of UHPC panel were investigated based on geometric parameters. Above all, to design the panel safely, it is necessary to understand the complex material and structure behavior of UHPC, not simply increase the thickness of the panel. The major findings of this study are summarized as follows.

The panel joints that were subjected to direct tensile load via bolt showed two types of failure modes. They behaved more ductile when showed cleavage failure than when showed net-tension failure. Therefore, it is desirable to intend cleavage failure to increase the ductility. Increasing the edge distance, width, and thickness can be effective in increasing the joint strength. However, this increase should be preconditioned that there is no change in failure mode (e.g., cleavage failure to net-tension failure). The change of failure mode was also affected by the geometric parameters. Lastly, the stain concentration around the bolt hole was confirmed by the attached strain gauge and changed sensitively with the panel width.

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