Experimental Study on the Behavior of Bolted Joints for UHPC Panels

Soo-Hyung Chung, and Sung-Gul Hong

Abstract—Bolted joints for UHPC panels are essential in prefabrication. This is the case for UHPC structural system, particularly architectural design, where panels are used. To identify the economic and safe use of bolted joints of UHPC panels, a clear understanding of their mechanical behavior is needed. This paper investigates the tensile behavior of bolted joints for UHPC panels through direct tensile tests, especially focused on identifying the failure modes, strengths and stress distribution. The variables of the experiments were the specimen thickness, specimen width and the ratio between end distance and hole diameter.

Keywords—Bolted joint, UHPC, Tensile behavior, Failure mode

I. INTRODUCTION

ULTRA high performance concrete (UHPC) is a sustainable cementitious composite material which has been actively researched in the recent years. UHPC provides with characteristic value in 200MPa and 10 MPa in the average compressive and tensile strengths with the high ductility due to the existence of steel fibers. Furthermore, with the high liquidity, UHPC has remarkable self-compacting ability. Due to the close-packed micro-structures, it has also outstanding durability such as resistance to chloride penetration. However, characteristic values of UHPC can be changed easily by conditions of curing, such as temperature, humidity and other environmental factors. Accordingly, the using UHPC in precast elements is recommended. The precast UHPC element is not just for structural applications, but is for architectural applications (Fig.1). This study put emphasis on how the architectural UHPC panels get connected to the structure by bolted connections.

II. BOLTED CONNECTIONS AND FAILURE MODES

A bolted joints is susceptible to failure in many different ways whatever the material it is made. The Fig. 2 is the possible failure modes of bolted UHPC panels. (a) is bearing failure mode. This failure mode occurs by high stress concentration in the contact with the steel bolt. In the case of UHPC, tensile strength is remarkably low for compressive strength. Accordingly, possibility of bearing failure mode is very low. (b) is net tension failure mode. It is tensile failure of the element suffered with a crack development orthogonal to the tensile effort. (c) is Shear out failure mode which is occurred by shear force. However, due to the steel fiber in the elements, UHPC panels show high ductility. Finally, (d) is cleavage failure mode due to the tensile force. In tests performed by other researchers to cementitious materials, the most common failures observed were net tension failure and cleavage failure.
2) Aggregate
Established silica powder which particle-size distribution is 45–800 μm was used. This powder contains 97% of SiO$_2$ and the hardness and specific gravity are 7 and 2.65 g/cm$^3$.

3) Filler
Filler which has medium size between cement and silica fume improves a compressive strength of concrete by increasing poured density. Furthermore, it activates hydration reaction by supplying additional SiO$_2$ component. Australian product which has 2.2 μm of average diameter and 99% of SiO$_2$ was used.

4) Super Plasticizer
Super plasticizer which has 1.01 g/cm$^3$ of specific gravity and is for high flow/ high strength concrete was used.

5) Steel Fiber
The most commonly used steel fiber which has 0.2mm of diameter, 13 mm of length and 2500 MPa of tensile strength was used.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>PROPERTIES OF CEMENT AND SILICA FUME</th>
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<tbody>
<tr>
<td>Material</td>
<td>Finess/specific surface area (cm$^2$/g)</td>
</tr>
<tr>
<td>Cement</td>
<td>3492</td>
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<tr>
<td>Silica fume</td>
<td>200000</td>
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<table>
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<tr>
<th>Material</th>
<th>Chemical Composition (%)</th>
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<tr>
<td></td>
<td>Al$_2$O$_3$</td>
</tr>
<tr>
<td>Cement</td>
<td>4.65</td>
</tr>
<tr>
<td>Silica fume</td>
<td>0.25</td>
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<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical Composition (%)</th>
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<td></td>
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<tr>
<td>Cement</td>
<td>2.81</td>
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<td>Silica fume</td>
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B. Test set-up
The mix proportion and mixing procedure used in this experiment was optimized for materials proposed [1]. The mix proportion of UHPC was provided in Table II.

Concrete Mixer which has 60L of capacity and 60rpm of speed was used. Sand and silica fume were mixed first for dispersion of silica fume about 5 minutes. After that, cement and filler which was powder materials was inserted and mixed 5 minutes. Water and half of super plasticizer was mixed about 2 minutes and remaining super plasticizer was mixed about 4 minutes after 3-minute break time. Finally, steel fiber was mixed about 4 minutes and finished.

The molds were then placed on a flat table and the concrete was poured. The specimens were removed from the molds 24 hours after pouring, and the specimens were placed in a constant temperature and humidity chamber where they cured for about 48 hour (temperature: 90°, humidity: 100%). Then, they were left in laboratory environment until tested, Fig. 3.

A total of 18 different UHPC panels were tested under direct tension by two bolts inserted in the holes. One of the bolts was fixed to the universal testing machine (UTM) while the other was attached to the cross-head of the UTM. The specimens were tested under displacement control with a rate of loading of 0.005±0.0015 mm/sec, and the values of the load and displacement were recorded. The LVDTs were utilized to measure the displacements between hole and edge of panels.

C. Experiment Variables
The variables of test is shown in Fig. 4.

1) Ratio $\text{eld}$ is the ratio between the end distance $e$ (distance between the center of the bolt and the panel edge) to the hole diameter $d$. The three ratios investigated were $\text{eld}=2$, $\text{eld}=3$ and $\text{eld}=4$, corresponding to end distances of 48 mm, 72 mm and 96 mm (the hole diameter was kept constant at
2) Ratio \( w/d \) is the between the width of panel \( w \) to the hole diameter \( d \). The three ratios investigated were \( w/d=4 \), \( w/d=6 \) and \( w/d=8 \), corresponding to width of 96 mm, 144 mm and 192 mm.

3) Thickness \( t \): The two thickness investigated were \( t=20 \) mm and \( t=30 \) mm.

IV. RESULTS AND DISCUSSION

A. Failure Modes

The two main failure modes were observed, cleavage failure and net tension failure, are shown at Fig. 6. No shear out failure was observed due to the high shear strength of UHPC. Neither any bearing failure, was observed.

The cleavage failure is characterized by a major crack, parallel to the panel longitudinal direction, and after that two cracks from the hole are developed along the horizontal direction, providing an additional ductility. As the load increased, the crack opened until the ultimate load was reached.

In the net tension failure, a major crack was developed from the one of the external sides to the hole, with a center of rotation in the other external side. While other cracks also develop during increased loading, the main tensile crack controls the final load-carrying capacity.

B. Ductility Ratio

The ductility ratio was obtained as the ratio between the displacements associated to the post peak load of 80% of the maximum load, and the displacements associated to the linear slope reaching the maximum load as Fig. 8. A ductility ratio of cleavage failure mode was higher than the net-tension’s. Also, as the width of panels increased, so did the ductility ratio.

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Fig. 4 Experiment Variables
Fig. 5 Test set-up
Fig. 6 Failure modes (left : cleavage, right : net tension)
Fig. 7 Stress related with the deflection of cleavage failure (up) and net tension failure (down)
Fig. 8 Calculation of ductility ratio
C. Effect of End distance
The ratio of end distance to bolt diameter affected the failure mode of panels and the ultimate load capacity. For $e/d = 2$, all the panels failed in the cleavage failure mode. As the $e/d$ was increased to 3 and 4, the failure mode was changed by correlation between end distance and end distance. Also, ultimate load increased as end distance increased.

D. Effect of Width
The ratio of width to bolt diameter affected the failure mode of panels and the ultimate load capacity. As the $w/d$ was increased, the number of macro crack was increased. Also, the failure mode was changed (Fig. 9). It seemed that net tension failure mode was changed to the cleavage failure mode at the point which the width is two times longer than end distance.

E. Effect of Thickness
The thickness of panels affected only the ultimate load capacity, not failure modes. The change in ultimate load by thickness is shown in Table III.

V. CONCLUSIONS
In this study, the behavior of bolted joints for UHPC panels was investigated. The results of experiment were explained as follows.
1) The two types of failure modes were observed in the tension tested: a cleavage failure ahead of the bolt, a net tension failure along the net section.
2) Increasing the end distance, width and thickness is very effective in increasing the ultimate load capacity.
3) The failure modes were affected by correlation between end distance and width of panels. As the ratio between width and end distance increased, the failure mode tended to change from net tension failure to cleavage failure.
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REFERENCES


