Behaviour of Precast Concrete Beam-to-Column Connections using Steel Plate

AHMAD BAHARUDDIN ABD. RAHMAN, MOHD HAFIZI MOHD AKHIR and ZUHAIRI ABD HAMID

1Department of Structure and Materials, Faculty of Civil Engineering
Universiti Teknologi Malaysia,
81310 Skudai, Johor, MALAYSIA
2Public Works Department, Kangar, Perlis
3Construction Research Institute, Malaysia (CREAM), Jalan Chan Sow Lin, Kuala Lumpur
baharfka@utm.my, MohdHafizi@jkr.gov.my, zuhairi@cidb.gov.my http://www.civil.utm

Abstract: - This paper discusses the behavior of a proposed precast concrete beam-to-column connection using steel plate. The objective of the research was to develop a rigid precast concrete beam-to-column connection that can perform similarly to the monolithic connection. The experimental study comprised 3 precast concrete beam-to-column connections developed using steel plates with different parameters of corbel length and one monolithic connection as the control specimen. The behavior of the connection was investigated through the connection moment-rotation responses. The result indicates that the proposed connection closely resembles the monolithic reinforced connection. The greater the length of corbel the closer is the precast connection resembles the monolithic connection. The steel plate joint located at a corbel length of 300 mm performed closely to the monolithic connection.

Key-Words: - Precast concrete connection, hidden corbel, strength, ductility

1 Introduction

The use of Industrialised Building Systems (IBS) in particular the precast concrete construction contributes to sustainability practices by reducing construction waste, optimising materials and improving the site conditions. The IBS precast concrete framed building system, see Fig. 1, is basically component based construction, where components in buildings such as beams, columns and walls are manufactured in the factories and then delivered to site for installation to make a complete building. The loose precast concrete components are connected by structural connections. The success of construction system such as the speed and the stability of the overall frame depends on the connections, in particular the beam-to-column connections.

The connections between beams to columns are categorised further into two main groups namely pinned and rigid connections. There are some drawbacks of pinned connections, where beams are designed as simply supported resulting in large beams. This increases the use of concrete material. As an alternative, rigid connections if employed could reduce the use of concrete material in beams and in the case of low rise buildings, independent lateral stability systems such as shear walls could be excluded.

Fig. 1: Precast concrete framed building system

The main objective of this research is to study the structural behaviour of a proposed connection of hybrid beam-to-column for precast concrete frame which used steel plate to join the beam-to-beam part. The other objectives of the research was to obtain the relationship between applied moment and rotation of beam-to-column connection using steel plate.
The response of beam-to-column connections can be explained by the moment-rotation relationships obtained from the experimental tests. The important characteristics such as the stiffness and strength can be acquired from the M-\(\phi\) curves.

When subjected to a hogging moment \(M\), deformations at the interfaces compress the concrete locally at the bottom whilst tensile strains open the interfaces at the top, resulting in a rigid body rotation \(\phi\) of the end of the beam relative to the column, as shown in Fig.2 [1]. The behaviour of connection comprising ductility, strength and rigidity is fully defined by moment-rotation (M-\(\phi\)) as shown in Fig.3 [1].

![Fig. 2: Definition of relative rotation of a beam to column [1]](image)

![Fig. 3 Moment-rotation (M- \(\phi\)) [1]](image)

Many research works on precast concrete beam-to-column connections have been carried out to investigate the behaviour and performance as compared to monolithic reinforced concrete connections [1], [2], [3]. For example, Y.S Loo and B.Z Yao [4] conducted experimental tests on two types of precast concrete connection referred as Type A and Type B, see Fig.4. The proposed connections performed satisfactorily with the bending moment strength higher than the monolithic connection.

![Type A](image)

![Type B](image)

Fig. 4: Proposed precast concrete connection by Y.C. Loo [4].

Jay E. Ochs and Mohammad R.E [5] conducted on precast concrete connections consisted of steel plates or angles embedded in the columns and beams which would facilitate field erection. The test results show that the precast concrete connections with specific details performed similarly to the monolithic reinforced concrete connections. The precast concrete connections were strong enough to force the formation of plastic hinge away from the column face.

Geraldine S. Cheok and H.S. Lew [6] conducted experimental study on post-tensioned precast concrete beam-to-column connections under cyclic load. The objective was to develop a moment resistant precast concrete connection that is economical and easily constructed. The results show that the post-tensioned connection is as strong and ductile as a monolithic connection.

The difficulty in achieving rigid connections is to ensure that the top and bottom reinforcement bars of the beams are continuously lapped and then anchored to the columns. To achieve this continuity,
various methods of lapping and splicing of reinforcement bars have been proposed [7], [8], [9], [10], [11].

2 Experimental Program

2.1 Materials

All specimens were cast with concrete in Grade 30. Concrete cubes were prepared and tested on the day of testing to determine the compressive strength of the concrete specimen, see Fig. 5.

Fig. 5: Preparing concrete cubes for

Fig. 6 and Fig. 7 show the dimensions of monolithic and precast concrete specimens respectively. The main steel reinforcement bars for the beams and columns were 12 mm diameter high yield deformed bars, while the stirrups were 6 mm diameter bar in grade 250. All specimens had a 25 mm cover.

2.2 Specimen Descriptions

Table 1 shows the dimensions of the specimens. A total of 4 specimens were prepared. One monolithic specimen acted as the control specimen and the other three precast concrete specimens were denoted as SP-1, SP-2 and SP-3. The beam and column cross sections were 150 mm x 200 mm and 180 mm x 180 mm respectively. For each specimen, the length of column was 1500 mm while the beam had a total length of 1000 mm. The precast concrete beams were designed with different corbel lengths of 550 mm, 650 mm and 750 mm respectively.

Fig. 8 shows the precast concrete connection using steel plates. The connections consisted of two pieces of steel plates which were cast inside the column corbel and beam respectively. The complete beam-to-column specimens are shown in Fig. 9.

Fig. 6: Monolithic specimen
Table 1 Specimen details

<table>
<thead>
<tr>
<th>No. Specimen</th>
<th>Connection Type</th>
<th>Length of Connection (mm)</th>
<th>Length of Column (mm)</th>
<th>Length of Corbel (mm)</th>
<th>Length of Beam (mm)</th>
</tr>
</thead>
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<td>Monolithic</td>
<td>-</td>
<td>1500</td>
<td>-</td>
<td>1000</td>
</tr>
<tr>
<td>2</td>
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<td>150</td>
<td>1500</td>
<td>100</td>
<td>550</td>
</tr>
<tr>
<td>3</td>
<td>SP-2</td>
<td>150</td>
<td>1500</td>
<td>200</td>
<td>650</td>
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<tr>
<td>4</td>
<td>SP-11</td>
<td>150</td>
<td>1500</td>
<td>300</td>
<td>550</td>
</tr>
</tbody>
</table>

Fig. 7: Precast concrete specimens SP-1, SP-2, SP-3

Fig. 8: Connection details
2.3 Experimental setup

Testing on connection for specimens was conducted at day-28 or after the concrete strength had reached 30 N/mm². To enable clear observations on the cracks during testing, the specimens were coated with white paint.

Fig. 10(a) shows the experimental setup of beam-to-column connection. The locations of Low Voltage Displacement Transducer (LVDT) to measure the beam and column deflections are shown in Fig. 10(b). Using hydraulic jack, increasing point load was applied on the precast beam at a distance of 900mm from column face. The increasing load was applied until failure of the connection.

Beam displacements were monitored using LVDTs at locations 3 and 4, whereas column displacements were monitored at locations 1 and 3. Beam rotation, $\phi_{beam}$ and column rotation, $\phi_{column}$ are then calculated based on the beam and column deflections. Then, the connection rotation, $\phi$ is the relative rotation between the beam and column rotations, in which $\phi = \phi_{beam} - \phi_{column}$. Two values of connection rotation namely case 1 and case 2 were evaluated. Case 1 rotation is calculated as Case 1:($\phi_3 - \phi_2$) and Case 2 rotation is calculated as Case 2:($\phi_4 - \phi_2$).

3 Results and Discussion

3.1 Monolithic Specimen

Fig. 11(a) shows the load deflection response of the monolithic reinforced concrete connections. The load deflection response was non-linear even at the initial stage of loading. The maximum applied load was 22.70 kN.

Figure 11(b) shows the corresponding moment-rotation response of the monolithic connection. The
moment resistance reached 22.47 kNm and the corresponding connection rotation was 11.21 milliradians. The corresponding crack pattern of monolithic specimen at failure is shown in Fig. 11(c).

3.2 Precast concrete specimen SP-1

Specimen SP-1 had the shortest length of corbel of 100mm. The concrete strength of connection at the testing of the connection was 36N/mm².

Fig. 12(a) shows the load-displacement of precast specimen SP-1. The maximum load that could be resisted by specimen was 15 kN with the corresponding displacement of 15.2mm.

When applied load reached 17 kN, first cracks started to occur at column and beam-to-column connection. These cracks were minimal, about 20mm length. However, cracks in the connection became critical when the applied load reached 20kN. At this stage, the cracks had extended up to 80% of the beam depth.

First cracks of 35mm were observed to have occurred at middle part of beam-to-column connection when applied load was 12 kN. Increasing the applied load to 14 kN resulted in the cracks propagating to the end of corbel up to 75% of beam depth, as shown in Figure 4.7 (b). The cracks continued to extend and eventually, the connection failed at 14.85 kN of applied load.
3.3 Precast concrete specimen SP-2

Specimen SP-2 had a corbel length of 200mm from column face. The concrete strength for both beam and column were 36 N/mm$^2$ at 28 days, whereas the connection had concrete strength of 33 N/mm$^2$. The concrete strength complied with the desired strength of 30 N/mm$^2$ at 28 days.

The load-displacement graph is shown in Fig. 13(a). The maximum load resisted was 19.2 kN and the maximum displacement was 20.3 mm at point 4.

3.4 Precast concrete specimen SP-3

Specimen SP-3 had the longest length of corbel, which was 300mm from column face. The strength of concrete at 28 days was 33 N/mm$^2$ for precast beam and column, whereas 35 N/mm$^2$ for the connection part.

The maximum load carried by this specimen was 19.7 kN and displacement reached 27.9 mm. The load-displacement graph is shown in Fig. 14(a).
resistance of 19.5 kNm and the corresponding rotation was 21.91 milliradians. When the maximum moment resistance had been exceeded, the connection rotations increased abruptly, similar to other specimens.

Furthermore, it is found that the distance of corbel from column face affected the load carrying capacities and the corresponding rotations of specimens with same dimensions of connection. When the distance of corbel from column face increases, load resistance and rotation will subsequently increase.

3.5 Comparison of Load-deflection Response

The maximum load carried by monolithic specimen was 22.7 kN. Hence, it is clear that all precast specimens had lower load carrying capacity than the monolithic. The difference of maximum load between the monolithic and specimen SP-3 with maximum load resistance of 19.7 kN was 3 kN or 13.22%. Whilst, specimen SP-2 had a difference of 3.5 kN or 15.42%. Meanwhile, specimen SP-1 showed a difference of 7.7 kN or 33.92%, with the maximum load of 15 kN.

Specimen SP-3 had achieved the highest deflection value of 27.9mm, followed by specimens SP-2 and SP-3 with deflection values of 20.3 mm and 15.20 mm, respectively.

3.6 Comparison of Moment-rotation Response

Figure 16 presents the moment-connection rotation of case 2. It can be seen that the precast specimens SP-1, SP-2 and SP-3 showed lower moment resistance as compared to the monolithic. In terms of stiffness of the connection, precast concrere specimens showed almost similar stiffness to the monolithic as can be seen from the slopes of the curves. As compared to the monolithic, the precast concrete specimens experienced early loss of stiffness which translated into lower moment resistance. This loss of stiffness was triggered by the cracks at the beam-to-corbel interface.
From the above results, it is seen that the precast specimen with longer corbel length is more capable in resisting moment and subsequently producing larger connection rotation.

However, specimen SP-1 performed greater ductility if compared with other precast ones. Ductility of specimen SP-3 is found to be the poorest among the three precast specimens.

4 Conclusion
Based on the results of this experimental study, the following conclusions can be drawn:

1. Specimen SP-3 performed well among other precast specimens when load-displacement relationship and moment ratio-connection rotation relationship were examined. It attained the highest load and moment resistance. Its characteristic resembled the monolithic specimen.
2. Specimen SP-1 with shortest corbel showed good ductility if compared with other precast specimens. The connection shows better ductility when the corbel length is short.
3. Precast specimen which has the maximum length of corbel accommodates more applied moment with greater rotation.
4. The length of corbel influences the strength and ductility of connection in which the longer the corbel the stronger is the connection.

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References: