Cyclic Behaviour of Beam-Column Joints with Corbels Under In-Plane Lateral Loads

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Abstract. Corbels appearance in precast beam-column joints has a significant impact on the behaviour of the transition zone at the end of the beam which could help in delaying the yielding of the top reinforcement bars and increase the stiffness of the joint. The presence of corbels also released the development of unnecessary strain at the top of the internal reinforcement bars. Hence, the main objective of this paper is to access the emulative approach for beam-column joints with corbels in terms of structural behaviour for any seismic action through experimental work. Comparison of the experimental hysteresis loops (load versus displacement) and seismic performance for the three types of joints were made. Three full-scale sub-assemblages of corner, exterior and interior precast beam-column joints with corbel were designed using BS8110 Code of Practice. These three specimens were constructed and tested in a heavy structural laboratory under in-plane lateral cyclic loading. The corner, exterior and interior beam-column joints were tested starting from ±0.01% until 1.35% drift, ±1.00% drift and ±1.15% drift, respectively. This study found that the existence of corbels in precast joints can delay the yielding of the top reinforcement bars and increase the stiffness of the joint. However, the experimental result has proved that the corbel for corner beam-column joint was the weakest point of the joint based on the crack damaged at the corbel. On the other hand, the experimental work found that precast beam-column corner joint specimen exhibited 21.5% more ductile behaviour as compared to other two specimens. However, the ductility values for all specimens were recorded at less than 3, indicating that precast beam-column joint specimens were not able to take moderate to strong earthquake excitation.

1. Introduction
In Malaysia, beam-column joints with corbels are commonly used in low-rise precast buildings due to cost saving, faster construction, easy handling and erection as shown in Figure 1 [1]. Interior beam-column joints with different depth of beams which were designed according to non-seismic code of practice suffered poor/unsatisfactory shear strength, stiffness, energy dissipation and shear deformation [2, 13]. There are several factors that have influenced the seismic performance of both interior and exterior beam-column joints with corbels. [3] found out that the interior beam-column joints with additional bars (diagonal and straight) showed fewer cracks in column as compared with beam-column joint without additional bars. The performance of a wet joint in a moment resisting precast frame is still unproven and for this reason, [4] and [5] carried out an experimental work to compare monolithic and
precast concrete beam-column joints when they were subjected to incremental gravity loadings. The study has found out that the corbels in precast joints appeared to delay the yielding of the top reinforcement bars and increase the stiffness of the joint. The presence of corbels also slackened the development of excessive strain at the top of the internal reinforcement bars. On the other hand, a study discovered that the existence of corbels in precast buildings has a significant impact on the behaviour of the transition zone at the end of the beam [6]. Therefore, an emulative approach is more compatible than a monolithic approach in terms of structural behaviour for any seismic action. Hence, the main objective of this paper is to compare the experimental hysteresis loops (load versus displacement) and seismic performance for the three types of joints of the precast reinforced concrete building. Two-storey precast school building was selected as the prototype building in this study. Based on the experimental hysteresis loop results, the residual displacement and the seismic performance in terms of effective stiffness, displacement ductility and equivalent viscous damping of precast beam-column joints were obtained.

Figure 1. Typical corbel beam-column joint in Malaysia [1]

2. Design of precast beam-column joints with corbel and the measurement of the seismic performance
When designing structural elements under earthquake loading, the ductility of the structure must be taken into consideration. The load versus deformation of flexural members at yield and ultimate moment is mainly dependent on moment-curvature characteristic because strains are the most important parameters associated with flexural deformation of a member. This study uses the concept of Direct Displacement-Based Design (DDBD) which was developed in 1993, which later used an equivalent damping concept to measure the hysteretic energy absorbed during inelastic response. The DDBD was developed as a simple method of designing ductile structures to achieve target displacement limits that could be strain-based or code drift-limit based [7]. In the DDBD approach, both concept and procedure of moment-rotation analysis for ductile structures and related them to the global member behaviour were proposed [8]. This concept is also known as the “Monolithic Beam Analogy (MBA)”. The procedure was designed to be validated with any type of beam-column joint which is characterised by “unbonding” concepts for partially bonded and unbonded tendons, unbonded length in mild steel and hybrid connection. In this study, the emulative cast-in-place joint is assumed to have full continuity which is provided by crossing the longitudinal reinforcement bars across the beam-column joint area. A simplified approach can be derived by assuming an equivalent stress block to represent the distribution of stress in concrete according to BS8110 as shown in Figure 2.

The specimen was designed in accordance to BS8110 which has inadequate detailing to take any earthquake loading as compared to Eurocode 8. In this study, the $F_{\text{dowel}}$ is estimated as $p_l A_{sd}$ where $p_l$ is the shear stress of the 25mm diameter dowel bar (taken as 520.9 N/mm$^2$) and $A_{sd}$ is the area of the dowel bar; $F_d$ is the tension force in the reinforcement bar and $F_{cc}$ is the compression in concrete. The compressive strength of concrete is taken as $0.67f_{cu}$ where $f_{cu}$ is the compressive strength of concrete.

Figure 3 shows the typical precast school building which is normally constructed in a low seismic zone, such as Malaysia, Singapore and Thailand. These types of precast buildings are also known as Industrialised Building System (IBS) where the duration to complete the construction precast school building only takes between six months to one year. Figure 4 shows the plan view of the prototype
building. To evaluate the overall seismic performance of the prototype precast school buildings under seismic load, three types of beam-column joints with corbels were selected. Apparently, these beam-column joints namely the corner joint marked as BC1-2C, interior beam-column joint marked as BC2-3I and exterior beam-column joint marked as BC3-2E. These three types of precast beam-column joints with corbels were designed using non-seismic code of practice (BS8110). Three sub-assemblages of full-scale beam-column joints with corbels were designed and constructed.

The seismic performance of these specimens is measured by analysing the hysteresis loops to determine in-plane lateral capacity, effective stiffness, displacement ductility and equivalent viscous damping. The ability of the beam-column joints to resist deformation in response to the applied force is considered as the effective stiffness (K_e). On the other hand, ductility is measured to determine the capacity of a material to deform permanently when subjected under a load. Therefore, the displacement ductility factor (µ_δ) is taken as the ratio of the peak nonlinear displacement Δ_u (taken as the ultimate displacement) to the yield displacement Δ_y. Another variable is the equivalent viscous damping, which is defined as the amount of energy dissipated occurs due to internal friction within cyclically stressed material and slide at internal planes during deformation is also determine as the equivalent viscous damping. The percentage of equivalent viscous damping (ξ_eq) which is applied on a beam-column joint can be estimated by using equation 1, where E_D is the area enclosed by the hysteresis loops and E_SO is the area under the equivalent linear hysteresis curve (or hysteresis loops) [9].

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ξ_{eq} = \frac{1}{4\pi} \left( \frac{E_D}{E_{SO}} \right)
\]
3. Construction and testing of specimens

For this study, column-foundation and beam’s free end were designed as pinned jointed (to achieve points of contra-flexure during testing) at which no bending occurs and it is the point at which the bending moment curve intersects with the zero line. The dimensions of columns are 400 mm x 400 mm x 3500 mm. The beam dimensions vary between 400 mm x 750 mm x 3500 mm, and 500 mm x 750 mm x 3500 mm. Half-cast beams were seated on corbels and connected via dowel bars diameter 25 mm. Cast-in-place concrete with a compressive strength of 40 N/mm² at beam-column joint to provide semi-rigid connection. The cast-in-situ concrete at the beam-column joint was expected to behave similarly to the monolithic behaviour with the semi-rigid joint, where bottom part of the beam-column joint is a precast element and the top part behaves like a monolithic joint. The experimental works were carried out in the Heavy Structural Laboratory, Faculty of Civil Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia. Figure 5 shows the loading regime imposed on the sub-assemblages of all specimens using the control displacement method. The displacements were calculated from the specified drift percentage. Each specimen was tested starting from initial drift of ±0.01% and continuing with ±0.05% drift, ±0.1% drift, ±0.2% drift, ±0.5% drift, ±0.75% drift, ±1.00% drift, ±1.25% drift, ±1.15% drift and ±1.35% drift. The test was repeated for two cycles for each drift. Figure 6 show schematic arrangement of LVDTs, to measure displacement, which were placed beside the beam and column together with the actual experimental set-up of specimen BC1-2C which are ready for testing. Same setup was arranged for specimen BC3-3I and BC3-2E. The pin-ended actuator was connected to the top of the column by using two steel plates and four high strength threaded rods were inserted into the holes at the steel plates. Reversible lateral cyclic loading was used in this experimental work and applied by a 500kN double actuator. It was based on displacement control where the lateral displacement was fixed and calculated as the target percentage of drift. Drift (θ) is defined in percentage as the ratio of lateral displacement (Δ) over the height of the specimen (h) multiplied by 100 (θ = Δ/h x 100) [14]. Therefore, there are variations in the imposed loading on the sub-assemblages of beam-column joints. The specimens were tested until there was a strength degradation of the specimen. All experimental data were recorded using the data logger which was connected to the computer. (See also [10]).

Figure 5. Loading regime for the testing procedure for all specimens.
4. Experimental results

4.1 Visual observations of damages

Rigorous cracks were found in the cast-in-place area and at the edge of the corbel when subjected to ±1.35% drift. On the face of the in-plane corbel, transverse cracks of 425 mm length with gap openings of 8 mm were detected in specimen BC1-2C as shown in Figure 7(a). A wide diagonal shear crack of 295 mm in length with a gap opening of 8 mm was observed starting from the top edge of the in-plane corbel up to the middle surface of the in-plane corbel as shown in Figure 7(b). At ±1.35% drift, more cracks and damage were observed on the upper part of the beam-column joint and an opening gap between precast beam-column interfaces was measured as 25 mm. Figure 7(c) shows wider diagonal cracks of openings were observed at the upper column of the joint with measurements of 3 to 5 mm width on both sides of the column for specimen BC2-3I at ±1.0% drift. Figure 7(d) shows cracks were observed at the cast-in-place area (monolithic) which was detected as the weakest point of the interior beam-column joint for specimen BC3-2E at ±1.0% drift. A few horizontal cracks were also observed on the lower part of the column located at the bottom of the in-plane corbel. This damage occurred due to poor detailing at the beam-column joint and insufficient longitudinal and transverse reinforcement bars in the column. The minimum percentage of reinforcement bars required by BS8110 is 0.13% for $f_y=460\,\text{N/mm}^2$ and this joint is apparently not designed for a lateral load. Therefore, the loading which is considered in the design of sub-assemblages is to carry a gravity load (imposed and dead load).
Shear and diagonal cracks at the top of the column (BC3-2E)

Figure 7. Visual observations of cracks at corbel and the beam-column joints at the maximum drifts for every specimen.

4.2 Hysteresis loops, residual displacement and seismic performance of the beam-column joints

Figure 8 shows the experimental hysteresis loops for LVDT1 (located at the top of column) of all specimens together with the analytical result from push-over analysis. For specimen BC1-2C as shown in Figure 8(a), there is a good agreement between experimental result and the push-over analysis in the pushing direction only, despite there are some discrepancies between experimental and analytical work in the pulling direction due to the unsymmetrical arrangement of the specimen. For specimen BC2-3I and BC3-2E as shown in Figure 8(b) and (c), respectively, there are similarity in the load pattern between pushing and pulling directions due to the symmetrical arrangement of precast beams on both sides of the column for the specimen. From the hysteresis loops, the residual displacements ($\Delta_r$) for all specimens were obtained. Specimen BC2-3I has the highest residual displacement (21.36 mm) in pushing direction as compared to the other two specimens. The value of residual displacement can be related to the worst damages occurred to specimen BC2-3I after experimental work up to 1.15% inter-storey drift. The seismic performance for all three types of precast joint is also discussed from the aspect of stiffness, displacement ductility and equivalent viscous damping factor. Table 1 tabulates the value of lateral strength capacity, the residual displacement the seismic performance from the experimental work in pushing and pulling directions for all specimens at maximum drifts. Specimen BC3-2E shows higher stiffness values in both pushing and pulling directions. The location of the beam-column joint in a building affect the ability of the joint to resist deformation in response to the applied force. Effective stiffness values are important in estimating the maximum base shear before designing structural members subjected to lateral loading. Specimen BC1-2C exhibited higher displacement ductility ($\mu_\Delta$) value as compared to specimen BC2-3I and BC3-2E at pushing and pulling directions. All specimens experienced the largest ultimate lateral displacement in the pushing direction and the highest yield displacement in the pulling direction. In general, the overall ductility of all the specimens was recorded not more than 3. From the experimental work, the ductility values are less than 3 and classified as Ductility Class Low (DCL) in Eurocode 8 and are not suitable to carry seismic loading [11]. In addition, the sub-assemblages of specimens in this study are not designed to carry the seismic loading. To survive under moderate and severe earthquake loading, the ultimate ductility of the structure should range from 4 to 14 based on previous study [12]. The highest value of equivalent viscous damping ($\xi_{eq} = 17.52\%$) occurred in the first cycle of the corner beam-column joint (BC1-2C) at 1.15% inter-storey drift. Usually, the equivalent viscous damping for the first cycle is higher than the second cycle because more energy is required to resist the lateral capacity of the structure within the elastic region. Once the energy has reached the yield force in the first cycle, less energy is required in the second cycle to resist the lateral capacity in the inelastic region. For a low seismic region, it is recommended to use $\xi_{eq}$ ranging from 12% to 17% for designing a precast beam-column joint.
Figure 8. Experimental hysteresis loops for all specimens at LVDT1

Table 1. Lateral Strength, Residual Displacement, Effective Stiffness, Displacement Ductility and Equivalent Viscous Damping for all three specimens

| Specimen      | Max. drift (%) | Direction       | Lateral Strength (kN) | Residual Displacement (mm) | Effective Stiffness (kN/mm) | Displacement Ductility | Equivalent Viscous Damping (%) |
|---------------|----------------|-----------------|-----------------------|---------------------------|-----------------------------|------------------------|--------------------------------|
| BC1-2C (Corner Joint) | 1.35          | Pushing (+ve)   | 36.10                 | 17.4                      | 0.82                        | 2.28                   | 8.05                           |
|                |                | Pulling (-ve)   | -72.93                | -2.18                     | 1.85                        | 2.19                   |                                |
| BC2-3I (Interior Joint) | 1.15         | Pushing (+ve)   | 57.68                 | 21.36                     | 1.45                        | 1.92                   | 17.52                          |
|                |                | Pulling (-ve)   | -61.72                | -5.12                     | 1.80                        | 2.16                   |                                |
| BC3-2E (Exterior Joint) | 1.00         | Pushing (+ve)   | 87.15                 | 10.55                     | 2.93                        | 1.70                   | 10.66                          |
|                |                | Pulling (-ve)   | -77.15                | -4.94                     | 2.90                        | 1.61                   |                                |

Figure 9 shows the first cycle of the storey shear envelope curve for all three specimens, namely BC1-2C, BC2-3I and BC3-2E from the experimental results. At +1.0% inter-story drift, specimen BC2-3I has the highest value of lateral force ($F_{max}=125.54kN$) as compared to specimen BC3-2E ($F_{max}=87.15kN$) and BC1-2C ($F_{max}=36.95kN$). This is due to the high self-weight of the specimen BC2-3I which consists of a one-tier precast column with three corbels and three precast beams. Furthermore, the arrangement of beams made the joint more durable compared to other two specimens which required more force to resist these loads.
Figure 9. Storey Shear Envelope Curve for All Specimens

5. Conclusions and recommendations

When all the three specimens were tested under in-plane reversible lateral cyclic loading, the seismic performance and crack patterns were observed, marked and recorded. The seismic performance and response of beam-column joint can be determined based on the shape of the hysteresis loops, cracks propagation, effective stiffness, displacement ductility, equivalent viscous damping and storey shear envelope curves. The corner joint specimen of the prototype precast school building experienced the worst damage at the in-plane corbel. Larger gaps opening and closing between precast beams and column were also observed. Nevertheless, the damage was due to the unsymmetrical condition of the specimen where the in-plane corbel was the weakest point for the whole structure of the precast school building. For the corner joint, it is recommended that the reinforcement bars in the in-plane corbels be increased so that the joint can resist lateral loading from seismic action. On the other hand, the interior and exterior precast joints specimens revealed severe damage at the upper joint of the column. The damage at the column for interior and exterior joints were also called captive column, where the upper part of the column is the weakest point at non-seismic precast beam-column interior and exterior joints. Major cracks at the cast-in-place (monolithic) area near the beam-column joint were also observed for all specimens. Overall investigation showed that precast beam-column specimens with monolithic cast-in-place at the joint will experience severe damage in moderate to strong earthquake excitation if not designed in accordance with the current seismic code of practice. Besides, interior precast beam-column joint has the highest value of lateral force ($F_{max}=125.54\,\text{kN}$) and highest residual displacement (21.36mm) as compared to other specimens. This can be related with the worst damages occurred to the specimen. The existence of corbels in precast joints was believed to delay the yielding of the top reinforcement bars and increase the stiffness of the joint. The ductility values for all specimens were recorded at less than 3, indicating that the specimens were not able to take moderate to strong earthquake excitation. It is recommended that buildings to be designed in accordance with a current seismic code of practice such as Eurocode 8 by considering earthquake loading and Malaysian hazard maps.

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References

[1] Tiong, P.L.Y, Adnan, A. and Hamid, N.H., (2013), “Behaviour factor and displacement estimation of low-ductility precast wall system under seismic actions”, Earthquakes and Structures, 5(6), 625-655.

[2] Xing, G.H., Wu, T., Niu, D.T. and Liu, X., (2013), “Seismic behaviour of reinforced concrete interior beam-column joints with beams of different depths, Earthquakes and Structures, 4(4), 429-449.

[3] Xilin, L., Tonny, H.U., Sen, L., and Fangshu, L. (2012), “Seismic behaviour of interior RC beam-column joints with additional bars under cyclic loading, Earthquakes and Structures, 3(1), 37-57.

[4] Ahmad, B.A.R., Leong, D.C.P., Saim, A.A. and Hanim, O. (2006), “Hybrid Beam-to-Column Connections for Precast Concrete Frames, Paper presented at the 6th Asia-Pacific Structural Engineering and Construction Conference (APSEC 2006), September 5-6, Kuala Lumpur, Malaysia.

[5] Ahmad, B.A.R., Rahim, G. and Zuhairi, A.H. (2008). “Comparative Study of Monolithic and Precast Concrete Beam-to-Column Connections, Malaysian Construction Research Journal, 20(2), 46-60.

[6] Ferreira, M.A., Elliot, K.S. & Hasan, S. (2010). State-of-Art Research Report: Precast Concrete Framed Structures with Semi-Rigid Connections. International Research Collaboration, University of Nottingham.

[7] Priestley, M.J.N., Grant, D.N. & Blandon, C.A. (2005). Direct Displacement-Based Seismic Design. Paper presented at 2005 New Zealand Society for Earthquake Engineering (NZSEE) Conference.

[8] Pampanin, S. (2003). Alternative Design Philosophies and Seismic Response of Precast Concrete Building. Structural Concrete, 4(4), 203-211.

[9] Chopra, A.K. (2007). Dynamics of Structures: Theory and Applications to Earthquake Engineering. Third Edition. Pearson Prentice Hall.

[10] Karayannis, C.G., Chalioris, C.E. and Sirkelis, G.M. (2008), “Local Retrofit of Exterior RC Beam-Column Joints using Thin RC jackets – An Experimental Study”, J. Earthquake Eng. & Structural Dyn., Vol. 37, pp. 727-746).

[11] BS EN (2004). Eurocode 8: Design of Structures for Earthquake Resistance – Part 1: General Rules, Seismic Actions and Rules for Buildings. European Committee for Standardization.

[12] Cheok, G.S. and Lew, H.S. (1993), “Model Precast Beam-to-Column Connections Subject to Cyclic Loading, PCI Journal, 38(4), 80-92.

[13] Sung, C.C., (2014), “Effects of joint aspect ratio on required transverse reinforcement of exterior joints subjected to cyclic loading, Earthquakes and Structures, 7(5), 705-718.

[14] ACI Committee 374. (2005). Acceptance Criteria for Moment Frames Based on Structural Testing and Commentary ACI 374.1-05, American Concrete Institute.