Experimental investigation on a non-seismic precast RC beam-column exterior joint under quasi-static lateral cyclic loading

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Abstract

Beam-column joints were detected as the weakest link in existing RC moment-resisting frames. The failure of beam-column joints, especially the exterior joint in a precast RC building commenced the collapse of the whole structure. Precast RC beam-column joints which were not designed in accordance with the seismic Code of Practice worsen the damage when subjected to seismic loading. This paper presents experimental work on a full-scale precast RC beam-column exterior joint with corbels when subjected to quasi-static lateral cyclic loading. The specimen was tested under reversible lateral cyclic loading up to a ±1.0% drift. Two numbers of cycles were applied for each drift level. Cracks, gap opening and closing, and spalling of concrete were monitored in successive two-cycle intervals of drift. The experimental observation showed that the cracks start to occur at +0.3% drifts and no damage was observed at the corbels. At ±1.0% drift, the specimen experienced major damage at the column above the joint and also at the monolithic cast-in-place area. The specimen exhibits a captive column damaged because of the weak column-strong beam condition of the specimen. Poor detailing of reinforcement and link spacing led to unconfined concrete inside the column. The wide link spacing measured as 190 mm centre-to-centre was unable to cater for a larger load, especially lateral loading from an earthquake. In this study, it can be concluded that a precast beam-column exterior joint experienced severe damage if not designed in accordance with the seismic Code of Practice. The stiffness degradation, displacement ductility and equivalent viscous damping for the tested specimen are also discussed in this paper.

Keywords: precast beam-column joint, corbels, quasi-static cyclic loading, hysteresis loops, displacement ductility, stiffness, equivalent viscous damping.

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1 Introduction

Beam-column joint is the crucial part in a reinforced concrete structure where vertical and horizontal loads met and transfer the load to the foundation. In reinforced concrete buildings, the failure of beam-column joint was observed and causing the collapse of building after earthquake attack. Beam-column joints played an important role in determining the ductile of moment-resisting frames [1–3]. Therefore, the integrity of structural in RC building should be safe and stable under minor, moderate and severe earthquake excitations. Ductile beam-column joint is closely related to the detailing of transverse and longitudinal bar, poor workmanship issue, the placement of reinforcement in joints and usage of seismic code of practice.

The failures of beam-column joints in reinforced concrete building were observed in some of catastrophic failures during past earthquake events. Good example was the 1999 Kocaeli Earthquake where joint shear failures were observed during the earthquake. Joint shear failures may results in non-ductile performance of reinforced concrete moment-resisting frames, which were designed and constructed before the development of current seismic codes [4]. In New Zealand, large numbers of reinforced concrete framed buildings which were built before the 1970s were reported to moderately and severely damage in 2011 Christchurch Earthquake [5]. Before 1970, most of buildings were designed not to take earthquake loading. It can be concluded that the major reason for the damage in reinforced concrete building under earthquake loading is due to the non-ductile designs. Soft-storey mechanisms, inadequate reinforcement at beam-column connections and insufficient detailing of beam-column joints were the main causes of collapse of reinforced concrete buildings.

Precast structure seems to be more practical nowadays to overcome problems pertaining construction productivity and the quality of construction products, despite the shortage of skilled workers [6]. Precast concrete framed structures were more popular as compared to prefabricated steel framed structures due to price matters even though steel structures are relatively lighter in mass and lacking in stiffness [7]. Precast concrete products are widely adopted in Malaysia started in the year between the 1960s and 1980s, due to the rising demand from public housing projects including of low and medium cost apartments [8]. In Malaysia, British Standard (BS8110) was used for reinforced concrete design including precast and prestressed members which do not specify any requirement for seismic design or detailing of reinforced concrete structures [9]. Until 2004, there has been no record of earthquake damage in Malaysia and Singapore regions although ground motions due to long distance earthquakes centered in Sumatra have occurred [10]. The devastated earthquake event which destroyed Aceh, Indonesia in 2004 has triggered tsunamis leading to casualties in the area of Penang and Kedah in Malaysia. Therefore, it is of great concern that due to the lack of reinforcement detailing, the ability of the reinforced concrete structures in terms of strength, ductility, and energy dissipation capacity not be adequate to sustain earthquake loading. Therefore, the performance of beam-column joints in precast reinforced concrete structures needs to be tested because the connections are strongly needed not only to transfer loads but also to provide continuity and overall monolithic behavior in the entire reinforced concrete structure.

However, to date, no studies have been conducted on the effect of lateral cyclic loading on non-seismic precast beam-column joint with corbels which is designed in accordance to BS8110. Therefore, this paper aims to present the seismic performance of precast beam-column exterior joint with corbels under quasi-static reversible lateral cyclic loading. The crack patterns for the testing was monitored and recorded. The results include hysteresis loops, stiffness, ductility and equivalent viscous damping were analyzed and discussed.

2 Experimental set up and testing of specimen

2.1 Setting up and loading regimen

A full-scale of precast beam-column exterior joint with corbels were designed, constructed and tested in heavy structural laboratory. The sub-assemblage of specimen represents an exterior beam-column joint of a ground floor of double-storey precast school building. The one-way sub-assembly of beam-column joint consists of one column with one tier corbels and two beams which were designed in accordance to British Standard BS 8110. The compressive strength of the beams and columns is 50 N/mm^2. Figure 1 shows front and side elevation of the first subassembly of the exterior beam-column joint. The cross-section of column is 400x400mm, with Beam One and Beam Two are 500x750mm.

Figure 2 shows the experimental setup of the specimen sitting on strong floor with the foundation beam clamped to strong floor. The precast concrete column was partially supported by pinned connection to the beam foundation and the top of the column was free to move and rotate on x-y plane. Pinned supports conditions were designed at the end of all beams. The column is jointed to foundation using the extruder bar coming out from the foundation and attached together using grouting. The beam's free ends were designed as points of contra flexure for the beams and the column were achieved within the test setup. The foundation beam was clamped to strong floor using eight (8) numbers of highly treaded rods with diameter of 30 mm. Both beams were half-casted prior to the assemblage with column in the laboratory. The corbels were acting as support for all beams at right angle to each other. All beams were connected to the corbels using dowel bars with 25 mm diameter, followed by the installation of six high yield reinforcement bars with diameter of 25 mm through Beam One and Two, across the column. Wet cast-in-place concrete with compressive strength 40 N/mm^2 was poured to complete the joint between precast beams and precast column. Finally, the specimen was equipped with nine (9) numbers of LVDT at specified locations as shown in the schematic CAD drawing in Figure 3. Figure 4 shows the sub-assemblage complete with LVDT and the specimen is ready for testing.

The sub-assemblage of beam-column joint was tested under quasi-static reversible lateral cyclic loading. A double actuator with 500kN capacity load cell

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was connected to the reaction frame. In this experimental work, the target displacement is controlled in term of percentage drift and it is known as displacement control method. Drift is defined as the ratio of lateral displacement over the height of the column multiply by one hundred percent. In this study, seven sets of history drifts were applied to top of column at ±0.01%, ±0.05%, ±0.1%, ±0.2%, ±0.5%, ±0.75%, and ±1.0% drift. The loading regimen for this testing is shown in Figure 5. Two numbers of cycles were applied for each drift level. Cracks, gap opening and closing, and spalling of concrete were monitored in successive two-cycle intervals of drift. The specimen was loaded until ±1.0%. The damage on the specimen was visually observed and recorded.

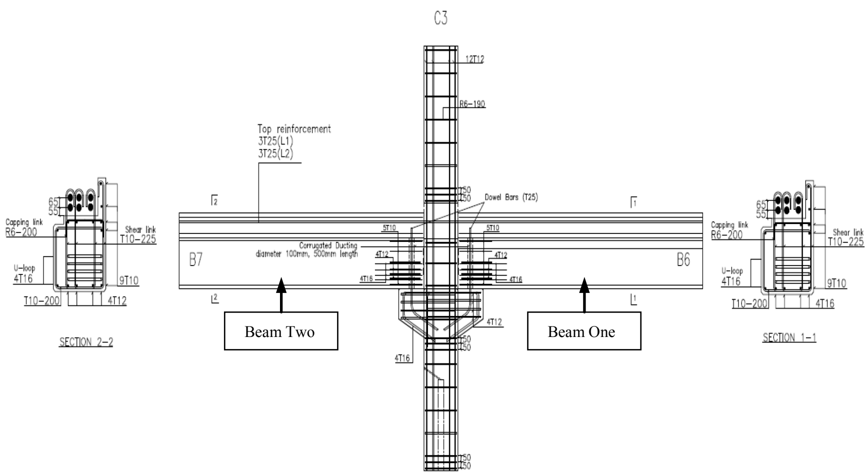

Figure 1: Detail dimension and detailing of the specimen.

Figure 2: Installation of precast elements on the strong floor.

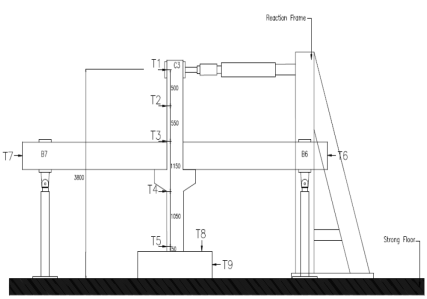

Figure 3: Schematic CAD drawing of LVDT location on specimen.

Figure 4: The specimen is ready for testing.

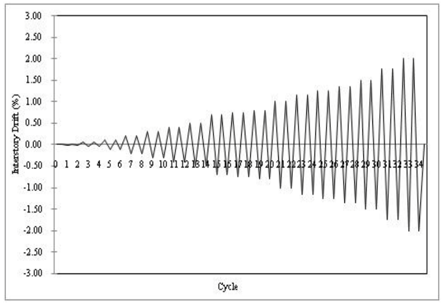

Figure 5: Loading regimen for testing the specimen.

2.2 Visual observation during experimental work

The response of specimen was remained elastic starting from ±0.01% until ±0.5% with successive cycles. At ±0.5% drift, hairline cracks below the corbel supporting Beam One and Beam Two were observed during experimental work. Within inelastic region, larger cracks were occurred at the cast-in-place area of the joint. Gap opening between surface of corbel and beam during loading and unloading of actuator leads to shear cracks which can be obviously seen at the upper part of the column. Figure 6 shows the front view of the sub-assemblage beam-column exterior joint where most diagonal crack occurred at the cast-in-place area. At ±1.0% drift (final drift), more severe cracks and damages occurred above the joint. However, cracks were also observed at the cast-in-place area (monolithic) which is detected as weak area of the exterior beam-column joint. The situation is known as ‘captive column’, due to strong beam-weak column under soft storey mechanism. After thorough inspection on the specimen, severe

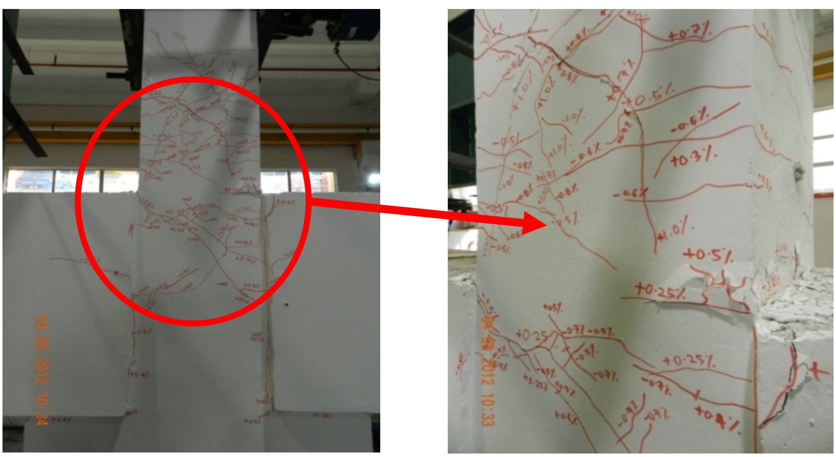

Figure 6: Shear and diagonal cracks were observed above the joint.

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diagonal cracks were observed especially at the upper part of column near the joint. Figure 7 demonstrates that the diagonal cracks between 3mm to 5mm width when measured using Vernier Caliper. Major shear cracks were also observed at the lower part of column which located at bottom of corbel as shown in Figure 8. The damage was due to poor detailing at the beam-column joint and insufficient reinforcement bar in the column. The wide spacing of mild steel link inside the column measured as 190 mm centre-to-centre was unable to cater larger load, especially lateral loading from earthquake. Although the minimum percentage of reinforcement required by BS8110 (which is 0.4% [11]) was met, however, this joint is not designed for lateral loading.

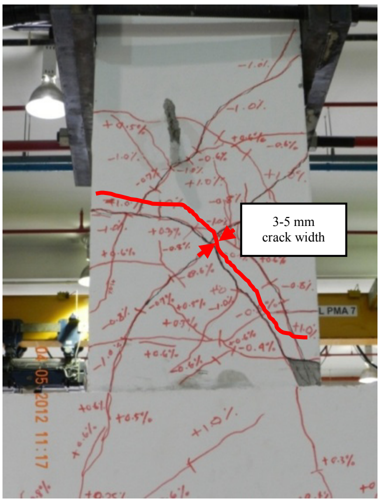

Figure 7: Diagonal crack width measured 3–5mm.

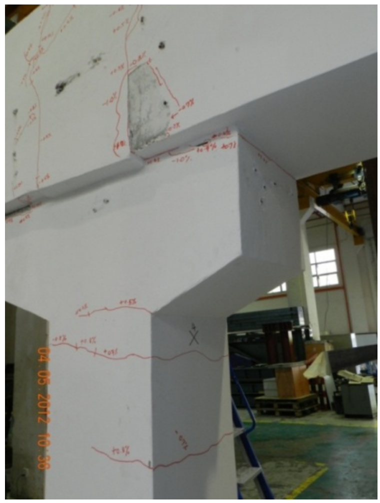

Figure 8 Cracks at bottom of column and near corbels.

3 Experimental result and discussion

3.1 Hysteresis loops

Figure 9 shows the hysteresis loops of the specimen at LVDT T1 which is located at the loading actuator. At ±1.0% drift, load value for the second cycle at positive (pushing) direction (77.51kN) is significantly lower than the first cycle (87.15kN), indicating that the specimen has experienced strength degradation at the second cycle of loading.

3.2 Stiffness degradation

Figure 10(a) and (b) shows the stiffness degradation traces of specimen in pushing (positive) and pulling (negative) directions, respectively, for both cycles.

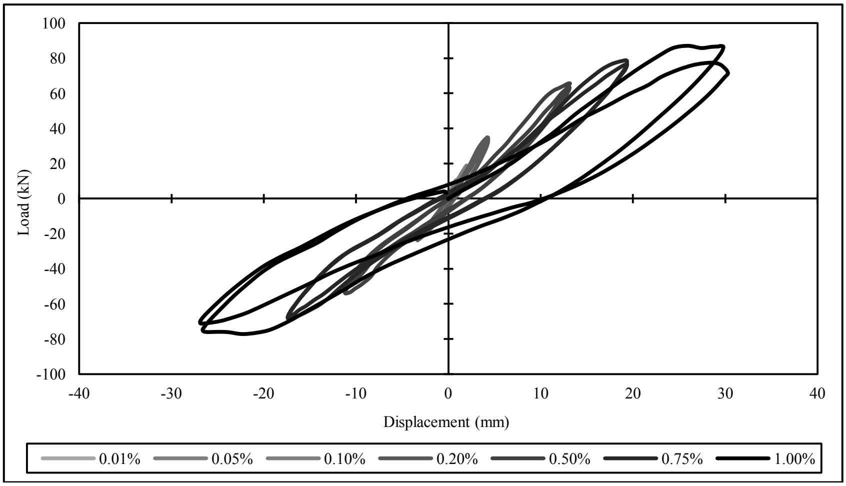

Figure 9: Load versus displacement for tested specimen.

At both directions, the specimen exhibits non-linear behavior starts from ±0.75% interstory drift. For both cycles at ±1.0% drift, pushing direction exhibits larger stiffness as compared to the pulling direction. It can be said that, at ±1.0% drift, the specimen is stiffer during pushing direction rather than pulling direction because the loading actuator acquired more force to push the specimen. The first cycle for both directions exhibits higher stiffness values as compared to second cycle. The specimen also demonstrates higher stiffness degradation at pulling direction as compared to pushing direction.

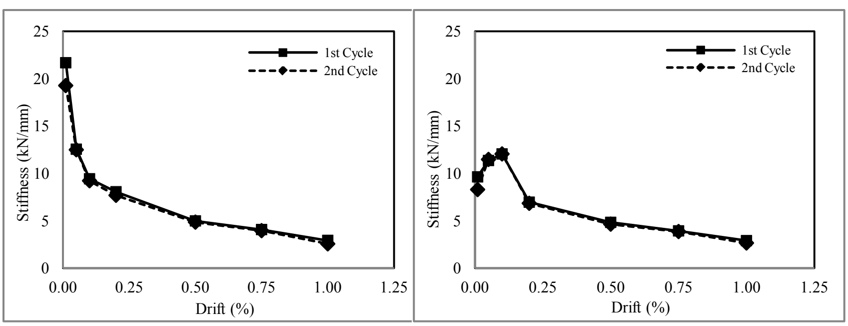

Figure 10: Stiffness degradation traces of tested specimen. (a) Pushing (positive) direction; (b) Pulling (negative) direction.

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3.3 Displacement ductility

The definition for yield displacement of experimental work is adopted from Park [12] as shown in Figure 11. It is the most realistic definition for the yield displacement for reinforced concrete structures. Based on reduced stiffness equivalent elasto-plastic yield, the yield displacement was found as 75% of the ultimate lateral load, H_u. The definition included the reduction in stiffness due to cracking near the end of the elastic range. Figure 12(a) and (b) shows the ductility versus drift curve for tested specimen during pushing and pulling directions. At pushing (positive) direction, the first cycle of loading has lower ductility values (1.70) as compared with the second cycle (1.90). Similar pattern at pulling (negative) direction was observed. It shows that the second cycle is more ductile as compared to the first cycle. All of the ductility values are less than 2.0 indicates that the design of tested specimen does not adequate for earthquake loading.

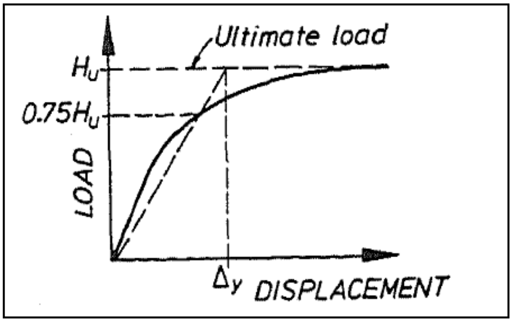

Figure 11: The realistic definition of yield displacement.

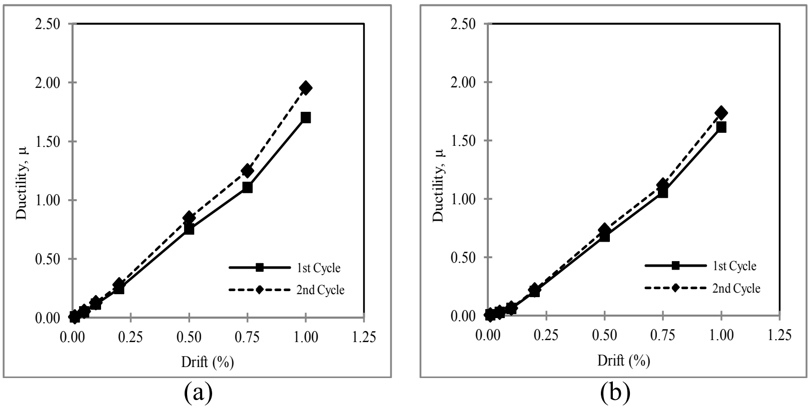

Figure 12: Ductility versus drift of tested specimen. (a) Pushing (positive) direction; (b) Pulling (negative) direction.

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3.4 Equivalent viscous damping

Figure 13 shows the equivalent viscous damping (ζ_{eq}) versus drift for both cycles of tested specimen. Overall, ζ_{eq} for first cycle is higher than second cycle because more energy is required to resist the strength capacity of beam-column joint as compared to second cycle. Furthermore, the energy absorption occurred in the first cycle leads to the smaller enclosed area of the hysteresis loop in the second cycle. However, at ±1.0% drift, second cycle exhibits higher value of equivalent viscous damping as compared to the first cycle. It is meaning to say that, at ±1.0% drift, the specimen absorbed more energy during the second cycle and suffered a lot of damage as compared to the first cycle. The first cycle normally implies for the first strike of the earthquake and second cycle implies for aftershock of the earthquake.

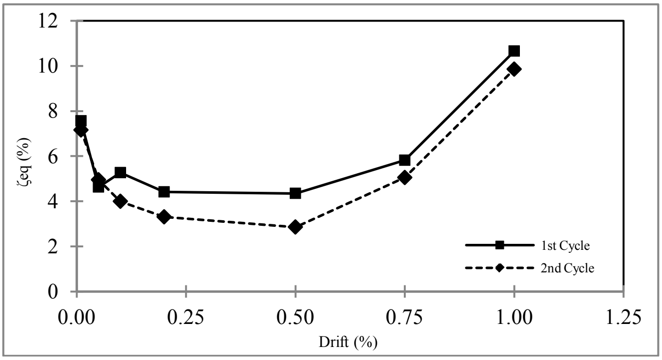

Figure 13: Equivalent viscous damping versus drift of specimen.

4 Conclusion and recommendation

Based on the visual observation, experimental results and discussion as mentioned in this paper, the conclusion and recommendation can be listed as follows:

1. The specimen of precast beam-column exterior joint with corbels was designed in accordance to BS8110, which have considered gravity loading (imposed and dead load) only. Therefore, the specimen studied in this paper experienced severe damage when subjected to quasi-static lateral cyclic loading as shown in experimental work.
2. On the other hand, the exterior precast joint revealed severe damage at the upper joint of the column, due to soft-story mechanism or so called strong beam-weak column design. Major crack at the cast-in-place (monolithic) area near the beam-column joint were also observed. The damaged of specimen tested in this paper would be significant and meaningful to visualize the real situation of earthquake excitation.
3. Since the ductility for the specimen is less than 3, this type of joint is not suitable to be constructed in medium and high seismic region. It is

recommended to use Eurocode 8 for the designed and construction of building in medium and high seismic region.
4. Future experimental work should focus more on seismic retrofitting of existing precast beam-column joints which are not design in accordance to seismic Code of Practice.

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