

# Seismic Performance of SFRC Beam-Column Joint with Corbel under Reversible Lateral Cyclic Loading

A.G. Kay Dora and N.H. Abdul Hamid

**Abstract**—Seismic performance of full-scale precast beam-column end joint with corbel mixed up together with Steel Fibre Reinforced Concrete (SFRC) is examined. The subassembly of beam-column joint was tested under reversible lateral cyclic loading up to  $\pm 1.5\%$  drift. The visual observation and experimental results showed that the cracks start to occur at  $+0.75\%$  drifts (pushing direction) at the cast-in-situ area in beam-column joint. Experimental result of the hysteresis loops (load versus displacement) showed a good agreement with the theoretical result obtained from moment-rotation analysis method. The elastic stiffness, secant stiffness, ductility and equivalent viscous damping for beam-column joint are also determined in this paper.

**Index Terms**—Beam-column joints, ductility, hysteresis loops, stiffness.

## I. INTRODUCTION

Most of beam-column joints of RC building in Malaysia are designed using British Standard (BS 8110) where there is no provision for earthquake loading. Therefore, these buildings are vulnerable to damage due to minor, moderate and severe earthquakes if earthquake occurs in West or East Malaysia. Based on previous research work done on beam-column joints had identified that beam-column joints played an important role in determining the ductile of moment-resisting frames [9, 5, 2]. The integrity of structural in RC building should be safe and stable under minor, moderate and severe earthquake excitations.

Steel fiber reinforced concrete (SFRC) is defined as a composite material made from portland cement, aggregate, sand and partial volume mixing of discrete discontinuous steel fibers. Steel fibers are added to concrete mixture not only to enhance the strength, but also to improve the toughness, ductility and energy absorption of the concrete. With the presence of steel fibers in the concrete, it will increase the lateral strength capacity, cracking, deflection and ductility of beam-column joints under any types of loading because of its' inherent properties [1].

A few researchers had explored the effectiveness of mechanical properties of steel fiber on the seismic performances of RC beam-column joint systems such as compressive strength, tensile strength, flexural strength, energy absorption, deflection, shear resistance and ductility. By adding steel fibers in flexural members could change the

stress distribution and increase the effective depth of element by reducing tensile cracks. By adding 1.5% steel fiber to concrete, the tensile and compressive strength would increase by maximum of 40% and 15%, respectively when the steel fibers aligned in the direction of the tensile stress [7, 8].

Previous study carried on beam-column joint with hooked end SFRC provided better confinement which led to less structural damages, greater shear capacity, greater stiffness and increase ductility by 15%. Besides that, additional of steel fiber which combined together with conventional reinforcement bars have significant effect on compressive strength of the structural members with increases in strength ranging from 0 to 25% [4]. Furthermore, the fibers do significantly increase the toughness of the concrete in term of post-cracking ductility or energy absorption of the material.

SFRC is also being used in retrofitting of RC structural members. A study was carried out on one-fourth scale outrigger beam-column frames. The first sample with deficient details and the second sample had same details and retrofitted with high-performance containing 1% steel fiber in SFRC sleeve around the existing beam and column region tested under reversed lateral cyclic loading [6]. From the experimental result, the hysteretic response of second sample had 6.2 times energy dissipation than the first sample. This result showed that the SFRC retrofitting increased the strength, ductility and energy absorption of the outrigger frame.

The advance growth of construction industry in Malaysia and the awareness of the earthquake attack to precast and RC buildings, the potential application of SFRC in precast concrete elements to resist dynamic loadings have created a new motivation of this study. Therefore, this paper aims to present the experimental results of the hysteresis loops of precast beam-column corner joints with SFRC added in the corbel area and tested under reversible quasi-static lateral cyclic loading. This type of RC beam-column joint with corbel is commonly constructed in precast building in Malaysia without considering the seismic loading.

## II. TEST SETUP AND METHODS

A full-scale of precast beam-column joint with corbels which is representing a corner joint of a lower floor of double-storey school building constructed in Teluk Panglima Garang, Selangor, Malaysia. The subassembly of beam-column joint consists of one column with one tier corbels and two beams which were designed using BS 8110, constructed the column and beam at open space and assembled them together at the Heavy Structural Laboratory, Universiti Teknologi MARA Malaysia, Selangor, Malaysia.

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Fig. 1 shows the front elevation of end corner for beam-column joint with corbel of a precast building of double-storey school building. The cross-section of column is 400x400 mm, beam one is 500x750 mm and beam two is 400x750 mm. The diagram on left hand side shows the beam-column joint of beam one and column whereas the diagram on right hand side shows the beam-column joints for beam two and column. Fig. 2 shows the subassembly of beam-column joints with corbel which is ready for testing. The two beams, columns and foundation were prepared outside heavy structural laboratory and assemble on strong floor. The compressive strength of the beam, column and foundation beam is 50 N/mm<sup>2</sup>. The foundation beam was clamped to strong floor using six numbers of highly treaded rods with diameter of 25 mm.

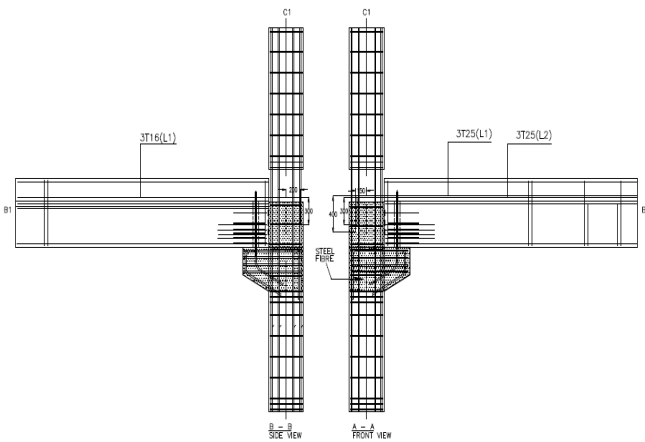


Fig. 1. Front elevation of beam-column joint with corbels



Fig. 2. Full scale beam-column joint subassembly is ready for testing



Fig. 3. SFRC in concrete at beam-column joint with corbels painted with yellow which is ready for instrumentation.

Fig. 3 shows corbels of beam-column joint painted with yellow color was mixed with 1% volume fraction of hooked end steel fibers. This corbel was designed using BS8110 and acting as support for the two beams at right angle to each other. The two beams were half-casted prior to the assemblage with column in the laboratory. Both beams were connected to the corbels using dowel bars with 25mm diameter, followed by the installation of high yield reinforcement bars with diameter of 16 mm and 25 mm across the column as shown in Fig. 3. Wet cast-in-place concrete Grade 40 was carried out to complete the joint between precast beams and precast column. This type of joint is considered as semi-rigid joint because it consists of semi precast structural compound and cast-in-situ concrete.

The subassembly of beam-column joint was tested under reversible lateral cyclic loading applied at top part of the column which representing the inflection point of the column. It is normally occur at mid-height for the prototype column. A double actuator with 500kN capacity load cell was bolted to the reaction frame. Fig. 4 shows the location of double actuator and eleven (11) LVDTs were installed at beam one and column. LVDT is used to measure the lateral displacement in pushing direction (positive drift) and pulling direction (negative drift). Strain gauges were attached to the reinforcement bars to measure the elongation and detect the yield strain of reinforcement bar under lateral cyclic loading. Fig. 5 shows the locations of double actuator attached to reaction frame and two LVDTs located at right hand side of the beam two.

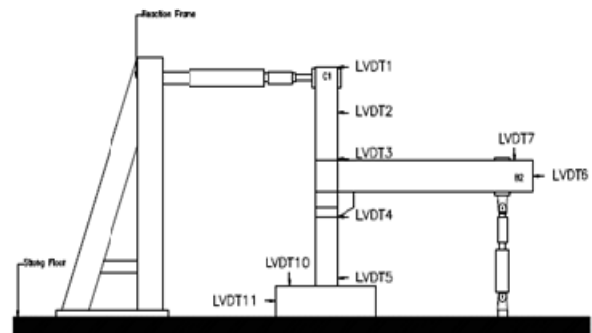


Fig. 4. Location of double actuator and LVDTs at front elevation

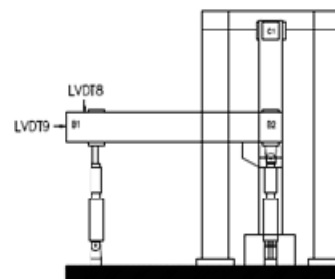


Fig. 5. Location of double actuator and LVDTs at right elevation

Fig. 6 shows the loading regime for the experimental work in the laboratory using control displacement method. In this method, the target displacement is controlled in term of percentage drift. Drift is defined as the ratio of lateral displacement over height of the column multiply by one hundred. In this study, nine sets of history drift were applied

to top of column at  $\pm 0.01\%$ ,  $\pm 0.05\%$ ,  $\pm 0.1\%$ ,  $\pm 0.2\%$ ,  $\pm 0.5\%$ ,  $\pm 0.75\%$ ,  $\pm 1.0\%$ ,  $\pm 1.25\%$ , and  $\pm 1.5\%$  drift. Each drift consists of two cycles of lateral displacements which imposed at the effective height the column.

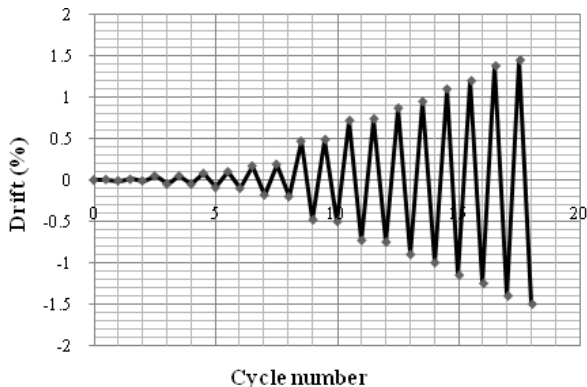


Fig. 6. Loading regime using control displacement.

### III. EXPERIMENTAL RESULT AND DISCUSSIONS

#### A. Material Properties

Fig. 7 compares the compressive strength of plain concrete and concrete with steel fiber ( $V_f=1\%$ ). The compressive strength behaves similarly either for plain concrete or concrete with steel fiber with difference in final compressive strength is only  $0.5 \text{ N/mm}^2$ . The drop of compressive strength of concrete with steel fiber towards pre-peak portion is caused by the low volume fraction and discontinuity between steel fibers element. Therefore, there is insignificant increase in final compressive strength in concrete with steel fiber.

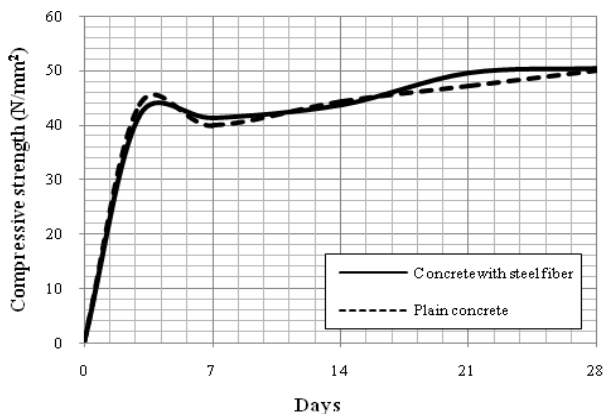


Fig. 7. Comparison of compressive strengths between plain concrete and concrete with steel fiber ( $V_f=1\%$ )

#### B. Visual Observation

The lateral cyclic loading was applied at top of column and the displacements of beams and column were measured using thirteen LVDTs. The crack hairlines were observed and measure at  $+0.75\%$  drift. The first cracks were appeared at first cycle of  $+0.75\%$  drift then extended for the next cycles. There were opening and closing gaps between beam and column interface during pushing and pulling of the column. The cracks was opened under tension and closed under compression. Fig. 8 shows most of the cracks occurred was at  $+1.0\%$ ,  $+1.25\%$  and  $+1.5\%$  drifts at the cast-in-situ concrete. This can be observed at upper part of beam-column joint

where the location of cast-in-situ area is. The yellow area shows concrete with steel fiber and no cracks was appeared at this area till the end of the experimental work. Most of the cracks occurred at top part of beam-column joint where the cast-in-situ concrete was poured to connect between column and joint. It can be concluded that the monolithic beam-column joint contribute to more cracks and no cracks was observed at precast joint at beam-column joint.



Fig. 8. Hairline cracks were observed at cast-in-situ beam-column joint located at upper part of the corbel.

Fig. 9 shows wider cracks were observed at  $1.5\%$  drift at top part of the cast-in-situ beam column joint above the corbels. Based on the visual observation, no cracks were observed in the corbel which prepared as precast concrete and a lot of cracks were occurred at cast-in-situ concrete above the corbel. In this case, plastic hinge zone mechanism occurred in cast-in-situ concrete where a lot of cracks were observed at the vicinity of connection of top bars from beam to the column.



Fig. 9. Wider cracks were observed at  $+1.5\%$  drift.

#### C. Comparison between Experimental and Prediction Results

Fig. 10 shows comparison of hysteresis loops of beam-column obtained from experimental results and predicted result using moment-rotation analysis under lateral cyclic loading. In this experiment, the subassembly was subjected to two cycles for each drift up to  $1.5\%$ . The prediction of lateral load versus displacement using the

concept of moment-rotation analysis proposed by [10] is plotted and compared with the experimental results. There is good agreement between the predicted result and experimental result.

The reinforcement bar in the beam-column joint was yielded at +0.75% drift with lateral displacement of 26.39 mm in positive direction (loading). Thus, beam-column joint is unsymmetrical and the joint remain elastic until it reached 1.5% drift in the negative direction (unloading) with 41.94 mm and lateral displacement. However for the loading part, the beam-column joint exhibits the non-linear behavior.

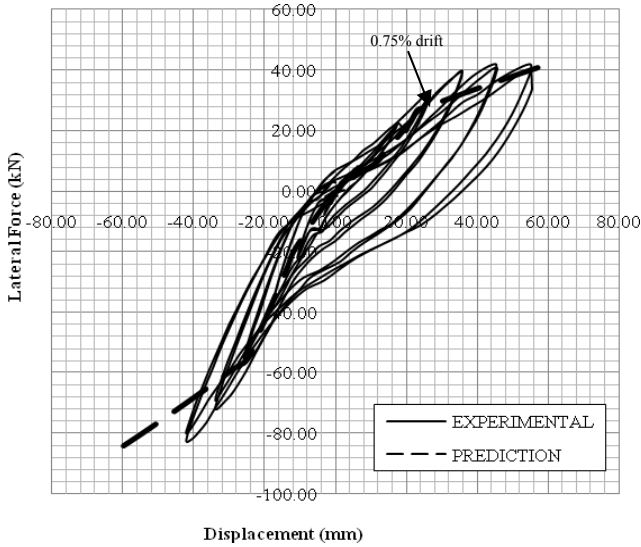


Fig. 10. Comparison between experimental hysteresis loops and prediction of moment-rotation analysis.

#### D. Stiffness and Ductility

Stiffness is the ratio of the force required to create a specified deflection. Stiffness can be defined as the ratio of force over deflection, which is expressed in kN/mm. The slope of load versus displacement graph will determine the stiffness of beam-column joint. Secant stiffness was calculated by finding the slope of a line drawn between maximum positive drift and maximum negative drift in inelastic region while elastic stiffness found by the slope of line drawn between yield drifts in elastic region.

The displacement ductility is defined as the ratio of lateral displacement ( $\Delta_x$ ) and yield lateral displacement ( $\Delta_y$ ). The hysteresis loops were used to calculate the elastic stiffness ( $K_e$ ), secant stiffness ( $K_{sec}$ ) and the ductility ( $\mu$ ). Table I shows the elastic stiffness, secant stiffness and ductility for the positive direction. Secant stiffness has lower value than elastic stiffness because the beam-column joint behavior under inelastic regions. The ductility of this system is less than 2 indicate that it does not behave very well under moderate and severe earthquake.

Table II shows the elastic stiffness, secant stiffness and ductility at negative direction. The ductility factor increased when the target drift increase. However, the maximum displacement ductility of 1.0 indicates the precast beam-column joint presented in this paper has low ductility and will experience severe damage when subjected to moderate or bigger earthquake excitation.

TABLE I: STIFFNESS AND DUCTILITY OF BEAM-COLUMN JOINT (POSITIVE DIRECTION)

Target drift (%)	Positive direction			
	Lateral Displacement $\Delta_x$ (mm)	Elastic Stiffness $K_e$	Secant Stiffness $K_{sec}$	Displacement ductility ( $\mu = \Delta_x / \Delta_y$ )
0.10	3.08	1.51	-	0.12
0.20	6.34	1.13	-	0.24
0.50	17.25	1.28	-	0.65
0.75	26.39	-	1.02	1.00
1.00	35.82	-	0.83	1.36
1.25	44.84	-	0.28	1.70
1.50	55.13	-	0.00	2.09

TABLE II: STIFFNESS AND DUCTILITY OF BEAM-COLUMN JOINT (NEGATIVE DIRECTION)

Target drift (%)	Negative direction			
	Lateral Displacement $\Delta_x$ (mm)	Elastic Stiffness $K_e$	Secant Stiffness $K_{sec}$	Displacement ductility ( $\mu = \Delta_x / \Delta_y$ )
0.10	3.08	3.20	-	0.03
0.20	6.34	2.08	-	0.07
0.50	17.25	1.85	-	0.29
0.75	26.39	2.26	-	0.44
1.00	35.82	2.13	-	0.62
1.25	44.84	1.75	-	0.81
1.50	55.13	1.34	-	1.00

#### E. Hysteresis Energy Dissipation

The hysteretic energy dissipation in terms of equivalent viscous damping is used in this study to model a nonlinear hysteretic system using displacement-based design. The most common method for defining equivalent viscous damping is to equate the energy dissipated in a vibration cycle of the actual structure and an equivalent viscous system. The area under the full load–displacement curvature obtained from the experimental work was computed and defined as the energy that could be dissipated by joint using equation (1) as follows:

$$\xi_{eq} = \frac{1}{4\pi} \left( \frac{E_D}{E_{SO}} \right) \times 100\% \quad (1)$$

where,  $E_D$  is the area enclosed by the hysteresis loops, and  $E_{SO}$  is the area under the equivalent linear hysteresis curve [3].

Fig. 11 shows the equivalent viscous damping versus drift. The experimental results are plotted for the first and second cycles. The equivalent viscous damping for second cycle is approximately differs 6.5% of the first cycle. The energy absorption occurred in the first cycle leads to the smaller enclosed area of the hysteresis loop in the second cycle. The equivalent viscous damping 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.

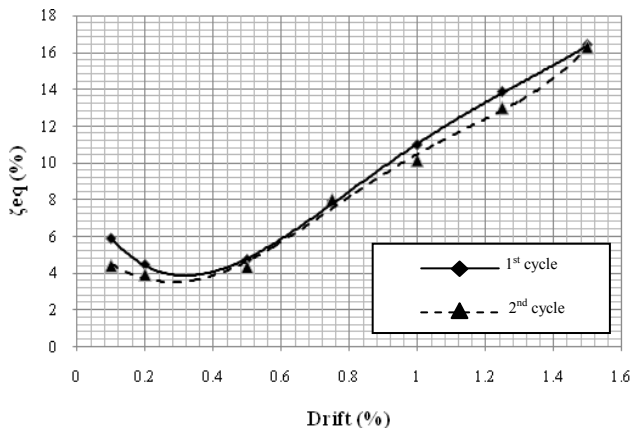


Fig. 11. Equivalent viscous damping versus drift

#### IV. CONCLUSION

This experimental study was conducted to investigate the seismic performance of precast beam-column corner joint with SFRC designed according to current practice in Malaysia. The subassembly was subjected to reversible lateral cyclic loading up to  $\pm 1.5\%$  drift. The visual observation and experimental results recorded shows that the cracks start to occur from  $+0.75\%$  drifts at the cast-in-place area of beam-column joints. Most cracks occurred during  $+1.0\%$ ,  $+1.25\%$  and  $+1.5\%$  drifts. Note that the cast-in-situ connection using normal concrete Grade 40 without steel fibers. The reinforcement bar in the beam-column joint was yielded at  $+0.75\%$  drift with displacement of 26.39 mm in positive direction (loading). The force-displacement response from experimental results shows agreement with prediction using moment-rotation analysis. Elastic stiffness ( $K_e$ ) and secant stiffness ( $K_{sec}$ ) were also calculated for both loading and unloading direction together with the displacement ductility. The displacement ductility shows that ductility increased by increasing the target drift with the maximum value of 2.09. Even though SFRC was provided at the beam-column joint and corbel areas, the result shows that the precast beam-column joint presented in this paper has low ductility and prone to severe damage when subjected to bigger drift or larger displacement due to lateral loading. Other types of joints such as column-foundation, wall-slab and wall-foundation can be tested to further prove the advantages of using SFRC in the improvement of seismic performance of structural joints.

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