

A Study on Seismic Behavior of Reinforced Concrete Knee Joint in Opening and Closing Action

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Abstract:

The beam-column joint is considered as the essential zone in a reinforcement concrete moment-resisting frame. Among the beam-column joints, the knee joint at the roof level is the most crucial element of the structure as less confinement makes the knee joint behavior most challenging during an earthquake. The poor performance of the knee joint during an earthquake causes detrimental failure of the structure resulting in a motivating number of experimental investigations of knee joint behavior under reversed cyclic loading. Even it is true that all major seismic design codes all over the world do not have specific seismic design codes for beam-column knee joints. That's why it becomes knee joint more crucial to be investigated to predict some important parameters for knee joint during a strong earthquake. In this paper three knee, joint specimens were conducted at the structural lab of The Hong Kong University of Science and Technology. The main goal of this study is to investigate the behavior of the knee joint under seismic excitation for both closing and opening action. Even hysteretic behavior and envelope curve have been studied to investigate joint performance. Consistent with observation, it can be seen that opening shear stress decreased with increasing the area ratio and becomes vice versa for closing shear stress.

Keywords- knee joint; Earthquake; shear stress; Opening action and closing action

1. Introduction

Beam column joints in a Reinforced concrete moment resisting frame are crucial zone for the transfer of loads effectively between the connecting elements (i.e. Beam and Columns) in the structure. In the normal design practice for gravity loads, the design check for joints is not critical and hence not warranted. But, the failure of reinforced concrete frames during an earthquake has demonstrated heavy distress due to the shear in the joints that culminated in the collapse of the structure. During an earthquake, the failure of beam-column joints is governed by bond and shear failure mechanisms which are usually brittle. Beam column having deficient reinforcement details are expected to respond poorly, even when subjected to modern seismic action.

1.1 Seismic Design of Beam-Column Joint in Ductile Frame

A beam-column joint is a part of the column where the beams join. Joints are considered brittle components in seismic design. Accordingly, the shear strength of a joint should be larger than the maximum shear force acting on the joint during an earthquake for an acceptable design. Beam-column joints in a ductile frame are classified into two types in seismic design. If beams are connecting to the joints from all four sides, and if the width of these beams is at least $\frac{3}{4}$ of the width of the column that they are joining to, then such a joint is classified as a confined joint. All other joints which do not satisfy the above condition are classified as unconfined joints. It can be clear that we can classify the knee joint as unconfined joints as it is situated at the rooftop of the structure where both horizontal and vertical shear should be considered for knee joint connection as the shear input from the column is higher in the knee joint. This is the major difference between the conventional beam-column joint and the knee joint whereas for conventional beam-column joint, column strength is higher along with the axial load and hence joint behavior is determined largely by shear input from beams.

1.2 Knee Joint Mechanism

^[6]Wall type corner forms another category of joints wherein the applied moments tend to either close or open the corners. Such joints may be referred to as knee joints or L-joints. The stresses and cracks developed in such a joint are shown in figure 1. Opening corner joint tends to develop a nascent crack at the reentrant

corner and failure is marked by the formation of the diagonal tensile crack. The opposite scenario takes place in producing force in a closing joint while comparing with the scenario of force in an opening corner joint. The major crack is developed along the corner diagonally. This joint shows better efficiency than the opening joint. During seismic action, the reversal of forces is likely and hence the corner joints have to be conservatively designed as opening joints with appropriate detailing. Failure of an opening corner or knee joint is primarily due to the formation of the diagonal tension crack across the joint with the outer part of the corner concrete separating from the rest of the specimen.

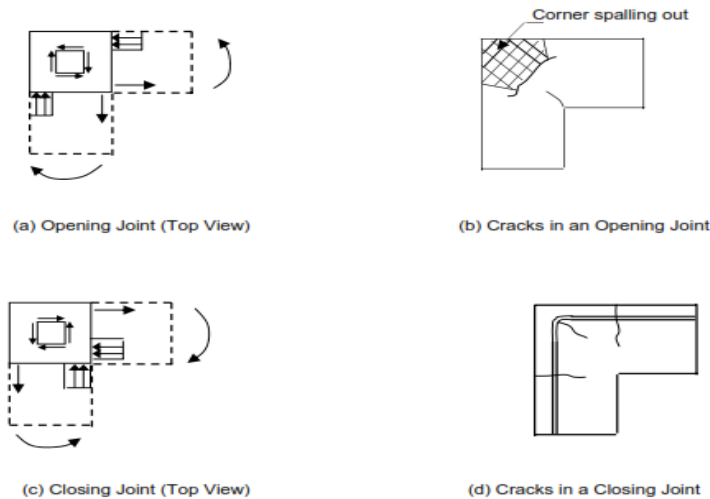


Figure 1: Knee Joint Mechanism

1.3 Experimental Test on Reinforced Concrete Knee Joint

^[4](Nilsson (1973) and Nilsson and Losberg (1976)) began an investigation on knee joint under monotonic opening action in 1965. This investigation was prompted by the failure of wing wall knee joints of bridge abutment in Sweden.

Nilsson identified the following possible failure modes for knee joints,

- Diagonal tension crack failure, which occurs in the joint corner because tensile stresses generated by external moments are not resisted by reinforcement.
- Splitting crack failure may occur when significant tensile stresses occur in the concrete perpendicular to the direction of the reinforcing bar. Such stresses may result in knee joints that are subjected to closing actions have a high reinforcement percentage for the bent anchorage reinforcement.
- Yielding of the reinforcement in the joint.
- Anchorage failure occurs as a consequence of bond deterioration between the concrete and reinforcement or local crushing of concrete under the bends in the reinforcement.
- Concrete compressive failure, which occurs as a result of the crushing of the concrete in the joint.

Nilsson determined experimentally that to ensure yielding of the main tensile reinforcement and for failure to occur outside the joint region, the area of the diagonal reinforcement should be about one-half of the area of the main tension reinforcement. Transverse reinforcement was not considered in the knee joint detailing schemes because of the difficulty encountered.

^[8](Swan (1969)) performed monotonic load tests on eighteen light-weight knee joint specimens. Thirteen specimens were tested under monotonic opening action and five specimens were tested under monotonic closing action. Very low efficiencies, between 0.09 and 0.6 were obtained for the conventional detailing schemes under opening actions. The test specimens which contained stirrups within the joint resulted in higher efficiency between 0.8 and 0.9.

^[7](Balint and Taylor 1972) continued the work done by Swann. In addition to testing knee joint specimens with common detailing schemes, they also investigated test specimens with two kinds of joint transverse reinforcement. Low efficiencies (between 0.22 and 0.6) were obtained for the conventional joint detailing schemes. Higher efficiencies were obtained for the test specimens that contained a haunch with diagonal hairpin reinforcement (efficiencies between 0.9 and 1.14). Similar efficiencies (between 0.85 and 1.04) were obtained for the test specimens that contained stirrups and mesh reinforcement in addition to the haunch and diagonal hairpin reinforcement.

^[3](Mayfield et al (1971, 1972)) tested several light-weight knee joints specimens with a variety of detailing schemes under both opening and closing actions. He found that the most efficient detailing schemes would require, in addition to the appropriate main tensile reinforcement, two types of diagonal reinforcement. The reasoning proposed by Mayfield et al (1972) was similar to that given by Nilsson (1973).

^[9](Jackson (1995)) tested five knee joint specimens that were detailed using intersection U-bars. From the test, Jackson found that the bar diameter of the main tension reinforcement appeared to be a more significant design parameter than the corresponding reinforcement ratio. When comparing the results for specimens who are detailing differed only in the diameter of the main tensile reinforcement, the specimens with the larger diameter reinforcing bar experienced more distress in the knee joint region than those specimens with the smaller diameter reinforcing bar.

^[1](Cote and Wallace (1994) and McConnell and Wallace (1995)) performed a reversed cyclic load test on the knee joint specimens. The goal of their investigation was to determine the effect of design parameters such as joint shear input and amount of joint transverse reinforcement on knee joint performance and to develop recommendations for the earthquake design of knee joints by investigating the ACI352 (1991) limits for horizontal shear input to the joint.

^[5](B. Abdelwahed et al. (2018)) performed behavior of Beam-Column knee joint under a closing moment using nonlinear finite element (FE) analysis with LS-DYNA. The variation was in the Beam's bar anchorage type and joint vertical stirrups. This study indicates that the anchorage beam's bar with U shaped produces better behavior than 90° standard hooks or headed ends. The contribution of joint vertical stirrups is more influential with headed bar anchorage. Increasing concrete compressive strength and beam reinforcement ratio improve joint ultimate capacity.

2. Methodology

To set the problems on the knee joint, a large scale experiment has been done in the structural lab of Hong Kong University of Science and Technology. A part of a large scale experiment on the knee joint has been done to understand the behavior of the beam-column knee joint. The study consists of two parts: an experimental component where three specimens of the beam-column knee joint with different beam-column reinforcement ratio were subjected to cyclic load tests simulating earthquake conditions, and an analytical model component, where the experimental data were analyzed to obtain the valuable information into the behavior of knee joint and subsequently to contribute in part, to the development of comprehensive design recommendation for such condition.

The main variables of this experimental study were: the effect of significant variables in the top and bottom reinforcement, joint dimension (i.e. angle of compression strut), the ratio of the flexural capacity of beam and column. Three specimens of the beam-column knee joint have experimented as a part of the full large scale of the experiment of the beam-column knee joint in the structural lab of the Hong Kong University of Science and Technology. These three specimens are varied in the beam top and bottom reinforcement ratio. Besides, all the specimens were designed to fail in joint shear than in member flexure.

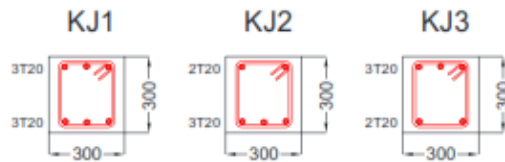


Figure 2: Test specimens details a) KJ1 b) KJ2 c) KJ3

The ratio of reinforcement of beam and column of three specimens are given below

Table 1: Beam-Column longitudinal reinforcement ratio

		Specimens 01 (KJ1)	Specimens 01 (KJ2)	Specimens 01 (KJ3)	Code Requirements
Beam	ρ' (Top reinforcement)	1.21	0.81	1.21	$\rho_{b,\min} = 0.3$
	ρ (Bottom reinforcement)	1.21	1.21	0.81	
Column		2.42	2.42	2.42	$1 < \rho_c < 8$

The required vs. provided values of stirrup spacing in a critical region for all the specimens are given below

Table 2: Stirrup spacing for the critical zone for Beam and Column

s_0	Specimen KJ1	Specimen KJ2	Specimen KJ3
Required	65mm	65mm	65mm
Provided	60mm	60mm	60mm

The spacing of stirrups for the non-critical zone are given below

Table 3: Stirrup spacing for the non-critical zone for Beam and Column

s_{\min}	Specimen KJ1	Specimen KJ2	Specimen KJ3
Required	130mm	130mm	130mm
Provided	130mm	130mm	130mm

2.1 Specimens preparation

2.1.1 Concrete

In concrete mix design, the material used uncrushed gravel aggregates with a nominal size of 12mm, river sand, and Portland cement. The testing cube strength test is given below:

Table 4: Concrete properties of specimens

Specimen	Concrete Strength (MPa)			Mean concrete strength (MPa)	Eq. Cylinder Strength (MPa)
	01	02	03		

KJ1	48.44	49.07	46.27	47.93	38.34
KJ2	49.73	47.38	50.76	49.29	39.43
KJ3	48.52	49.10	48.23	48.61	38.89

2.1.2 Reinforcement Steel

Two kinds of grades of reinforcement steel were used for all three specimens. A diameter of 20mm high yield reinforcement bar was used for the main longitudinal bar for beam and column and for stirrup for member and joint; 10mm diameter of reinforcement bar was used. The yield strength and modulus of elasticity of the reinforcement bar are given below:

Table 5: Steel properties of specimens

Diameter (mm)	Yield strength (MPa)	Ultimate strength (MPa)	Modulus of elasticity (GPa)
20	551.4	657.8	200
10	500.6	619.3	204.8

2. Loading Schemes

To have a real-life experience of lateral loading like an earthquake on a moment-resisting frame where reversed cyclic loading is predominant, a test set up was executed with the help and available lab facility in HKUST. Figure 3 shows the experiment set up by which a reversed cyclic diagonal external force is applied with the help of a 160KN capacity actuator and drift limit of 140mm in both directions.

The loading on specimens given in figure 4 is displacement controlled which started with the low value of 1.5mm peak to peak with the subsequent cycle until the failure of the specimens.

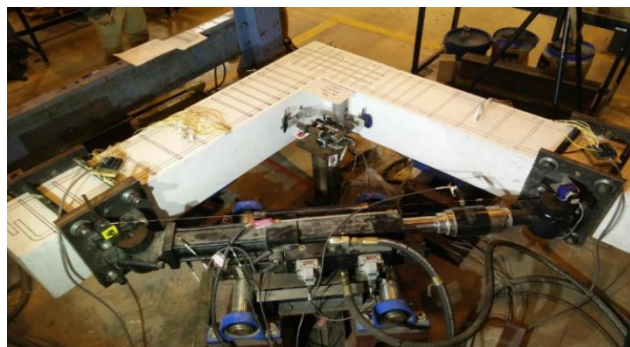


Figure 3: Test set up for testing knee joint

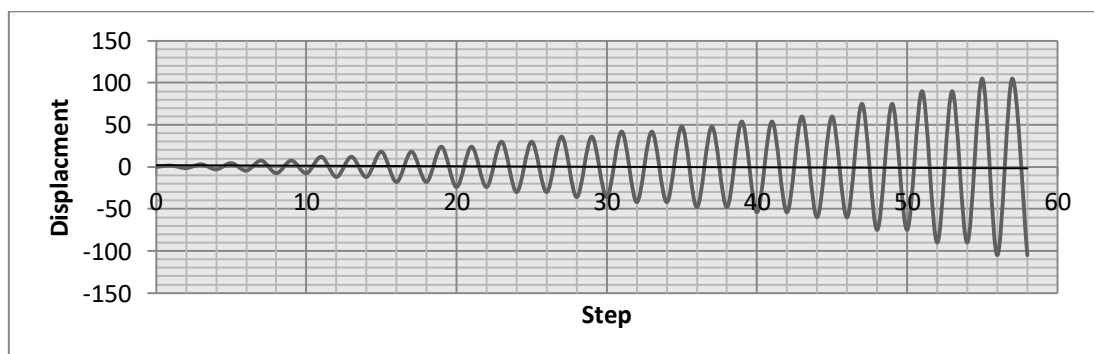


Figure 4: Loading chart with displacement history

3. Experimental Result & Discussion

After the experimentation on specimens obtained data of various structural parameters is used to identify the milestones in the behavioral response of the knee joint specimens for improved modeling of the problem. With the experimental data, I have tried to understand the joint behavior under the opening and closing action and joint shear input. The graph given below shows the variation of closing and opening shear stresses with ρ'/ρ .

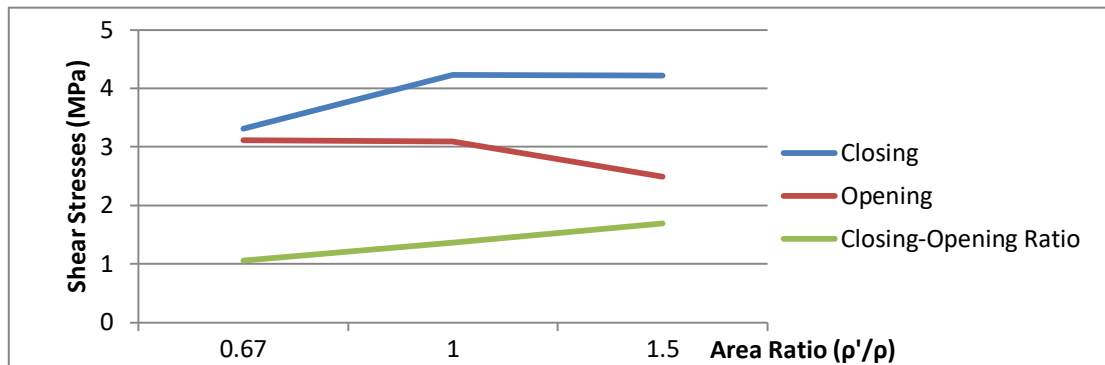


Figure 5: Variation of closing and opening shear stresses with ρ'/ρ

From the graph above, we can observe that the beam reinforcement ratios do affect the shear stresses in opening and closing actions. When ρ'/ρ changes from 0.67 to 1, the shear stresses increased significantly in closing action while when further increasing the ρ'/ρ ratio to 1.5, no significant changes are observed. While for the opening act, when ρ'/ρ is increasing from 0.67 to 1, there are no significant changes observed, but when ρ'/ρ turn to 1.5, and the decrease of shear stresses are observed.

I have also analyzed the results by comparing the horizontal and vertical shear strength. From the graph below, I have observed that there is not much difference between horizontal and vertical shear strength whatever in closing or opening actions.

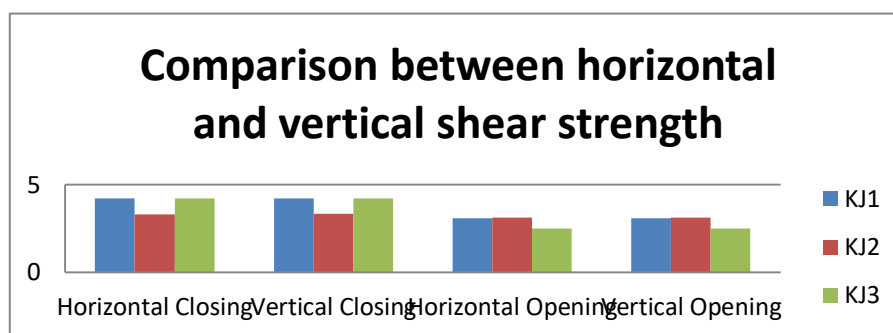


Figure 6: Comparison of horizontal and vertical shear strengths

3.1. Hysteresis behavior of specimens

To understand the energy dissipation of the specimens during the experiment, a hysteresis graph is used for closing and opening action. As noted before, only three specimens were conducted to understand the behavior of crack patterns under opening and closing action. The hysteresis behaviors of the knee joint of the specimens are described below

3.1.1 Specimen KJ1

Specimen KJ-1 consists of an equal reinforcement bar of the beam at the top and bottom of the specimen. This means the ratio of top reinforcement bar and bottom reinforcement bar of the beam is equal to 1. The hysteresis graph for specimens KJ-1 is shown in figure 7.

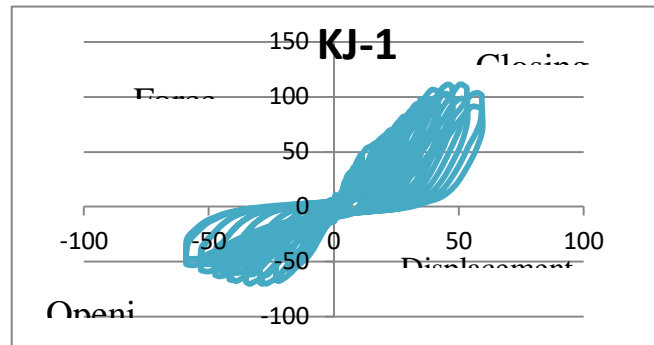


Figure 7: Hysteresis behavior of KJ1

From the figure, it can be seen that energy dissipation for the closing action of KJ1 is greater than for opening acts. The peak load for closing action was 112.9 kN and displacement was 50.5 mm at the peak load. Whereas peak load for opening action was 68.8 kN and displacement was 33.7 mm at the peak load. When the value of load reached 102.3 kN, the specimen becomes brittle under closing action and for opening action it was at 50.8 kN.

3.1.2 Specimen KJ2

Specimen KJ-2 consists of 3 numbers of reinforcement bars of 20 mm diameter at the bottom and 2 numbers of reinforcement bars of 20 mm at the top of the beam. The area of steel ratio of specimen KJ-2 is 0.67. The hysteresis graph for specimens KJ-2 is shown in figure 8.

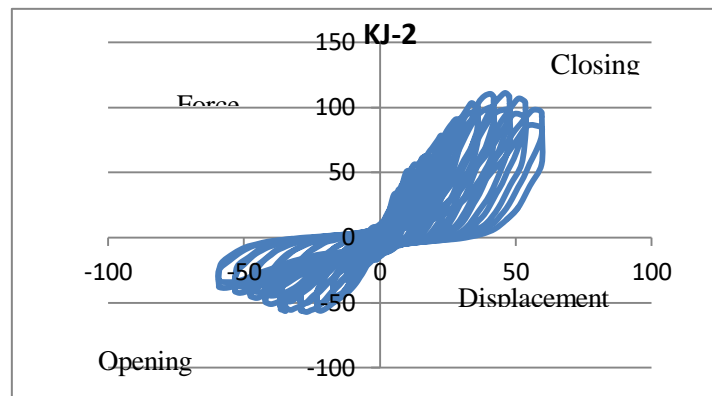


Figure 8: Hysteresis behavior of KJ2

From the graph, it can be seen that a closing resisting moment is much larger than an opening resisting moment. The dissipation energy area enclosed a big area in the opening action than the closing action. It can be seen that with a decreased area ratio of the reinforcement bar, the energy dissipation ratio of opening and closing energy becomes increased as compared to the first specimens KJ-1. The peak load for closing action 89.8 kN and displacement at the peak load was 45.2 mm. Whereas for opening action, peak load was 69.8 kN and displacement was 28.1 mm. As peak load under opening action becomes increased compared to specimen KJ1 where load for the opening peak was 68.8 kN.

3.1.3 Specimen KJ3

Specimen KJ-3 consists of 3 numbers of reinforcement bars of 20mm diameter at the top of the beam and 2 numbers of reinforcement bars of 20mm diameter at the bottom of the beam. The hysteresis behavior graph for KJ-3 is shown in figure 9

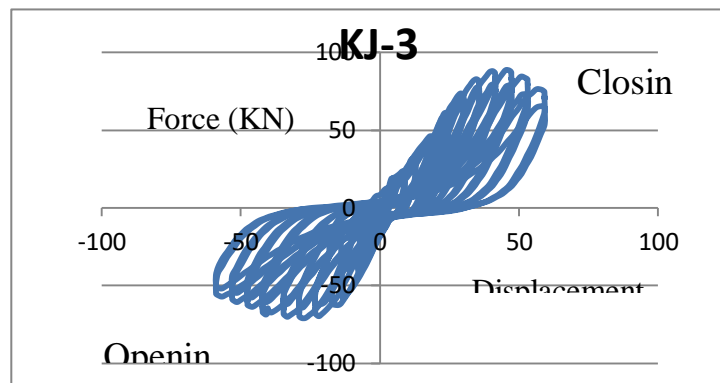


Figure 9: Hysteresis behavior of KJ3

The top and bottom reinforcement area ratio in specimen KJ-3 is 1.5. With increasing the area ratio of the reinforcement bar, the opening energy dissipation area become decreased compared to the other two specimens. Even opening and closing energy dissipation area ratio become decreased compared to KJ-1 and KJ-2. As the same amount of reinforcement bar was used in the bottom of specimen KJ-3 like specimen KJ-1, the contribution of closing action to total dissipation energy does not change much.

4. Conclusion

After having data and discussion on the acquired data of the specimens KJ-1, KJ-2, and KJ-3, some limitation may arise due to conduct a limited experiment to understand the behavior of knee joint under closing and opening action as this experiment was a part of a large scale experiment on the beam-column knee joint. As noted before that the main variation among these three specimens is the area ratio of the top and bottom reinforcement in the beam. The following conclusion can be addressed from the experimental data.

- Variation in area ratio shows the variation in shear stress in both opening and closing action. This kind of variation can be observed significantly for opening action rather than closing action.
- Higher opening shear stress is achieved with a low area ratio. With increased area ratio tends to decrease the ratio of opening to closing shear stress.
- Concrete spalling was dominated by high closing shear stress in specimen KJ-3 and high opening shear stress in specimen KJ-2.
- The lesser the ratio of joint horizontal opening and closing shear stress, the larger the ductile of the specimen.

5. Acknowledgments

It is mentioned before that this test was conducted at the Hong Kong University of Science and Technology as my M.Sc. thesis project. I am grateful to my M.Sc. supervisor and at the same time I would like to express my gratefulness and appreciation to the Lab staffs of The Hong Kong University of Science and Technology, without them it would be impossible to stand this project on time

6. Reference

- i. Cote, P.A., and Wallace, J.W. (1994), "A study of reinforced concrete knee joints subjected to cyclic lateral loading", Report No. CU/CEE 94/04, Dept. of Civil Eng., Clarkson Univ., Potsdam, NY, 143pp.
- ii. Kemp, E. L., & Mukherjee, P. R. (October 1968), *Inelastic behavior of concrete knee joints*. The

- Consulting Engineer, 44-48.*
- iii. *Mayfield, B., Kong, F., Bennison, A., & Davies, J. C. T. (1971), Corner joint details in structural lightweight concrete, Journal Proceedings, 68(5) 366-372.*
 - iv. *Nilsson, I. H., & Losberg, A. (1976), Reinforced concrete corners and joints subjected to bending moment, Journal of the Structural Division, 102(6), 1229-1254.*
 - v. *B. Abdelwahed et al. (2018), Reinforced Concrete Beam-Column Inverted Knee Joint Behaviour after Ground Corner Column Loss-Numerical Analysis, Latin American Journal of Solids and Structure, <https://doi.org/10.1590/1679-78254515>.*
 - vi. *Paulay, T., Park, R., & Priestley, M. (1978). Reinforced concrete beam-column joints under seismic actions, Journal Proceedings, 75(11) 585-593.*
 - vii. *Balint, P.S., and Tay Ior, H.P.J., "Reinforcement Detailing of Frame Corner Joints with Particular Reference to Opening Corners", Cement and Concrete Association, Technical Report 42.462, London, February 1972, pp.16.*
 - viii. *Swann, R.A., "Flexural Strength of Corners of Reinforced Concrete Portal Frames", Cement and Concrete Association, Technical Report TRN434, London, November 1969, pp. 14.*
 - ix. *Jackson, N., "Design of Reinforced Concrete Opening Corners", The Structural Engineer, V. 73, No. 10, July 1995, pp. 209-214.*