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Seismic Behaviour of RC Knee Joints in Closing and Opening Actions

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Abstract**—**Knee joints, the beam column connections found at the roof level of a moment resisting frame buildings, are inherently different from conventional interior and exterior beam column connections in the way that forces from adjoining members are transferred into joint and then resisted by the joint. A knee connection has two distinct load resisting mechanisms, each for closing and opening actions acting simultaneously under reversed cyclic loading. In spite of many distinct differences in the behaviour of shear resistance in knee joints, there are no special design provisions in the major design codes available across the world due to lack of in-depth research on the knee connections. To understand the relative importance of opening and closing actions in design, it is imperative to study knee joints under varying shear stresses, especially at higher opening-to-closing shear stress ratios. Three knee joint specimens, under different input shear stresses, were designed to produce a varying ratio of input opening to closing shear stresses. The design was carried out in such a way that the ratio of flexural strength of beams with consideration of axial forces in opening to closing actions are maintained at 0.5, 0.7, and 1.0, thereby resulting in the required variation of opening to closing joint shear stress ratios among the specimens. The behaviour of these specimens was then carefully studied in terms of closing and opening capacities, hysteretic behaviour, and envelope curves to understand the differences in joint performance based on which an attempt to suggest design guidelines for knee joints is made emphasizing the relative importance of opening and closing actions. Specimens with relatively higher opening stresses were observed to be more vulnerable under the action of seismic loading.

Keywords**—**Knee-joints, large-scale testing, opening and closing shear stresses, seismic performance.

I. INTRODUCTION

KNEE joints are very special and complicated of all the beam column connections in terms of their performance under cyclic loading. In comparison with the conventional interior and exterior joints, the following major differences can be observed in knee joints: little or no axial force in column member, significant tensile and compressive axial member forces under opening and closing actions, respectively. These significant differences result in an uncertain behaviour of knee joints as compared with conventional joints. In spite of these differences, there are no special provisions in major seismic design codes across the world due to the lack of comprehensive research available on seismic performance of knee connections. A major cause for complicated behaviour of knee joints is their significantly different closing and opening behaviour. Previous research works conducted on understanding the cyclic behaviour of knee joints observed lower opening shear stresses, typically in the range of 50-70% as compared with the closing shear stresses [1]–[4]. Due to lower relative opening shear stresses, it was considered that opening action is non-critical in a knee joint. However, knee joints are inherently weaker and more vulnerable in opening action due to the input tensile forces on the joints from members. As a result, opening shear stresses of relatively low magnitude as compared with closing shear stresses are also critical for the seismic performance of knee joints. Moreover, the relative magnitude of opening shear stress increases with decrease in the top-to-bottom beam reinforcement ratio. While major seismic design codes such as NZS3101-06 [5] and Eurocode 8-04 [6] do not have any special provisions for knee joints distinguishing from the conventional interior and exterior joints, ACI318-14 [7] provides a factor for the nominal shear strength of knee joints: categorised as "Other cases" in ACI352R-02 [8]. However, none of the existing major seismic design codes make any distinction between closing and opening actions for limiting shear stresses.

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II. PREVIOUS CYCLIC KNEE JOINT TESTS

Cyclic experimental tests on knee joints were started in early 1990s. Mazzoni et al. [2], Cote and Wallace [3] observed that the vertical U-stirrups improved the efficiency of the joint by contributing to carry the diagonal tensile forces in the joint. The shear stress was observed to be 20% and 55% for opening and closing actions respectively of the then existing ACI provisions leading to lower shear capacity value of $1.0\sqrt{f_c}$ MPa, prompting more work on assessing the shear capacity of knee joints and improving the efficiency of joints. Angelakos [9] conducted elaborative parametric studies on knee joints and suggested to limit a joint shear strength to $0.5\sqrt{f_c}$ MPa ($6\sqrt{f_c}$ psi) from an un-conservative ACI proposed value of $0.66\sqrt{f_c}$ MPa ($8\sqrt{f_c}$ psi). Megget [1], [10] observed maximum joint shear stresses of 50% of the then existing NZ Standards of $0.2f_c$ MPa, while the specimens with large main bars resulted in failure due to bond failure due to inadequate anchorage.

Priestley et al. [11] adopted a generalized approach in determining principal stresses taking into consideration both shear and axial forces and consequently limit them to avoid joint failure, thus accommodating the difference in closing and opening actions through axial force incorporation. Thus, suggesting limiting principal tensile and compression stresses to $0.29\sqrt{f_c}$ MPa and $0.3f_c$ MPa respectively to avoid joint failure. Further discussing the modes of failure for closing and opening actions, it was observed that extensive damage to the outer face under closing actions combined with possible inadequate anchorage of outer bars caused a discontinuity in tension force capacity around the corner by hooks tending to straighten, whereas in opening actions, a series of curved arch shaped cracks resulted in pushing the exterior corner aided by closing cracks resulting in brittle failure.

III. Closing vs. Opening Behaviour

While major seismic design codes apply the provisions for exterior joints to knee joints, there is no mention of the differences in performance of knee joints for closing and opening actions. It is also important to note that most of the research works on knee joints proposed a single nominal shear capacity value, with no mention to its specific applicability for closing and opening actions separately.

Knee joints experience an axial compressive and tensile forces acting through the members in closing and opening actions, respectively. While the compressive forces in the joint strengthen the joint enhancing the shear capacity, the tensile forces in the joint weaken the joint and reduce the shear capacity. This behaviour is not generally observed in conventional interior and exterior joints due to greater column axial load and also the continuity of the horizontal member through the joint.

Knee joints undergo significantly different load resisting mechanisms in closing and opening actions acting simultaneously under seismic loading, resulting in more complicated and vulnerable behaviour. Thus, to evaluate the comprehensive behaviour of knee joints in closing and opening actions, it is imperative to study knee joints under varying ratio of input opening to closing shear stresses, possibly resulting in different modes of joint failure.

IV. Experimental Programme

For the current study, top-to-bottom beam reinforcement was varied in order to achieve different opening to closing shear stress ratios. Experimental specimens were designed such that the ratios of flexural strength of beams are maintained at 0.5, 0.7, and 1.0 with consideration of axial forces in both opening to closing actions under seismic action, thereby resulting in the required variation of opening to closing joint shear stress ratios among the specimens. Three knee joint specimens KJ1, KJ2, and KJ3 were designed as per the ACI318-14 [7] and ACI352R-02 [8] design guidelines and tested under reversed cyclic loading applied diagonally on the specimens using a single 160 kN capacity hydraulic actuator (140 mm stroke). All the specimens were designed to fail in joint shear before member flexural capacity is achieved. All the experimental tests were carried out in the structural lab of The Hong Kong University of Science and Technology.

A. Specimen Geometry, Design and Material Details

All the three specimens had member lengths of 1800 mm each for beam and column, with cross section dimensions of 300 mm and 300 mm for depth and width, respectively. KJ1 was designed with 3-T20 bottom and 3-T20 top reinforcement ($\rho = \rho'$= 1.21%), KJ2 was designed with 3-T20 bottom and 2-T20 top reinforcement (ρ = 1.21% and ρ'= 0.81%) and KJ3 was designed with 2-T20 bottom and 3-T20 top reinforcement (ρ = 0.81% and ρ'= 1.21%). Columns in all the specimens were designed with 3-T20 outside and 3-T20 inside reinforcement. The outer bars from both column and beam were extended into other member to provide better anchorage and prevent an undesirable bond failure. Primary difference among the specimens (shown in Fig. 1) was the variation of top-to-bottom beam reinforcement ratios (1.0, 0.67, and 1.5 for KJ1, KJ2, and KJ3 respectively).

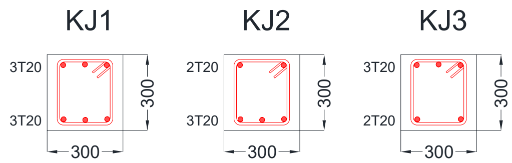

Fig. 1 Beam top and bottom reinforcement details for specimens

A total of 3-T10 joint horizontal closed stirrups with 135° hooks were provided as joint transverse reinforcement along with 3-T10 vertical U shaped stirrups, for the ease of placement, also ensuring adequate anchorage length for each of the stirrup legs. Fig. 2 shows the schematic diagram of loading apparatus along with the reinforcement details for specimen KJ1. Joint transverse reinforcement was provided according to the ACI352R-02 [8] design guidelines while taking into consideration, observations from parametric studies conducted on similar type of knee joints (both size and reinforcement) [12].

The properties of reinforcement provided in all specimens are shown in Table I.

TABLE I
PROPERTIES OF REINFORCEMENT STEEL

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

Characteristics of concrete used for knee joint specimens were assessed from a number of cube tests, casted along with the specimens. These cubes were placed along with the specimens in order to foster similar curing conditions. Cube strength was determined on the testing day for each specimen. All the cube tests were carried out with rate of loading which was 5 kN/s and a base load of 10 kN. The mechanical properties of concrete used for all specimens are listed in Table II. The observed variation in strength of concrete was primarily due to the ageing of concrete. Equivalent cylinder strength was calculated for each specimen based on the guidelines by EN206-1:2000 [13].

TABLE II
PROPERTIES OF CONCRETE

Specimen	Date of Testing	Mean Cube Concrete Strength (MPa)	Equivalent Cylinder Strength (MPa)
KJ1	19-Oct-16 (35 days)	47.93	38.34
KJ2	02-Nov-16 (49 days)	49.29	39.43
KJ3	26-Oct-16 (42 days)	48.61	38.89

B. Test Setup and Loading History

In order to accurately represent the state of stresses in the joint, test setup included a diagonally placed hydraulic actuator connecting the members of each specimen imparting reversed cyclic loading on specimens with successive closing and opening cycles. Ends of actuator were firmly connected to member ends of specimen using iron plates and fastened with 20 mm bolts replicating the points of contra-flexure in reality. Loading on each specimen was displacement controlled successive incremental closing and opening cycles.

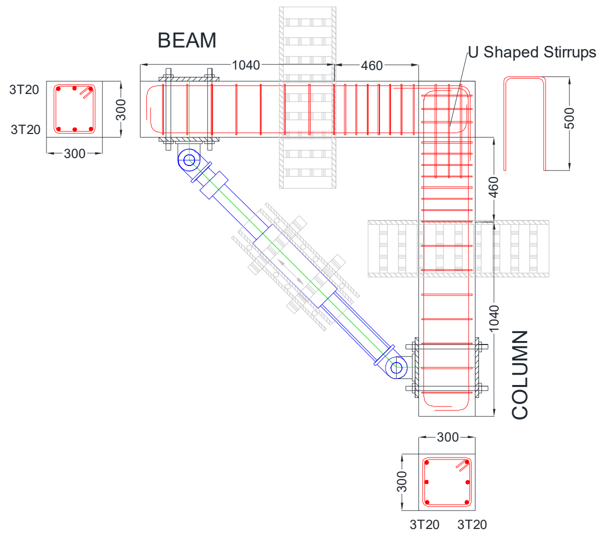

Fig. 2 Schematic diagram of test set up

The test setup and displacement controlled loading chart are presented in Figs. 2 and 3, respectively. Each cycle of loading included a closing and opening step for initial three cycles followed by two closing and opening steps per cycle until failure. Positive and negative displacement notations were assigned to closing and opening actions, respectively. No additional axial forces, apart from diagonally placed actuator, were applied on knee joint sub-assemblages before or during the testing as knee joints experience little or no axial due to their location at the top of moment resisting frames in reality.

C. Instrumentation and Data Acquisition

The data from the test during loading were obtained using various means. While the controller for hydraulic actuator provided continuous data of load vs displacement at every five seconds interval throughout the experiment, drift and deformation at various locations were captured using linear variable differential transformers (LVDTs) and wire potentiometers. Strain gauges were also attached to both main bars (at joint face) and joint transverse reinforcement to capture the local strains in each specimen.

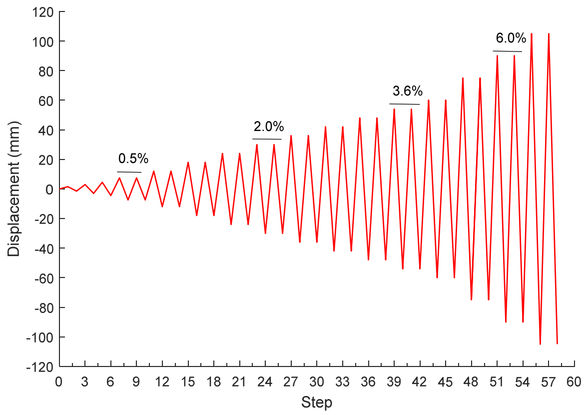

Fig. 3 Loading chart for experimental testing

V. EXPERIMENTAL RESULTS

In order to derive meaningful conclusions from the experimental data, several quantitative parameters were obtained from the data gathered during the testing of three knee joint specimens. The performance of knee joint specimens in terms of shear strength, hysteresis behaviour, and envelope curves are presented.

A. Joint Shear Strength

For each specimen, joint shear strength: shear input for the peak load (different for closing and opening) imparted on to the specimen was calculated for the axial-flexural loading by solving sets of force-moment equilibrium and strain compatibility equations separately for closing and opening actions. Axial forces in members are not negligible for knee joints, hence the contribution of axial forces was also considered in determining shear input.

$$V_j = \begin{cases} T'_{s,b/c} \ (closing\ action) \\ T_{s,b/c} - V_c \ (opening\ action) \end{cases} \quad (1)$$

V_j is the horizontal shear force acting on an imaginary horizontal plane at the middle of joint, T'_s is the tensile force in top/outer reinforcement of beam/column, T_s is the tensile force in bottom/inner reinforcement of beam/column, and V_c is the shear force in the column at the joint face.

$$v_s = V_j/(b_j.h_j) \quad (2)$$

where v_s is the joint shear stress generated through a shear input V_j calculated using (1) for both closing and opening actions on joint width b_j and joint depth h_j.

Joint shear strength values of tested specimens, derived from peak actuator loads in closing and opening actions, are presented in Table III along with the maximum tensile stresses in the beam reinforcement and the ratio of opening-to-closing shear strength. Variation of closing and opening shear stresses with respect to the top-to-bottom reinforcement area ratio is shown in Fig. 4.

While the top and bottom reinforcement determine the direct shear input on joint in closing and opening respectively (from (1)), opening shear stresses remarkably increased with decrease in area ratio, whereas closing shear stresses remained same (Fig. 4). It is believed that tensile member forces in opening action contributed in direct increase of shear input to the joint through tensile forces in the bottom reinforcement as concrete is weak in tension. However, in the case of closing, as the member forces are compressive in nature, the direct effect of member forces on increase of shear stresses is not significant. This can be seen from the remarkably different shear stress values of KJ1 and KJ2 in opening despite identical bottom reinforcement, while KJ1 and KJ3 with identical top reinforcement result in similar closing shear stresses.

TABLE III
SHEAR STRENGTH OF KNEE JOINT SPECIMENS

		KJ1 ($\rho'/\rho = 1$)	KJ2 ($\rho'/\rho = 0.67$)	KJ3 ($\rho'/\rho = 1.5$)
Peak Actuator Load (kN)	Closing	112.9	89.8	112.1
	Opening	68.8	69.8	56.1
Joint Shear Strength (MPa)	Closing	4.55	3.55	4.52
	Opening	2.75	4.40	1.34
$v_{opening}/v_{closing}$		0.60	1.24	0.30
Nominal Joint Shear Strength (MPa)		4.11	4.17	4.14
$\eta = \frac{v_{shear\ strength}}{v_{nom.strength}}$	Closing	1.11	0.85	1.09
	Opening	0.67	1.06	0.32

In addition, the nominal shear strength values proposed by ACI codal provisions [8] and shear strength to nominal strength ratios for closing and opening actions are presented in Table III. While KJ1 and KJ3 showed a dominating closing behaviour ($\eta > 1$), KJ2 showed a dominating opening behaviour. These values clearly show the incongruity in using a single value of shear strength for knee joints and call for the need of ascertaining possibly different shear strength values for closing and opening actions by considering major controlling parameters. More comprehensive studies are needed to verify and obtain a suitable joint shear strength and mechanisms of shear resistance of knee joints in closing and opening actions.

B. Hysteretic Behaviour

Hysteresis loops (Fig. 5) were generated against the actuator force and relative member tip displacement for each knee joint specimen. Energy absorption capacity of each specimen in both closing and opening actions was assessed by calculating the area occupied by the hysteresis loops (Table IV).

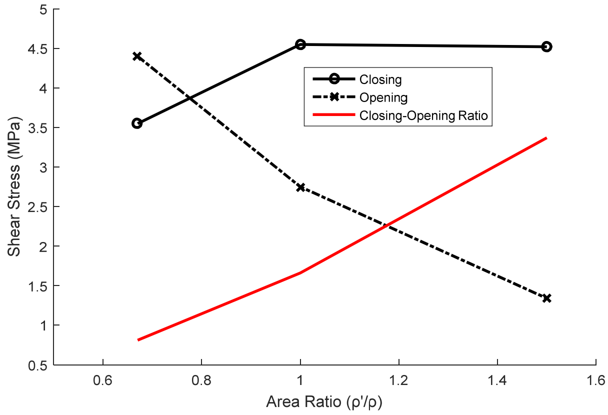

Fig. 4 Closing and opening shear stress variation with area ratio

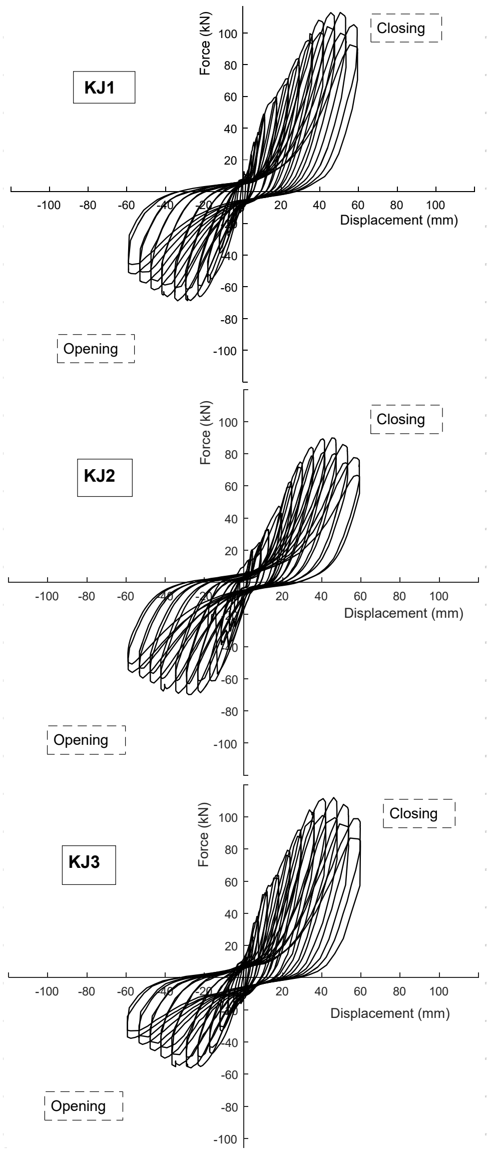

Fig. 5 Hysteretic behaviour of experimental specimens under reversed cyclic loading

The ratio of energy dissipation in opening to closing followed similar trend as observed for opening to closing shear stress ratios reinforcing the dominating behaviour of opening action in KJ2. In general, specimen KJ2 was observed to be more vulnerable during testing with greatest joint damage and more spalling of concrete as compared with other specimens, which is also reflected in the least total energy dissipation value among the three specimens (Table IV). Specimens KJ1 and KJ3 were observed to fail in a similar fashion in cracking pattern and joint damage with dominating closing behaviour. This was again reflected in the energy dissipation capacities for KJ1 and KJ3. Hence, it was observed that limiting the design opening shear stresses to 60% of closing shear stresses shall reduce vulnerability of knee joints under seismic excitations. More experimental tests are needed to validate this factor.

TABLE IV
ENERGY DISSIPATION CAPACITY

	KJ1	KJ2	KJ3
Total Energy Dissipation (kN.m)	33.0	27.8	32.6
Closing Energy Dissipation (kN.m)	17.5	13.2	19.0
Opening Energy Dissipation (kN.m)	15.5	14.6	13.6
Opening Energy/Closing Energy	0.89	1.11	0.71

C. Backbone Envelope Curves

A backbone envelope curve was plotted (Fig. 6) from the points corresponding to peak loads in each primary cycle (first cycle of loading for a given displacement).

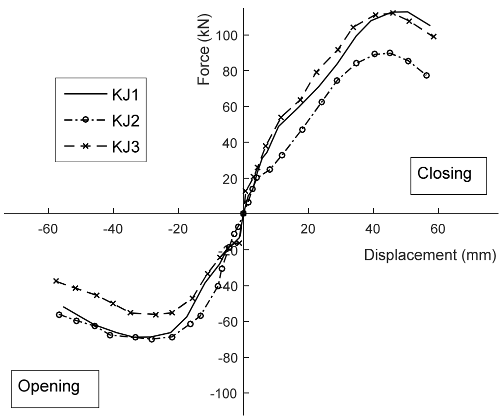

Fig. 6 Backbone envelope curves for experimental specimens

It can be seen that the peak closing loads and stiffness variation were similar for KJ1 and KJ3 with equal top reinforcement, whereas KJ1 and KJ2, with equal bottom reinforcement, showed similar behaviour under opening loads. Hence, the amount of reinforcement at the top and bottom of beam had major role in determining the capacity and stiffness in both closing and opening actions.

VI. CONCLUSIONS

The experimental results of three knee joint specimens under reversed cyclic loading have been presented in this manuscript. The primary difference in performance of knee joints in closing and opening actions was studied. In order to study the knee joints under varying opening to closing shear stress ratios, the top-to-bottom beam reinforcement ratio was varied. The following conclusions were drawn from the experimental results obtained:

1) Variation in the top-to-bottom reinforcement area ratio resulted in significant variation of opening-to-closing shear stress ratios. While decrease in reinforcement area ratio increased the opening shear strength (more than 200% from KJ3 to KJ2), no significant variation in closing shear strength was observed (less than 1%).
2) Tensile and compressive member forces played major role in performance of knee joints in opening and closing actions respectively, creating different shear resisting mechanisms, and hence, they are supposed to be considered separately for design.
3) Varying closing and opening strength values showed the need for ascertaining closing and opening shear capacities separately by studying the resisting mechanisms, considering major parameters, affecting the performance of knee joints.
4) Considering the more vulnerable behaviour of knee joint under relatively higher opening stresses, it is strongly recommended to limit the design opening stresses to 60% of design closing stresses.

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