An Efficient Model for Predicting the Shear Strength of RC Knee Joint Subjected to Opening and Closing Moment

Moiz Tariq

00000-277869

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7th January, 2021

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I certify that this research work titled "*An efficient model for predicting the shear strength of RC knee joint subjected to opening and closing moment"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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Moiz Tariq
00000-277869

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by

Moiz Tariq

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Dr. Azam Khan (Assistant Professor)	Dr. Usman Hanif (Assistant Professor)	Dr. Hammad Anis (Assistant Professor)

Dr. Rao Arsalan Khushnood
(Assistant Professor & HOD Structural Engineering)

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It is certified that final copy of MS thesis written by **Mr. Moiz Tariq**, Registration No. **00000277869**, of **NUST INSTITUTE OF CIVIL ENGINEERING (NICE)** has been vetted by undersigned, found complete in all respects as per NUST Statutes/Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of MS degree in Structural Engineering.

Signature: ___________________________

Name of Supervisor: **Dr. Azam Khan**

Date: ___________________________

Signature: ___________________________

Head of Department: **Dr. Rao Arsalan Khushnood**

Date: ___________________________

Signature: ___________________________

Dean: **Dr. S. Muhammad Jamil**

Date: ___________________________

ABSTRACT

Reinforced concrete (RC) beam-column knee joints are intrinsically distinct from the traditional RC interior and exterior joints. The RC knee joint has two distinct load resistance mechanisms. Its shows different behavior at the time of reversed cyclic load for closing and opening. Given the many distinct variations in the behavior of shear strength in RC knee joints, the main design codes in the world do not provide any specific design RC knee joint. This is because there is no profound research on the knee joint. An investigation for predicting the shear capacity of reinforced concrete (RC) knee joints under opening and closing moment has been proposed in this research. Experimental data in the literature were used to test the exactness and reliability of the proposed model. The proposed model could forecast with good accuracy the experimental response of poorly defined RC knee joints under opening and closing moment. Parametric experiments have been performed to demonstrate the profound influence of different geometric and material properties on the RC knee joints. A method will render the model ideal for practical applications.

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Thursday, January 7, 2021 ***Moiz Tariq***

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LIST OF ACRONYMS

b_j	Width of joint
b_b	Width of beam
b_c	Width of column
C_{bc}	Axial compressive concrete force in beam
C_{bs}	Axial compressive steel force in beam
C_{cc}	Axial compressive concrete force in column
C_{cs}	Axial compressive steel force in column
D_j	Effective depth of column
F_{bt}	External tensile force in beam
F_{ct}	External tensile force in column
$\mathrm{F_{bc}}$	External compressive force in beam
F_{ct}	External compressive force in column
F_j	Standard value of joint shear strength
$f_c{}'$	Concrete compressive strength
f_{yb}	Yield strength of longitudinal beam reinforcement
f_{cd}	Design concrete compressive strength
f_{ck}	Characteristic cylinder concrete compressive strength
h_b	Depth of beam
h_c	Depth of column
M_b	Beam moment
M_c	Column moment
N	Sample size
p_t	Principal tensile stress
p_c	Principal compression stress
T_{sb}	Opening moment tensile force in reinforcement
T_{sb}'	Closing moment tensile force in reinforcement
V_n	Nominal shear capacity
V_u	Factored shear capacity
V_{jhd}	Horizontal joint shear
v_{jh}^{o}	Joint shear strength of knee joint under opening behavior
v_{jh}^{c}	Joint shear strength of knee joint under closing behavior
v_{jh}	Horizontal Joint shear strength
v_{jv}	Horizontal Joint shear strength
v_{jh}^{Exp}	Experimental horizontal joint shear strength
v_{jh}^{Est}	Estimated horizontal joint shear strength
v	Degree of freedom
$\overline{\mathrm{X}}$	Sample mean
α	Level of significance
γ_{RE}	Seismic bearing capacity coefficient
θ	Rotation
ϕ	Strength reduction factor
μ	Population mean
ρ_b	Longitudinal Tensile reinforcement ratio

1 INTRODUCTION

1.1 Background

Moment resisting frames are conventional in building structural systems. Researchers have striven to improve ductility building and accurate assessment of overall building capacity. It is essential to understand, evaluate, and estimated the beam-column joints to ensure a controlled failure of moment-resisting frames under earthquake excitation. To improve the ductility of the RC moment resistant frames, member flexural failure before the joint shear failure is a fundamental criterion. Work on earthquake-resistant design has seen significant progress over the last few decades, with notable work on conventional RC beam-column joints. (Interior and Exterior) [1–5]. As a result, the overall ductile efficiency of the RC building having moment-resisting frames has improved up to a great extent.

Due to the complex and unique behavior, few numbers of studies had conducted on the RC knee joints, which are seen at the roof level of moment-resisting frames. The behavior of the knee joint is different from the conventional RC knee joint in terms of force acting on the joints and the way they are resisted within the joint. In the conventional beam-column joint (Interior and Exterior), the adjacent members undergo a double bending curvature when subjected to the seismic excitations. However, in the case of the knee joint, the adjacent members do not experience moment reversals. Because of this behavior, the knee joint undergoes closing and opening instead of moment reversal. This behavior tends to produce the tensile stresses on the outer side of the joint and compressive stresses on the interior side of the joint when subjected to the closing moment and vice versa.

Different design codes (ACI 318-14 [6], EN1998-1 2004 [7], NZS 3101-2006 [8], AIJ [9], GB50010 [10]) extended the joint design provision for the exterior knee joint to the more complex knee joint. However, the behavior of the knee joint is much more complex and different from the conventional knee joint because of discontinuous joint sub assemblage, which creates an undesirable axial force in the members. Knee joint, when subjected to the seismic loading, undergo successive opening and closing action when leads to the vulnerability of shear behavior of knee joint. Therefore, the implementation of joint design provisions used for conventional interior and exterior joints on the knee joint leads to an unconservative design scenario for knee joints.

1.2 The Design Philosophy of Earthquake-Resistant Structures

To design seismic-resistant buildings economically, while meeting severe displacement requirements during earthquakes, sufficient ductility must be incorporated through the design. The ability of the structure to undergo large amplitude deformation in inelastic range without any reduction in strength is termed as ductility. Capacity design principal is used to achieve the ductility of the structure [11]. Different elements in the force-resisting system are chosen carefully, designed, and detailed for the energy dissipation under expected deformations. In the structural members, such critical regions are called as plastic hinges and are detailed for inelastic flexural behavior while inhibiting a shear failure [12].

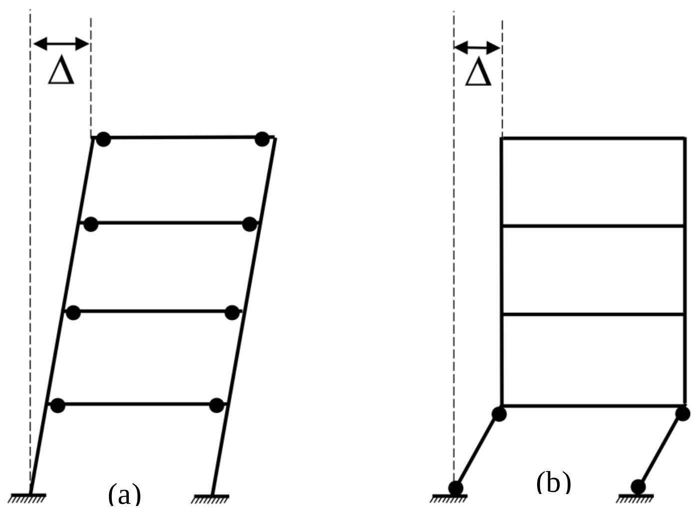

Figure 1.1: Plastic Hinge formation and building deformation

(a) Beam plastic hinge formation (b) Column plastic hinge formation

Plastic hinges are considered to form in beams and columns when subjected to the seismic action. In the column, plastic hinges can create a situation, as shown in Figure 1.1. Plastic hinges in the beam can cause the structure to sway.

1.2.1 Design Criteria for Beam-Column Joints

In the RC structure, beam-column joints are the most vulnerable sections when subjected to seismic forces. The joint region experiences a higher shear force than the adjacent beam and column due to the moment reversal. According to the capacity design principle, the RC joints need to be designed to prevent shear and brittle failure in the joint region.

RC joints are considered as the source of unsuitable source of energy dissipation because it exhibits poor hysteretic properties both in shear and bond mechanisms in RC joint. Congestion of the reinforcement in the joint region is more likely to occur if the joint is design to withstand high shear stresses, which lead to the results of brittle failure. The sheer design of joint, including substantial column weak beam design, is adopted for preventing joint failures while addressing the issue of reinforcement congestion in the RC knee joint.

1.3 Types of RC Beam-Column Joints

Beam and column in the RC structure are connected through joints. The design of the RC structure is generally carried out, assuming that the joints are rigid. In reality, the RC joints are not rigid. High-stress concentration has been observed in the joint region when the RC structure is subjected to seismic forces. Based on the number of the member connected to the RC joint, they are classified into different types, as shown in Figure 1.2.

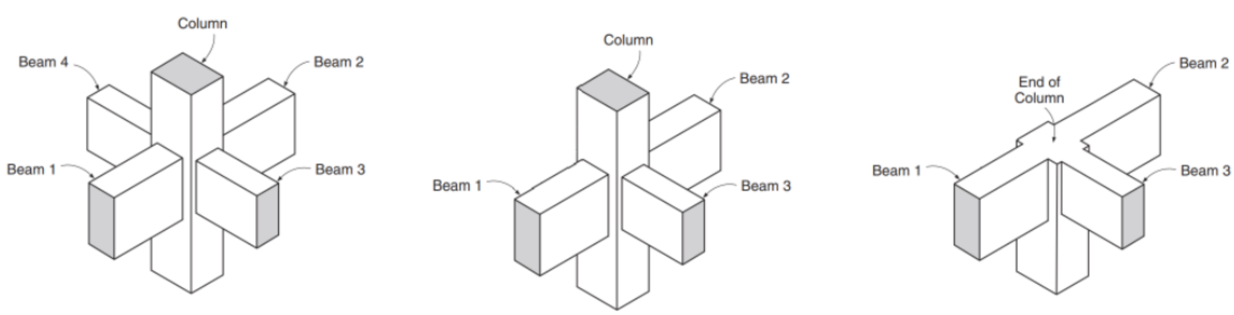

Figure 1.2: Types of RC Joints (a) Interior Joint (b) Exterior Joint (c) Corner Joint

The interior joint is located within the structure of the building. A total number of 6 RC elements are connected to the interior joint. Generally, the joints are constructed to resist different types of force from the adjacent beam and column members. Fig 1.3 shows different types of forces acting on the anterior joint.

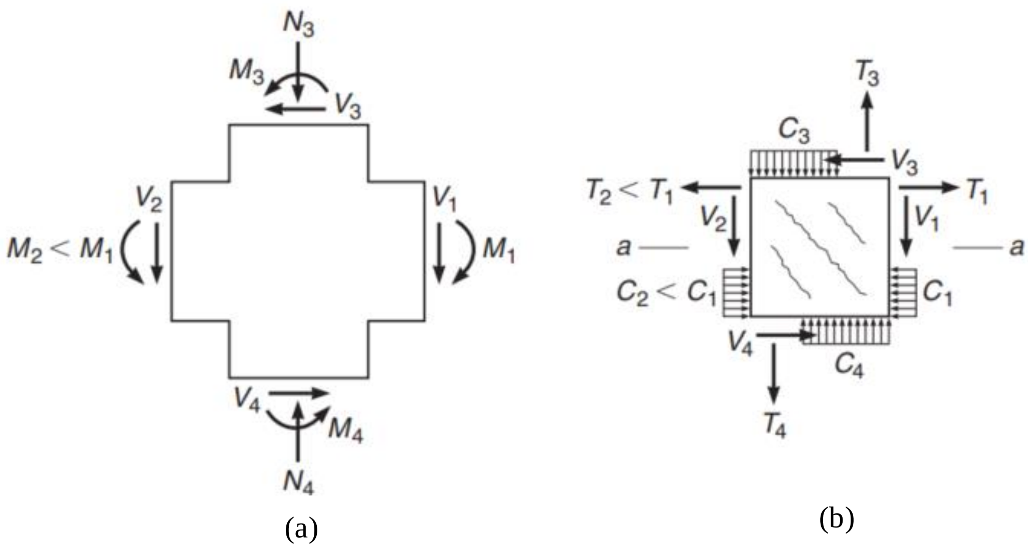

Figure 1.3: Forces acting on the interior joint under gravity load (a) External Forces (b) Internal Forces

Exterior joints are generally at the external façade of the building. Such joints are generally known as T-joints. Five adjacent elements are connected to the exterior joint. The forces on the exterior joints are shown in Fig. 1.4

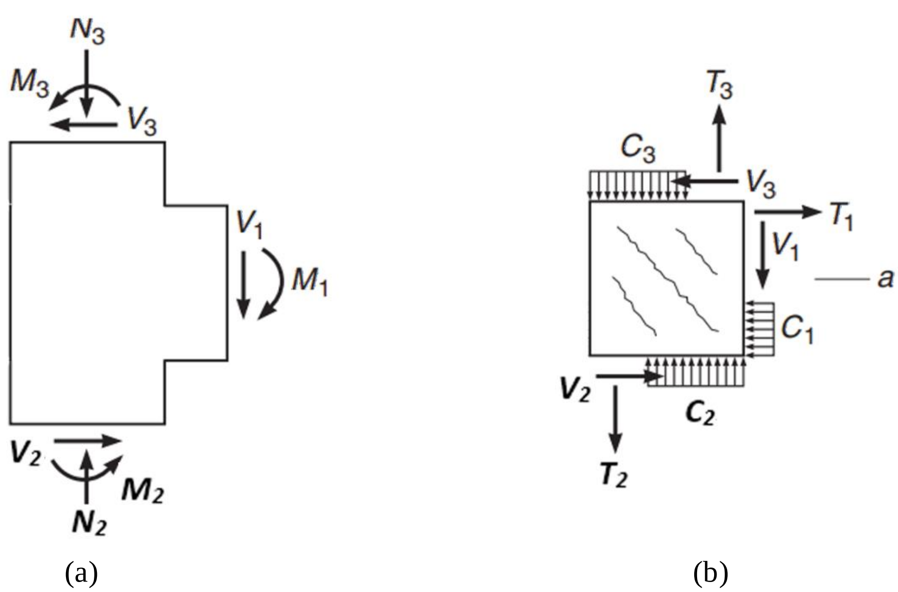

Figure 1.4: RC Exterior Joint (a) External Forces (b) Internal Forces

The RC knee joint is a corner joint, usually found at the top story of the multistory building. At this corner, the termination of both beams and columns occur. A total number of 4 elements are connected to this joint. The behavior s of these joints are relatively different from the other joints, especially when subjected to cyclic loadings such as opening moment and closing moment. Because of less confinement as compared to the interior and exterior joints, their joints are more vulnerable to failure when subjected to seismic loadings.

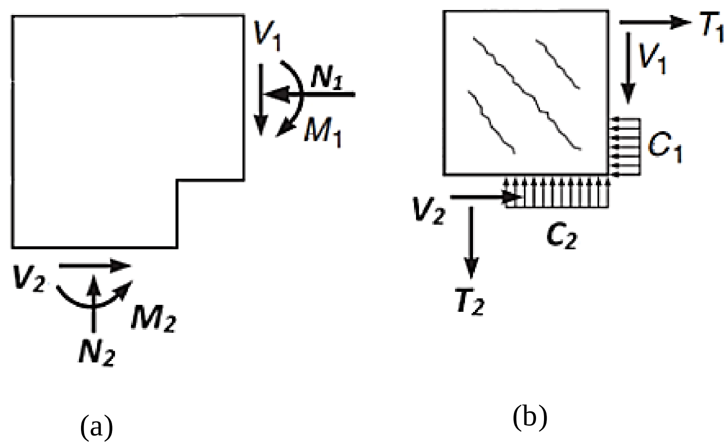

Figure 1.5: Reinforced Concrete knee joint.

1.4 Problem Statement

It has been observed that many design codes across the world (ACI 318-14[6], EN1998-1 2004[7], NZS 3101-2006[8], AIJ[9] ,GB50010[10]) have not captured the behavior of the knee joint. These codes don't provide any particular kind of design provisions for the knee joint. The empirical equation provided by these codes to estimate the shear strength under seismic loads overestimate the capacity of the knee joint.

1.5 Research Significance

Pakistan, unfortunately, is surrounded by active seismic plates. After the 8th October-2005 earthquake, a significant number of casualties and injuries in the affected region were associated with the complete failure of RC buildings. Among different features of construction that appear to be responsible for the widespread collapse of buildings, one of them was a weak connection RC joint. To address this problem, this research will provide significant scientific knowledge and ground to cover those gaps in the current building codes of Pakistan. This research will fill the loopholes and gaps in the field of RC beam-column joints. This study can also be applied in the practical field under seismic load and make it more feasible for the inhabitants of that building. The influence of this research on design practice is very significant as it permits the non-collapse and operational design of the moment-resisting frame system.

1.6 Research Objectives

A systematic study on knee joint has been carried out in this research, which will address the research gaps and also enhance the understanding of knee joint under cyclic loading. The main objectives of this study are as follows:

1. To study the behavior of the knee joint under seismic loading.
2. To study the complete force transfer mechanisms of the knee joint when subjected to the cyclic loading.
3. To propose an efficient model for estimating the shear strength of the knee joint under reversed cyclic loading.
4. Validating proposed empirical model with experimental data.
5. Comparison of proposed prediction model with previously proposed models.

2 REVIEW OF LITERATURE

During the design phase of structure, it is assumed that RC joints are considered as rigid elements. However, this assumption is inappropriate when the structure experiences extreme massive moment and shear, subjected to cyclic loading, i.e., earthquake loading or wind loading.

The response of a structure when subjected to reversed cyclic loading, the amount of energy dissipated for the structural elements can be assured form the flexural yielding and ductility of the structural component. The behavior of the knee joint under the lateral loading is very complicated as compared to the other RC joint.

2.1 Experimental Studies on RC Joints

In the mid-1960s, to understand better behavior of the RC knee joint, experimental programs based on monotonic loading started. The main focus on these studies will mainly focused on the studying of the shear capacity and identifying effective reinforcement detailing under static load. A review on the monotonic studies on knee joint is presented in this section.

Kemp and Mukherjee [13] tested four portal frames and L shaped specimens to find the strength and rotational capacity of the tensile longitudinal reinforcement with having variation. The test results indicate that, the lower tensile reinforcement (0.49%), the member failed in the flexure revealing the ductile nature. While on the other hand the members with high tensile reinforcement will failed suddenly due to the formation of the diagonal crack before the plastic hinge form in the adjacent member. The author concludes that there are three types of failure to control the strength of the joint namely, tensile, flexural and shear which are dependent on the amount of the tensile reinforcement.

Mayfield et.al [14] tested 12 specimen under monotonic closing and opening loading, having variation in the joint shear reinforcement. The author observed an efficient behavior of joint under higher closing moment for all the joints, as compared to the opening moment. From the experiments, the author has concluded that the joint having joint stirrup arrangement of 6,7,8 and 11 perform reasonably well under opening moment.

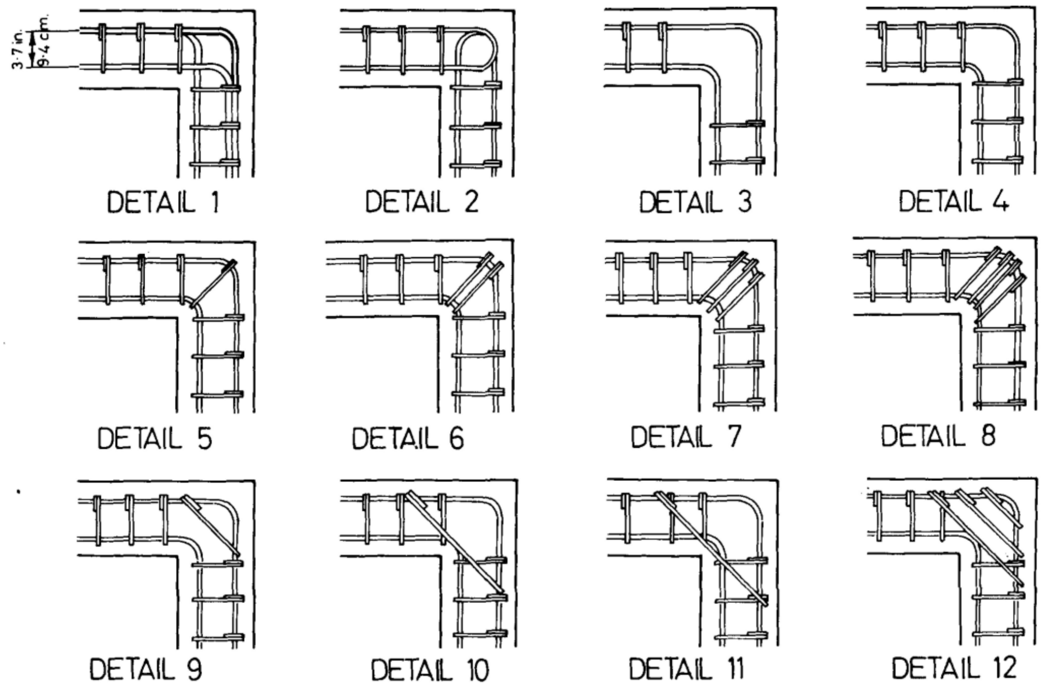

Figure 2.1: Detailing of Specimens (Mayfield et al.1971)

Mayfield et al. [15] proceed his research work and performed experiment on 54 knee joints under monotonic opening moment to understand the opening behavior having 28 different detailing. The author concludes that the joint stirrups having reinforcement details (1 through 8) and joint 6 with 180^{o} anchorage show reasonable ductility and efficiency under opening moment.

Moreover, type 1 detailing, which is analogous to the type 10 detailing, shows improved joint efficiency by resisting the development of the tension in longitudinal reinforcement. Type 2 detailing similar to the type 4 detailing, control the growth of the crack originating at the re-entrant corner under opening behavior . On the other hand, the efficiency of Type 2 joint was negligible on the overall efficiency of joint. The detailing according to Type 26 shows the best results as shown in Fig (2.2).

Nilsson and Losberg [16] have done a wide range of experiments on the RC knee joint under monotonic opening moments. The main purpose of there research was to identify different modes of failure: diagonal tension failure, splitting failure, failure due to yielding, anchorage failure and due to crushing of concrete. It has been found that the stirrup type of the detailing enhance the ductility and efficiency of the joint up to 79%. However, the adoption of such detailing makes the concrete difficult to cast during construction process. The author recommends the use of detailing with the loops of longitudinal reinforcement, that enhance the efficiency up to 77%.

Skettrup et al. [17] performed three test on the RC knee joint subjected to the opening moment. The author concluded that the capacity of the joints decreases with respect to flexural members as you increase the tensile reinforcement in the flexural member. The complex arrangement of the stirrup in the joint show some good efficiency of the joint, but providing such arrangement make congestion and interrupt the flow of concrete in the RC joint.

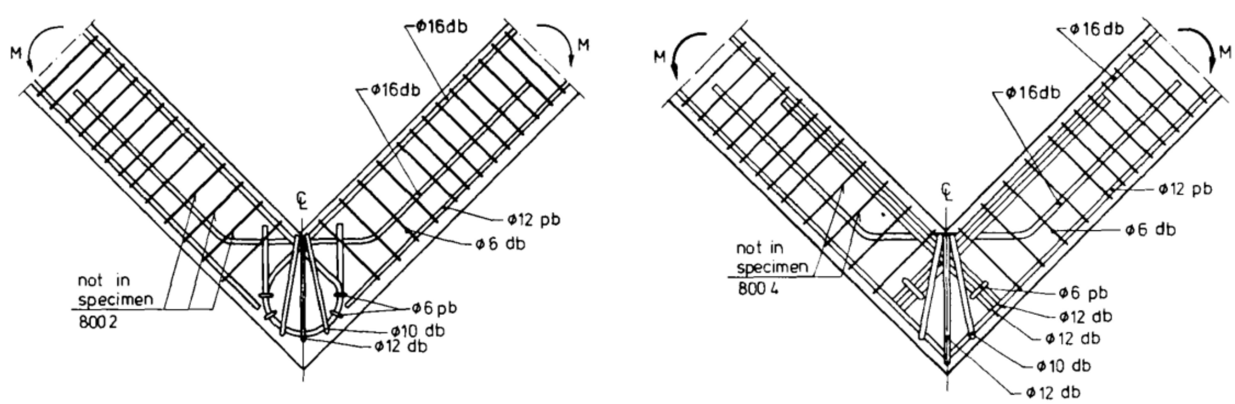

Figure 2.2: Detailing of specimens (Skettrup et al.1984)

Leo et al. [18] conducted twenty-seven full-scale RC knee joints subjected to monotonic closing moment to study the impact of the detailing of reinforcement on the strength and ductility of the joint. The author observed that simple splicing of column bars as shown in Fig 2.3(a) was inadequate to allow the adjacent members to reach its full flexural capacity. The author found that the splicing within the joint as shown in

Fig 2.3(d) will show good performance and efficiency and allow the adjacent member to achieve its full flexural capacity.

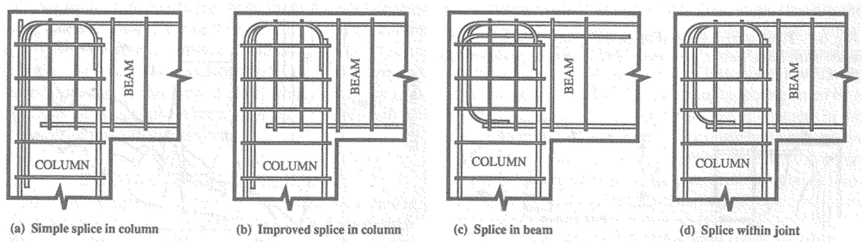

Figure 2.3: Detailing of RC knee joint test by (Leo et al. 1994)

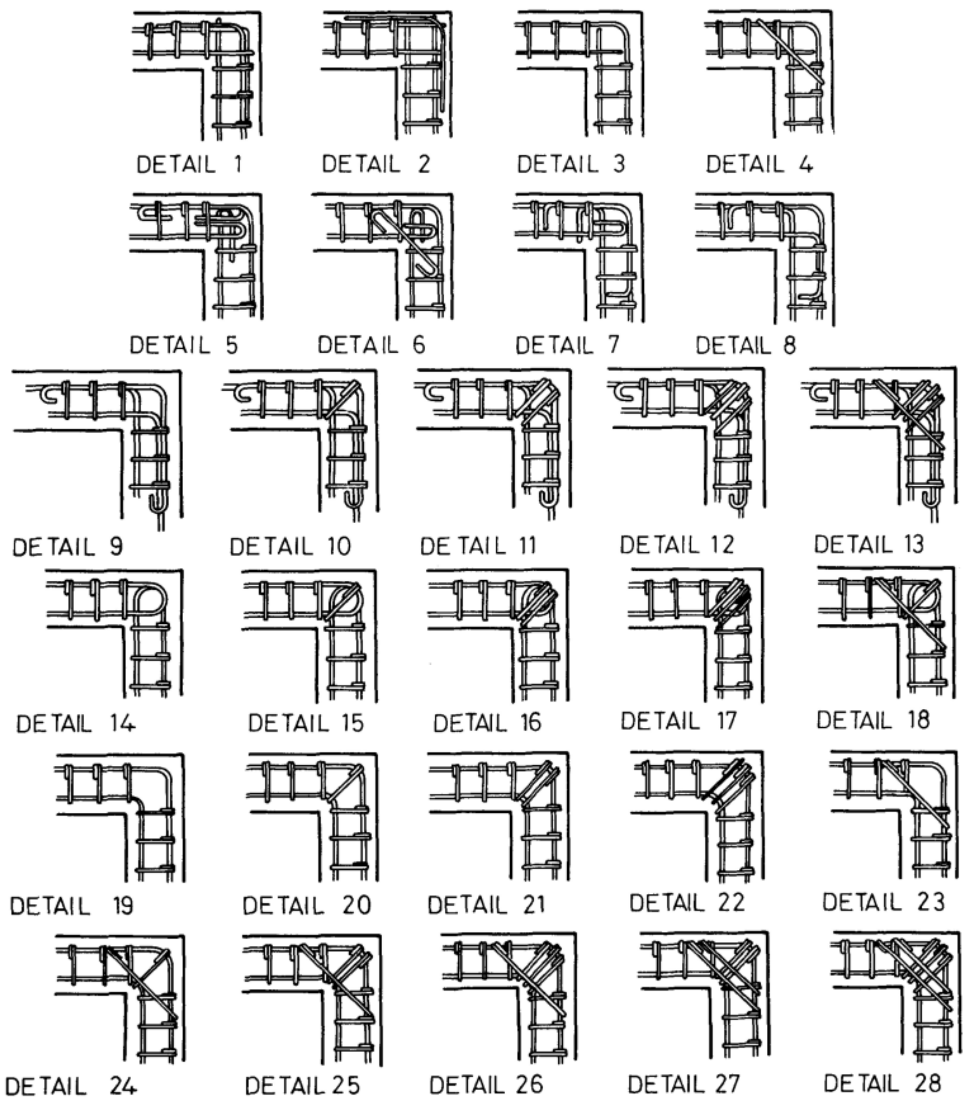

Figure 2.4: Detailing of Specimen Mayfield et al. (1972)

Jackson [19] performed an experiment on 5 RC knee joint specimens having intersecting longitudinal bars in U-shaped without any stirrup. The main aim of study was to see the impact of the tensile reinforcement and the anchorage steel on knee joint. It was found that the U-shaped found confinement in the joint but marginally enhance the ductility of the RC joint.

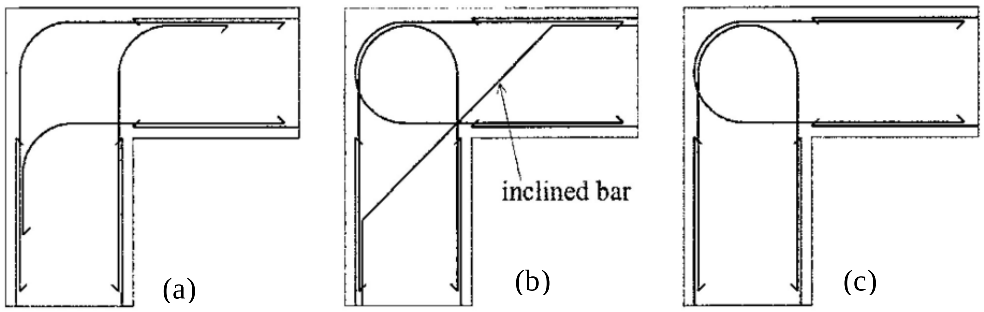

Figure 2.5: Detailing of Specimen (Johansson 2001)

Johansson conducted an experimental and literature study of longitudinal reinforcement detailing on knee joint under monotonic closing and opening moments. Total number of eleven specimen, three under monotonic opening moment and eight under monotonic closing moment, respectively. It has been observed that extensive spalling of concrete of joint when subjected to the closing moment. Also, the impact of the inclined bars have very small effect on the strength of the knee joint and were not much effective in improving the efficiency under opening moment. However, the effect of inclined bar is determine when subjected to closing moment.

2.2 Analytical Studies on RC joints

Paulay and Priestley [12] suggested the idea of the strut and tie mechanism. This strut and tie model is famous for predicting the behavior of RC joints. The internal forces generated in the concrete combine to form a diagonal strut while the forces are transferred through a steel reinforcement bar through bonds and make truss mechanisms.

Vollum [20] found that the strut-and-tie model is ideal for capturing the behavior of the stress state of the RC knee joint. The beam-column exterior joints were modelled. The joint was considered a failure; the diagonal stress reached the cracking strength of concrete. Due to inherent complexities associated like prejudgment of the stress field, this model has some limitations in its applicability.

Ortiz [21] used the mechanisms of Strut-and-tie to estimate the shear strength of the RC joint with and without transfer reinforcement. The joint proposed by Ortiz [21] is shown in figure 2.1.

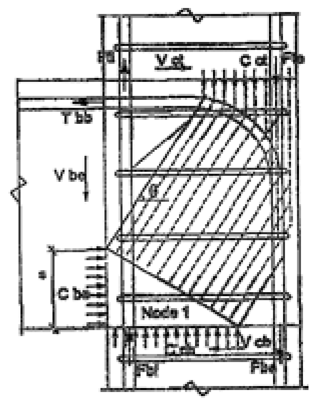

Figure 2.6: RC beam-column joint as considered by Ortiz (1993)

The plane section remains plane adjacent to the joint block is used to calculate the boundary forces. To evaluate the strength of the diagonal strut, a semi-empirical approach was adopted by Ortiz. The design strength of concrete was considered as proposed by the CEB model (1990).

Parker and Bullman [22] proposed a model to predict the shear strength of the RC joint. The shear force in the joint was assumed to be resisted by an inclined compression field or strut in the concrete. Based on the principle of minimum potential energy, the inclination and dimensions of the strut were determined. The model proposed by Parker and Bullman [22] is shown in figure

Hwang et al. [23] estimated the joint shear strength using the model named "softened strut and tie model." This model was considering the equilibrium, compatibility, and constitutive laws to estimate the cracked reinforced concrete. The joint shear resisting mechanisms, according to this model, was composed of:

1. The diagonal strut mechanism
2. The horizontal mechanism
3. The vertical mechanism

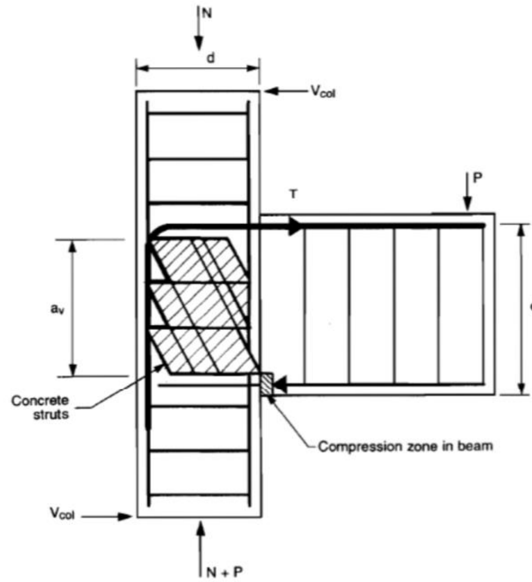

Figure 2.7: Parker and Bullman (1997) model for beam-column

The equilibrium of this model is satisfied by equating all the horizontal compressional force component that is transferring from the concrete diagonal strut, tension force in the horizontal stirrup and horizontal component of the vertical ties to the joint horizontal shear. However, the concrete model adopted in this was a softening concrete model proposed by Belarbi et al. [24]. The average strain in the joint panel was considered as a condition for the strain compatibility. As in this model, horizontal and vertical strain in unreinforced joints is assumed, this model is not able to predict the joint shear failure without beam reinforcement yielding. This model still considers as beneficial because it takes into account the axial load on the joint.

2.3 Average Plane Stress Plane Strain-Based Models

Pantazopoulou and Bonacci [25] assume that the joint is well confined, and using the average stress and strain values developed a model to estimate the shear strength of the RC joint. It was observed that the column shear stress, as well as principal tensile strain, increases with the increase in the column axial load. This behavior leads to a decrease in the compressive strength of the diagonal strut. This study achieves the effect of the axial column load on the joint shear strength.

Wong [26] proposed the Modified Rotating-Angle Softened-Truss Model to predict the shear strength of exterior joints. Based on the compatibility equation by modifying

1. Modified compression field theory
2. Softened truss model rotating-angle
3. Softened truss model fixed-angle

In deep beams, a shear span to depth ratio was taken to take the effect of the joint aspect ratio. A large number of numerical iterations was required to find the shear strength of the RC knee joint.

Tsonos [27] presented a relatively new formulation based on the assumption that vertical and horizontal joint shear forces are equal to vertical and horizontal force acting on the joint. Based on this assumption, strut-and-tie mechanisms were proposed. The biaxial concrete strength curve was assumed and represented by a fifth-order polynomial equation. This model also takes into account the confined concrete strength by considering the model proposed by Scott et al. [28]. This model generally gives a perfect comparison with the experimental database having joint shear reinforcement. However, in the case of an unreinforced joint, it sometimes over predicts the shear strength up to 15-17%.

Priestley [29] suggested a principal tensile stress model assesses the shear strength of beam-column joints without joint reinforcement, which will be compared with the joint average principal tensile stresses. It is also compared with some critical values that represent the diagonal shear failure and cracking. The critical values suggested by Priestley [29] considering only the concrete strength is $0.29(f_c')^{0.5}$ and $0.42(f_c')^{0.5}$ for maximum shear strength of the exterior joint. The model estimates the joint shear strength with good approximation and also takes into account the axial load on the joint. However, sometimes it is argued that, because the diagonal compressive strut carries more joint shear, the principal tensile stress approach is considered to be on the conservative side. Some literature recommends that the principal tensile stress approach gives good approximation when the axial load on the structure of the column is less the 30%.

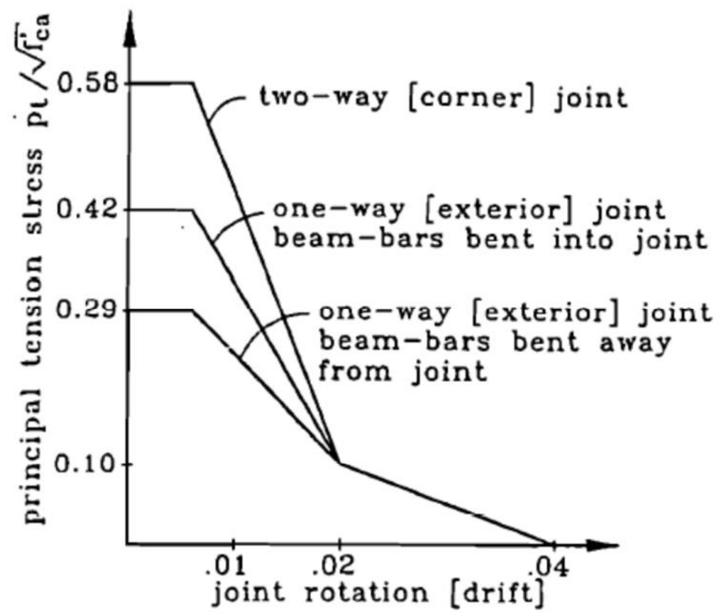

Figure 2.8: Principal tensile stress values proposed by Priestley (1997)

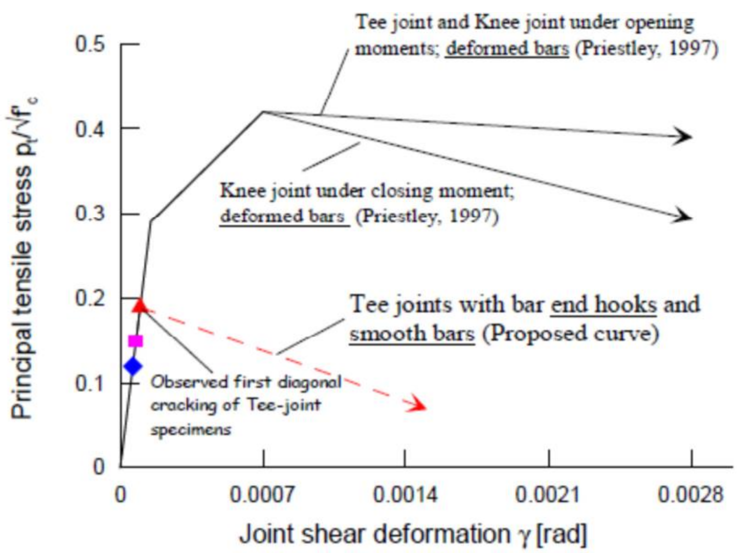

Figure 2.9: Principal tensile stress vs joint shear deformation relationship (Priestley 1997)

Genesio [30] proposed the recommendation for the critical values of principal tensile stress and corresponding joint shear deformation based on experiments. The joint aspect ratio, beam longitudinal reinforcement ratio, and axial load on the column were generally considered during formulation. The detailed 3D finite element analysis approach using the micro-plane model with relaxed kinematic constraint as constitutive law was used. The bond between solid concrete elements and steel elements was idealized by taking the solid concrete elements and bar elements, respectively.

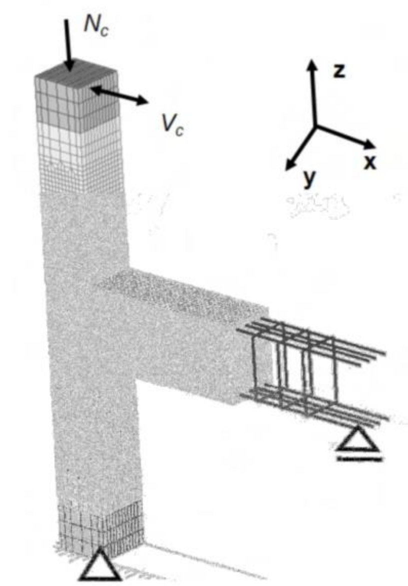

Figure 2.10: FE model of beam-column joint proposed by Genesio

According to Genesio [30], strength corresponding to first diagonal cracking and maximum joint strength can be found using equations below:

First diagonal cracking

$$\frac{p_t}{\sqrt{f_c'}} = k_o + k_1\left(2 - \frac{h_b}{h_c}\right) \quad (2.1)$$

Ultimate Strength

$$\frac{p_t}{\sqrt{f_c'}} = k_o + k_1\left(2 - \frac{h_b}{h_c}\right) + k_2\frac{(n_{c,o} - n_c)}{100}\rho_b,\ for\ n_c \leq n_{c,o} \quad (2.2)$$

$$\frac{p_t}{\sqrt{f_c'}} = k_o + k_1\left(2 - \frac{h_b}{h_c}\right),\ for\ n_c \geq n_{c,o} \quad (2.3)$$

Where k_o and k_1 are empirical non-dimensional coefficients that are dependent on the joint detailing, joint aspect ratio, and axial load on the column. $n_{c,o}$ represents the upper limit value of the axial load and $\rho_{b,}$ are beam longitudinal reinforcement ratio.

2.4 Seismic Analysis of the Buildings

The seismic analysis of the structure is divided into four analytical procedures based on the complexity of the Analysis: Linear Static, Linear Dynamic, Nonlinear Static, and Nonlinear Dynamic.

In 1987, the report published by Applied Technology Council (ATC) [31] titled as evaluation of the seismic resistance of the existing buildings, ATC-14 [31], which provide guidelines for all types of building material and construction. The first step in this process was the selection of the building based on their construction type. For each building, the set of evaluation statements are defined that are appropriate for them. A more detailed analysis is required if the structure does not meet the defined criteria. The capacities of the structural material were mainly evaluated using building codes. However, the equivalent lateral force procedure is used to calculate the demands.

It is observed that the guidelines and procedures proposed by the ATC-14 [31] and FEMA-178 [32] were based on the conventional linear elastic method. The elastic analysis is somewhat useful as it gives an indication of the structural capacity. Besides this, it also gives information regarding the first yielding of the member, but this analysis is unable to predict the redistribution of forces and failure mechanisms. To overcome this issue, a non-linear analysis is better to understand the behavior of the structure that is subjected to different types of cyclic loading.

A report Seismic Evaluation and retrofit of concrete buildings was published by ATC back in 1996. A simplified non-linear static analysis was described in this report. A better understanding of building performance can be observed because of the mutual dependency of capacity and demand. Using this procedure, the designer can judge and experience the knowledge of a more refined level than the conventional procedure.

From the above discussion, it is concluded that inelastic analysis considers all those parameters that influence the global performance of the structure. Taking into account the effect of a structural component, non-structural elements, and other factors that show the failure modes and progressive failure of the building. The non-linear dynamic analysis is always a big task to perform, which needs more resources. To overcome this issue, a non-linear static procedure is followed, which captured a reasonable behavior of the structure under cyclic loading.

2.5 Existing Seismic Design Codes Provisions

Different seismic design codes have incorporated the design of different types of beam-column joints. This section summarizes the joint design provisions provided by four major seismic codes, i.e., American code (ACI Committee 318-14) [6], Eurocode (BS EN 1998-1 2004) [7] , New Zealand code (NZS 3101 2006) [8], Architectural Institute of Japan [9], Chinese code (Chinese Standard GB50011 2010) [10].

ACI (318-14) [6] has divided RC joints into two types of categories. Type 1 connections are meant to design without taking into account the effect of inelastic deformation. Type 2 connections are designed, which incorporate the deformation of joint under cyclic load. The design shear force and nominal shear strength models provided by ACI (318-14) [6] are further discussed below:

ACI (318-14) [6] and ACI (352R-02) [33] both calculate the shear input by considering the flexural hinges in the adjacent members. Shear forces are considered to transfer into the joint through reinforcement which is equal to αf_y. α represents the stress multiplier and f_y is the yield stress of the reinforcement steel. The value of α given by guidelines is 1.0 for Type-1 and 1.25 for Type-2.

The design shear force in the RC joint is computed at the center of the joint. The shear force is considered at the boundaries of the joint. For design purpose, the following equation should be satisfied

$$\phi V_n \geq V_u \tag{2.4}$$

Where, V_n, V_u represents the nominal and ultimate shear strength, respectively. The value of ϕ, according to ACI, is 0.85.

$$V_n = \gamma\sqrt{f_c'(psi)}b_j h_c \tag{2.5}$$

$$V_n = 0.083\sqrt{f_c'(MPa)}b_j h_c \tag{2.6}$$

$$b_j = minimum\left\{\frac{b_b+b_c}{2}, b_b + \sum\frac{mh_c}{2}, b_c\ \right\} \tag{2.7}$$

Where, $b_j, h_c, b_b, b_c, \gamma$ represents the effective joint breath, depth of column, a width of the adjacent beam, width of the column, and shear strength factor shown in Table 2.1. ACI 318-14 [6] restricts that the depth of the column should not be less that one half of the depth of the adjacent beam connected with the joint. It should be remembered that the value of γ for Type 1 joint is given in 318-14 [6], and for Type 2, the value of γ is given in ACI 352R-02 [33].

Table 2.1: ACI 352R-02 recommendation for shear strength factor

Classification	Type -1	Type-2
A. Joints with a continuous column		
A.1. Joints confined on four vertical faces	24	20
A.2. Joints confined only on three vertical faces	20	15
A.3. Other cases	15	12
B. Joints with a discontinuous column		
B.1. Joints confined on four vertical faces	20	15
B.2. Joints confined only on three vertical faces	15	12
B.3. Other cases	12	8

The influencing factor of eccentricity is considered through the modification factor m. The value of m is equal to 0.3 for the joints whose eccentricity exceeds $\frac{b_c}{8}$.

ACI 352R-02 [33], recommends that the summation of the nominal flexural strength of the column component is 1.2 times the beam component, to avoid the development of the plastic hinges. This condition applies to the Type 2 connections. RC connections at the roof level this verification is not applicable. Therefore, the conventional design theory of strong-column weak-beam criterion is not applicable.

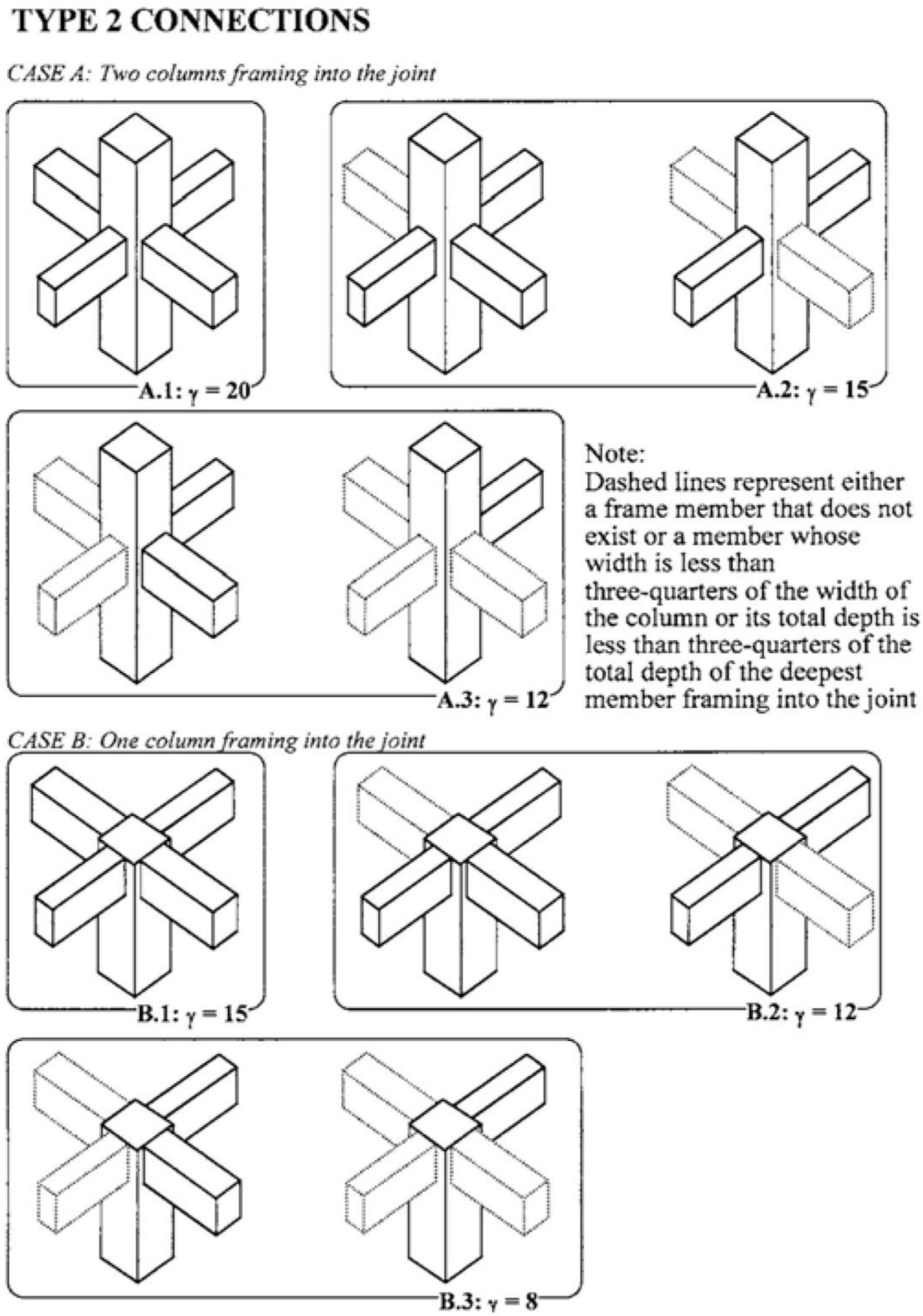

Figure 2.11: ACI 352R-02 recommended values for γ

NZS 3101:2006 [8] Concrete structure standard proposed that 70% of beam top and bottom column reinforcement should pass and anchored in the column when the RC joint experienced shear when subjected to gravity or earthquake load. In NZS 3101:2006 [8], the design recommendations for the exterior joint are extended for the knee and corner joint because there are no particular guidelines for the design of the knee joint. Therefore, the guidelines recommended for the exterior joint will be discussed below.

For the seismic loads, calculate the shear force of the RC joint when it is expected that the plastic hinge will be created in the adjacent structural components of the RC joint, assuming that reinforcement of the member will yield. The horizontal joint shear recommended equation by NZS 3101-06 [8], to avoid the concrete crushing is

$$V_{jh} \leq 0.20 f_c' b_j h_c \ \ or \ 10 b_j h_c \tag{2.8}$$

Effective joint shear width of recommended by the code is

$$if \ b_c \geq b_w : b_j = minimum\{b_c, b_w + 0.5h_c\} \tag{2.9}$$

$$if \ b_c < b_w : b_j = minimum\{b_w, b_c + 0.5h_c\} \tag{2.10}$$

However, In RC joint the shear is resisted by both the concrete strut and joint transverse truss mechanism. So, the sum of two horizontal shear transfer mechanisms is considered the following equation.

$$V_{jh} = V_{ch} + V_{sh} = V_{ch} + A_{jh} f_{yh} \tag{2.11}$$

Where, V_{ch}, V_{sh} represent shear force transferred contributed by concrete strut and joint transverse shear reinforcement.

If V_{jh} is the nominal shear strength of the joint, ϕ is the safety factor and $V_{jh(d)}$ is designed horizontal shear force, then the equation for the design of joint horizontal shear is:

$$V_{jh(d)} = \phi V_{jh} \tag{2.12}$$

Eurocode 8 (2004) [7] proposed the guidelines for the RC joint of the structure corresponding to Ductility High Class. Like NZS 3101 [8], the Eurocode 8 [7] is also unable to provide proper provision for RC knee joint. That why we will extend the recommendation and provision of the exterior joint on the knee joint. The design provision of Eurocode for the exterior joint is presented here.

Eurocode 8 [7] suggest that the worst scenario of the seismic action should be considered during the estimation of the horizontal joint shear. The formation of the plastic hinge in the adjacent beam members for the conventional joint (interior and exterior) is

$$V_{jhd} = \gamma_{Rd}(A_{s1} + A_{s2})f_{yd} - V_c \quad (2.13)$$

$$V_{jhd} = \gamma_{Rd}A_{s1}f_{yd} - V_c \quad (2.14)$$

Where A_{s1} and A_{s2} represents the reinforcement of the beam in the top and bottom position. V_c and γ_{Rd} is the overstrength factor which should not be less than 1.2.

$$V_{jhd} \leq \lambda\eta f_{cd}\sqrt{1 - \frac{v_d}{\eta}}\, b_j h_{jc} \quad (2.15)$$

Where V_{jhd} is the design shear force in the horizontal direction. The value of λ is 1.0 for the interior joint and 0.8 for the exterior joint. The distance between the extreme layer of the column reinforcement is represented as h_{jc}.

$$\eta = 0.6\left(1 - \frac{f_{ck}}{250}\right)(MPa) \quad (2.16)$$

Where, f_{ck} and f_{cd} shows the compressive cylinder test and compressive design strength of concrete. The recommendations, according to Eurocode guidelines for the selection of joint breath is shown in Eq 2.17 and 2.18:

$$if\ b_c \geq b_w : b_j = minimum\{b_c, b_w + 0.5h_c\} \quad (2.17)$$

$$if\ b_c < b_w : b_j = minimum\{b_w, b_c + 0.5h_c\} \quad (2.18)$$

Where, b_c b_w are the column and beam width respectively and h_c represent the depth of the column.

Chinese Code GB50011 [10] cannot propose any particular type of provisions and guidelines to estimate and design joint shear stress. One of the significant drawbacks of this code is, it cannot differentiate between various types of RC joints, based on their geometry and behavior. Therefore, for exterior and knee joints, this code cannot provide any particular type of provisions.

$$V_j = \frac{\eta_{jb}\Sigma M_b}{h_{b0}-\alpha's}\left(1-\frac{h_{b0}-\alpha_{s'}}{H_c-h_b}\right) \quad (2.19)$$

Where h_{b0} represents the beam cross-section effective depth. The distance between the below and above the inflection point is denoted with H_c. The depth of the beam is represented by h_b. In the equation (), the η_{jb} denotes the coefficient for the strong connection, which is allotted based on seismic grades. The value of η_{jb} for seismic grade one, two, and three are 1.5,1.35 and 1.2, respectively. The simplified form of equation (2.19), considering that the lever arm of the moment $h_{b0} - \alpha_s{'}$ and $\eta_{jb} = 1.5$, the equation becomes.

$$V_j = 1.5(f_y A_s - V_c) \quad (2.20)$$

Where V_c Denotes the shear force in the column member. A_s Represents the area of reinforcement in the beam. The shear capacity of the RC joint is determined as

$$V_n = \frac{1}{\gamma_{RE}}\left(0.1\eta_j f_t b_j h_c + 0.05\eta_j N\frac{b_j}{b_c} + f_{yv}A_{svj}\frac{h_{b0}-\alpha_s}{s}\right) \leq 0.3\eta f_c' b_j h_c \quad (2.21)$$

Where b_c and b_b are the width of the column and beam. h_c represents the depth of the column section. A_{svj} denotes the area of steel in the joint. $s\ and\ b_j$ represents the spacing between the stirrup and joint width. The effective joint width is given as:

$$if\ b_c = b_j\ when\ b_b > 0.5b_c \quad (2.22)$$

$$if\ b_j = b_b : 0.5h_c\ when\ b_b > 0.5b_c \quad (2.23)$$

The eccentricity is limited to one-quarter of the column width between the centerline of the beam and column members. For the eccentricity, the effective width of the joint b_j is given by

$$b_j = 0.5(b_b + b_c) + 0.25h_c - e \quad (2.24)$$

2.6 Joint Shear Reinforcement

ACI 318-14 [6] and ACI 352R-02 [33] recommend the provision of the joint shear reinforcement regardless of the magnitude of induced shear force value. ACI believes that the provision of the shear reinforcement will enhance the shear resisting performance of the concrete joint by providing the shear reinforcement. The extension of the column shear reinforcement in the RC joint. This provision applies to the Type 1 connections. Two layers of shear reinforcement should be provided having pitch not exceeding 6 inches between the top and bottom beam reinforcement. The volumetric ratio of the shear reinforcement is given as

$$\rho_s = 0.45\left(\frac{A_g}{A_c} - 1\right)\frac{f_c{'}}{f_{yh}} \tag{2.25}$$

Where A_g and A_c represents the gross column and joint core area, respectively. $f_c{'}$ and f_{yh} is the concrete compressive stress and yield strength of shear reinforcement.

RC joints with a discontinuous horizontal face at the end of the column, two layers of vertical transverse shear reinforcement shall be provided—U-shaped stirrups with 135° hooks along with enough length of legs to provide maximum tension development.

The amount of volumetric transverse reinforcement ratio for the spiral and rectangular hoop is given below in equation (2.26), (2.2.27)

$$\rho_s = 0.12\frac{f_c{'}}{f_{yh}}\ but \geq 0.45\left(\frac{A_g}{A_c} - 1\right)\frac{f_c{'}}{f_{yh}} \tag{2.26}$$

$$\rho_s = \frac{A_{sh}}{s b_c"} = 0.3\left(\frac{A_g}{A_c} - 1\right)\frac{f_c{'}}{f_{yh}}\ but\ \geq 0.09\ \frac{f_c{'}}{f_{yh}} \tag{2.27}$$

Where A_{sh} defines the total area of transverse joint reinforcement legs having joint core dimensions b_c". s represents the spacing of the transverse reinforcement. For delayed deterioration the closed hoop and single-leg cross ties having hook angle of 135° and leg length of $6d_b$ is provided.

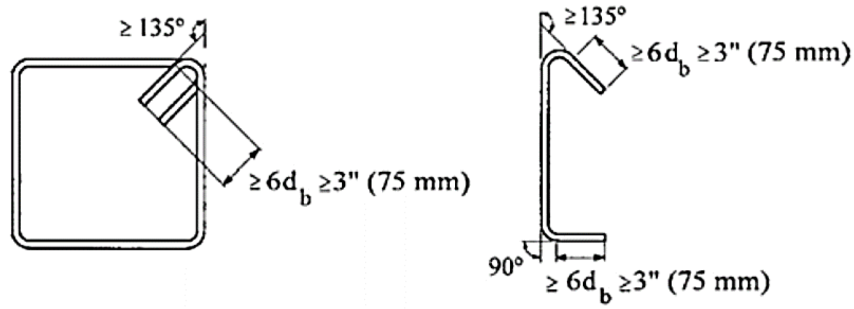

Figure 2.12: ACI 352R-02 recommendation for transverse reinforcement

The shear strengthening in the joint is based on preventing premature bond failure and efficient control of a tension failure plane extending from one corner of the joint to the diagonally opposite edge. Eq 2.28 represents the total area of horizontal transverse reinforcement corresponding to horizontal joint shear force.

$$A_{jh} = \frac{V_{jhd} - \phi V_{ch}}{\phi f_{yh}} \ where\ \phi V_{ch} = V_{jhd}\left(0.5 + \frac{C_j N^*}{A_g f_{c'}}\right) \tag{2.28}$$

In this code, it is believed that the shear resistance is directly provided through the truss mechanisms. The contribution of the concrete strut is subtracted from the design shear force to estimate the joint shear reinforcement. It is evident that concrete strut contribution equal to half of the total shear resistance is given by equation Eq 2.29.

$$A_{jh} = \frac{V_{jhd}\frac{h_b}{h_c} - \phi V_{ch}}{\phi f_{yh}} where\ \phi V_{ch} = 0.6 V_{jhd}\frac{h_b}{h_c} + C_j N^* \tag{2.29}$$

For horizontal joint shear of the exterior joint, the amount of total joint shear reinforcement area is given by Eq 2.30

$$A_{jh} = \frac{6V_{jh}^*}{f_c' b_j h_c}\left(\frac{\beta f_y A_s}{f_{yh}}\right)\left(0.7 - \frac{C_j N_o^*}{f_c' A_g}\right) \ where\ 0.85 \leq \left[\frac{6V_{jh}^*}{f_c' b_j h_c}\right] \leq 1.20 \tag{2.30}$$

Where β represents the ratio of the compressional beam reinforcement area to the tension beam reinforcement area, the value of the β should not be taken greater than 1. The axial tension is taken negatively and is represented as $C_j = \frac{V_{jh}}{V_{jh}+V_{jz}} = 1.0$. According to this code, in joint, at least 40% of shear should be carried by the shear reinforcement.

The effective reinforcement in the horizontal direction should be uniformly distributed between the beam top and bottom reinforcement. The spacing of the hoop and ties in the vertical spacing shall is limited to either ten times the diameter of the bar or 200mm, whichever is less.

Follow the concept of strong column weak beam; the vertical joint reinforcement should be provided according to Eq 2.31, so that the plastic hinge should be created in the beam. The joint vertical reinforcement to transfer the tensile reinforcement of the can be intermediate longitudinal bars of the column, vertical ties of column, and anchorage of beam and column in the joint. The maximum spacing of the vertical joint reinforcement in the horizontal direction should not exceed the one fourth of the adjacent lateral dimension or 200mm.

$$A_{jv} = \left(\frac{0.7}{1+\frac{N_O^*}{f_c' A_g}} \right) A_{jh} \frac{f_{yh}}{f_{yv}} \frac{h_b}{h_c} \tag{2.31}$$

To avoid the additional forces in the form of torsional forces, the eccentricity of the joint is taking indirectly by considering the limited effect of the joint width through Eq 2.32.

$$b_j \leq 0.5(b_w + b_c + 0.5h_c) - e \tag{2.32}$$

Eurocodes 8 (2004) recommends that sufficient shear reinforcement should be provided in the joint to provide the confinement in the joint. The code also aims to limit the maximum tensile in concrete equal to f_{ctd}, where f_{ctd} is the design value of concrete tensile strength. The joint shear reinforcement according to Eurocode 8 (2004) is shown in Eq 2.33:

$$\frac{A_{sh} f_{ywd}}{b_j h_{jw}} \geq \frac{\left(\frac{V_{jhd}}{b_j h_{jc}}\right)^2}{f_{ctd} + v_d f_{cd}} - f_{ctd} \tag{2.33}$$

Where A_{sh} shows the total area of the horizontal hoop, h_{jc} *and* h_{jw} is the distance of reinforcement at extreme fiber in beam and column. The normalized design axial load from the column is denoted by v_d.

A simpler expression is proposed to avoid the complexity to find the area of the joint shear reinforcement, provide to enhance the integrity of the RC joint even after diagonal cracks appear in the interior and exterior joint, shown in Eq 2.34 and Eq 2.35, respectively. The distribution of the horizontal joint reinforcement calculated is assumed to be uniform within the depth.

$$A_{sh} f_{ywd} \geq \gamma_{Rd} (A_{s1} + A_{s2}) f_{yd} (1 - 0.8 v_d) \tag{2.34}$$

$$A_{sh} f_{ywd} \geq \gamma_{Rd} A_{s2} f_{yd} (1 - 0.8 v_d) \tag{2.35}$$

To calculate the joint shear reinforcement in the vertical direction, Eq OOI is proposed

$$A_{sv} \geq \left(\frac{2}{3}\right) A_{sh} \left(\frac{h_{jc}}{h_{jw}}\right) \tag{2.36}$$

2.7 Summary of the Design Codes

The design code provisions for the seismic design of RC joints are summarized in this section. The provisions of codes to estimate the joint shear strength and the mechanisms of resisting shear considered by all the famous seismic design codes are summarized in Table 2.2. It should be noted that the shear strength of the joint is considered as the function of concrete compressive strength by all the four aforementioned design codes. The axial load factor is taken by only two design codes, i.e., Eurocodes 8 [7] and Chinese code GB50011[10]. However, none of the code is providing any special provision for the RC knee joint except the ACI 352R-02 [33], which recommends some special design criteria for knee joint along with a lower estimation of strength with respect to interior and exterior joint. The rest of the practical design codes not even discussed the RC knee joint as a different case. The opening and closing behavior of the knee joint is not highlighted as different behavior by any of the seismic design codes.

Table 2.2: Recommended Equations to estimate the joint shear strength

Seismic Codes	Joint shear resistance mechanism	Joint shear strength (MPa)
ACI 352R-02	Diagonal strut	$0.66\sqrt{f_c'}b_j h_c$
ACI 318-14	Diagonal strut	$1.0\sqrt{f_c'}b_j h_c$
NZS 3101-06	Diagonal strut and truss	$\min\{0.20 f_c' b_j h_c, 10 b_j h_c\}$
EN 1998-1:2004	Mohr's theory or Diagonal strut and truss	$0.8\eta f_{cd}\sqrt{1-v_d/\eta}b_j h_{jc}$
GB 50011:2010	Diagonal strut and truss or Strut-and-tie	$0.3\eta_j f_c' b_j h_c$

Table 2.3 summarized the recommendation for the effective joint width. Eurocode 8 and NZS 3101-06 consider the impact of beam width, column width, and depth, while on the other hand, the effect of the beam-column eccentricity is taken into account by ACI 352R-02 [33], NZS 3101[8] and GB 50011 [10]. Eurocode 8 [7] doesn't have any recommendations for effective joint width but put some limitation on the eccentricity.

Table 2.3: Effective Joint width and eccentricity Provisions

Seismic Codes	Effective joint width	Eccentricity provision
ACI 352R-02	$\min\{\frac{b_b+b_c}{2}, b_b+\sum\frac{mh_c}{2}, b_c\}$	$e > b_c/8 : m = 0.3$ Other cases: $m = 0.5$
ACI 318-14	$b+h$	$b+h \le b+2x$
NZS 3101-06	$b_c \ge b_w : \min\{b_c, b_w+0.5h_c\}$ $b_c < b_w : \min\{b_w, b_c+0.5h_c\}$	$b_j \le 0.5(b_w+b_c+0.5h_c)-e$
EN 1998-1:2004	$b_c > b_w : \min\{b_c, b_w+0.5h_c\}$ $b_c < b_w : \min\{b_w, b_c+0.5h_c\}$	$e \le b_c/4$
GB 50011:2010	$b_b > 0.5b_c : b_j = b_c$ $b_b < 0.5b_c : b_j = b_b+0.5h_c$	$b_j = 0.5(b_b+b_c)+0.25h_c-e$

2.8 Concluding Remarks

From the aforementioned literature review, it is clear that the majority of the experimental work on the knee joint is done under static loading. The joints are critical during the transfer of shear and moment from the adjacent beams and columns when subjected to seismic loading. But such critical behavior of joint cannot be captured under a monotonic experimental setup. The primary objective of the monotonic loading was to recognize the suitable shear and longitudinal reinforcement, along with the aim, to enhance the efficiency and strength of the knee joint. However, the reasonable seismic behavior of RC knee joint is captured when the joint is subjected to reverse cyclic loading, which in return, produce the opening and closing behavior in the common core. The spalling of the concrete and excessive at the outer face of the joint is expected to reduce the strength of the knee joint when subjected to the cyclic loading of different magnitude.

More specifically, the estimation of shear strength of opening and closing behavior s of the knee joint is still to be addressed with more details. The overall capacity of the joint either depends upon the opening or closing behavior when subjected to reverse cyclic load is still unknown by different design codes. The resisting mechanisms for opening and closing of the joint are different, which impart different closing and opening capacity of the knee joint.

Although the past researcher has proposed a lot of analytical models. Most of these models are either very complex for there implementation in the practical field. The models recommended by different codes are mostly the function of the concrete compressive strength. However, form the past studies it has been found that the capacity of RC joint is not dependent on the compressive strength of the concrete alone, but it depends on many other factors such as reinforcement yield strength, longitudinal reinforcement ratio and other geomantic properties of the structural member adjacent to the joint. The application of the codel provisions based on the non-conservative estimation of shear strength may lead to the wrong design of the joint. An efficient and reliable model is needed which can estimate and model the shear strength of RC knee joint under both opening and closing behavior when subjected to the reverse cyclic loadings.

3 MATERIALS AND METHODS

3.1 Sources of Experimental Data

For the RC knee, different studies about the shear strength have been published. In order to proposed a model, a large database is established from the previous research about the knee joint shear strength. This study consists of the test results of 61 experiments, performed by different researchers. The experiments from 1991 to 2018 is selected to perform the statistical analysis. Few experiments are omitted on basis of different reasons. The data is given in Table 3.1-3.5. These data include variation in the geometric size of column, beam, concrete strength, tensile and compression reinforcement ratio, shear reinforcement of the beams and columns, variation of applied load. Some database does not provide any important parameter that my effect any shear strength of knee joint. This study includes more that fifteen parameters but the number of parameters was than reduced to 7, because many parameters are reported to be not affected during the experiment procedure.

3.1.1 Mazzoni (1991) [34]

Three knee joint specimens were tested by Mazzoni et.al [34] in (1991). The design of these knee joints were according to design provisions ACI352 (1985). The poor performance of knee joint was observed in outrigger knee joint bridge of the China Basin and I-980 freeways during the earthquake of the Loma Prieta. Fig 3.1, shows the details of the experimental setup. The experimental setup was established horizontally on the lab floor. A two-way single actuator was used to apply the reverse cyclic load and produce opening and closing behavior in the joint. The knee joint shear input was expected about 10.2 rather than the nominal value of 12, due to the uncertainty in the concrete strength. The reverse cyclic load on the knee joint is applied till capacity of the knee joint deteriorate up to one-half of the peak value.

In the test specimen the author attributed the deterioration of strength to spalling of the concrete cover and loss of anchorage reinforcement in the joint. Results from reverse cyclic loading test reviled that, under closing behavior the specimen was able to reach the expected joint shear input and the peak resistance over many cycles at drift levels about two to three times of the drift achieved by the specimen.

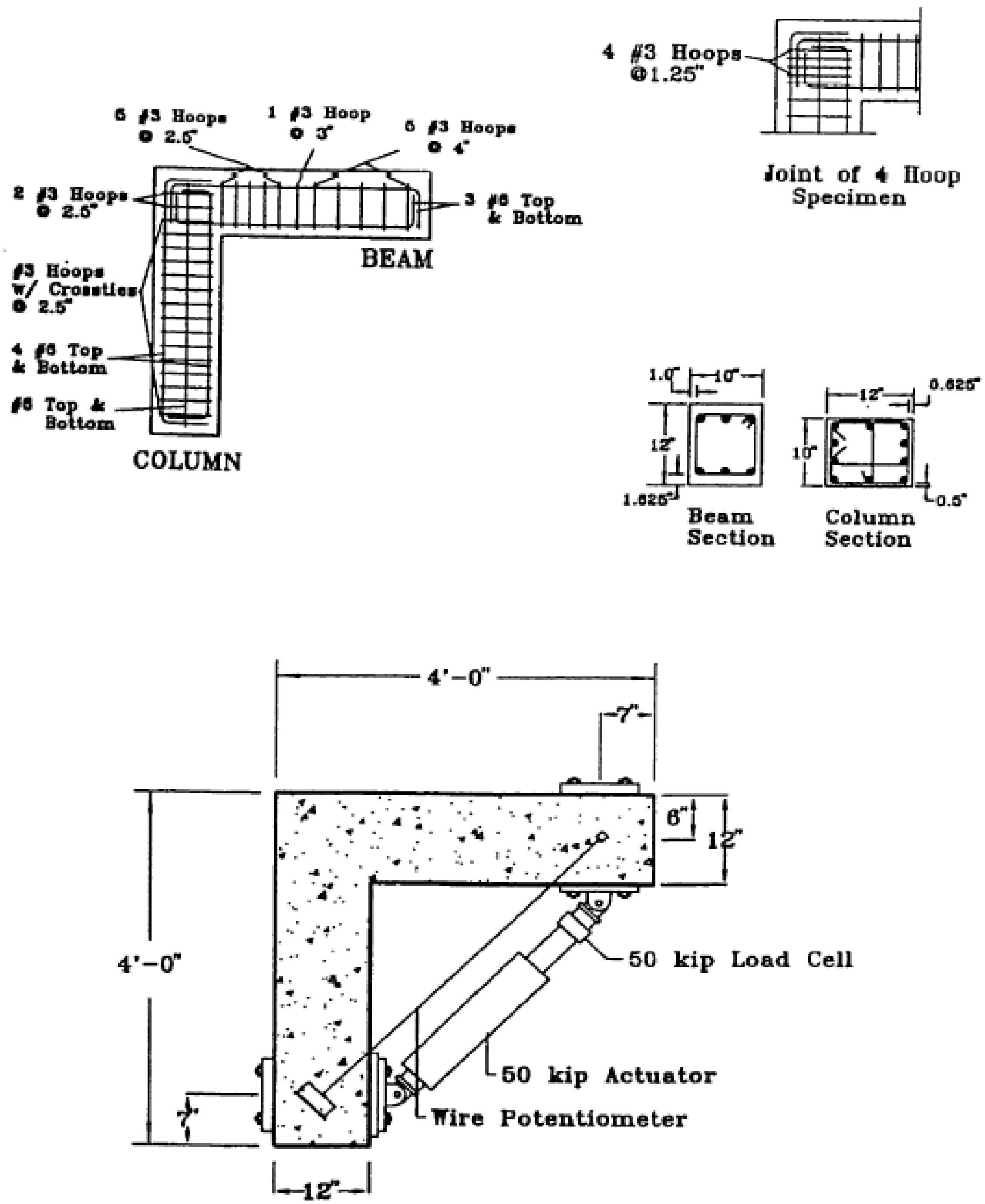

Figure 3.1: Experimental details of Specimen tested by Mazzoni et.al 1991

3.1.2 Cote and Wallace (1994) [35] McConnell and Wallace (1995) [36]

Experimental tests were carried out on the beam column knee joint. The main aim was to observe the behavior of the knee joint both under opening and closing moment, which were designed on the basis of ACI-1991. The experimental results obtained showed that the nominal shear strength of RC knee joint was less than value suggested by ACI 352-91 i.e., $12\sqrt{f_c'}$. Also, it was seen that under the reverse cyclic loading the knee joint didn't sustained the shear stress as predicted by the code. Especially, these joints didn't reach the expected shear stress when subjected to the opening behavior. The experimental details of the knee joint and connected structural elements are shown in Table 3.1:

Table 3.1: Cote and Wallace 1994 & McConnell and Wallace 1995

Specimen ID	**f_c' (MPa)**	**f_{yb} (MPa)**	**L_b (mm)**	**b_b (mm)**	**b_c (mm)**	**h_b (mm)**	**h_c (mm)**
Cote and Wallace (1994)							
KJ#1	45.70	448.00	1500.00	229.00	406.00	406.00	406.00
KJ#2	49.80	448.00	1500.00	229.00	406.00	406.00	406.00
KJ#3	45.00	448.00	1500.00	229.00	406.00	406.00	406.00
KJ#4	45.60	448.00	1500.00	229.00	406.00	406.00	406.00
McConnell and Wallace (1995)							
KJ#5	31.50	448.00	1750.00	279.00	406.00	406.00	406.00
KJ#6	33.00	448.00	1750.00	279.00	406.00	406.00	406.00
KJ#7	32.90	448.00	1750.00	279.00	406.00	406.00	406.00
KJ#8	36.30	448.00	1750.00	279.00	406.00	406.00	406.00
KJ#9	38.50	448.00	1750.00	279.00	406.00	406.00	406.00
KJ#10	37.90	448.00	1750.00	279.00	406.00	406.00	406.00
KJ#11	35.00	448.00	1750.00	279.00	406.00	406.00	406.00
KJ#12	32.90	448.00	1750.00	279.00	406.00	406.00	406.00
KJ#13	31.70	448.00	1750.00	279.00	406.00	406.00	406.00

3.1.3 Megget (1998) [37]

Two one-half scale reinforced concrete knee joint of a reinforced concrete frame building designed according to the New Zealand Standard (NZS-3101)[8]. Fig 3.2 shows the detailing of the specimen and the experimental setup used by Megget.

The experimental setup was laid horizontally on the flat on the floor. A hydraulic jack consists of two loading cells was used to load the RC joints as shown in Fig 3.2 and Table. An opening and closing action of two complete cycles were performed at ¾ yield and displacement ductility of 2,4,6,8. An opening and closing action of one complete cycle was performed at the displacement level of 10.

In the beam top and bottom, four D12 reinforcement bars were used in both the specimens. Under the closing moment the joint reach the expected joint shear stress. In the specimen with conventional 90 degrees hook anchorages, the deterioration and the spalling of the concrete cover is occurring too quickly. The specimen did not reach to the design shear capacity when subjected to the opening shear. The poor performance of the knee joint under opening action was due to the damage caused to the compression zone due to bond deterioration as a result of several loading cycles.

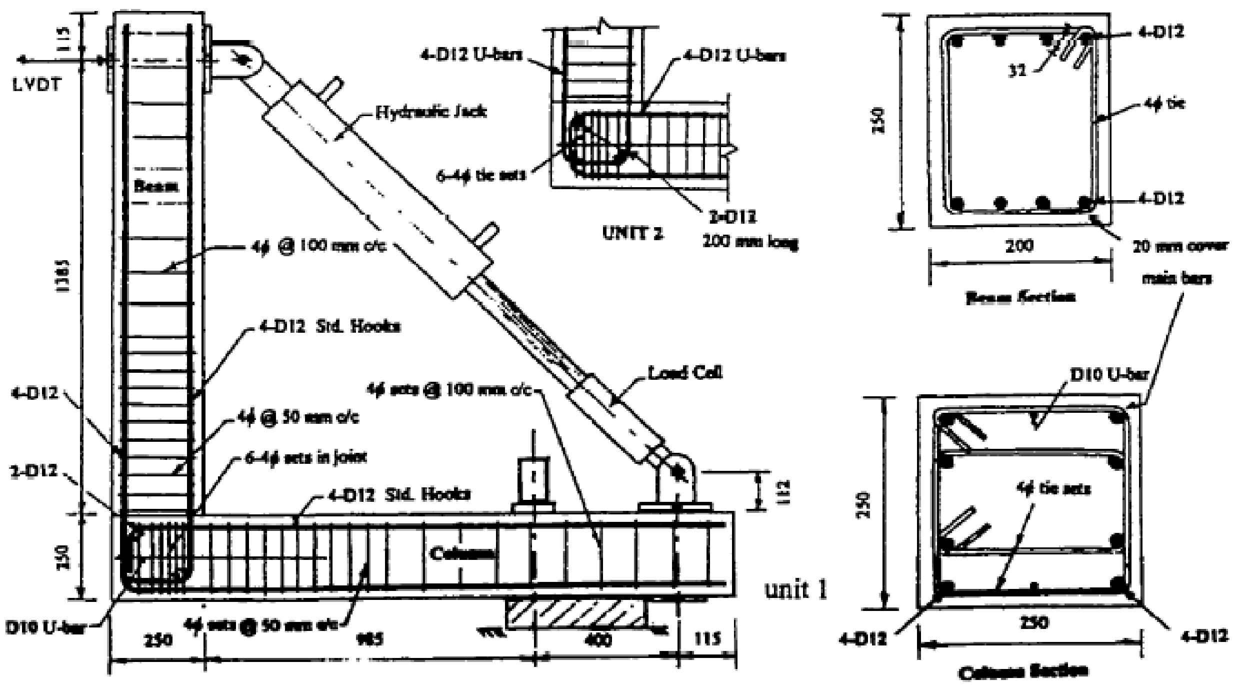

Figure 3.2: Experimental detailing of setup and Specimen (Megget 1998)

Table 3.2: Experimental details of structural members Megget (1998)

Specimen ID	f_c' (MPa)	f_{yb} (MPa)	L_b (mm)	b_b (mm)	b_c (mm)	h_b (mm)	h_c (mm)
Megget (1998)							
KJ-1	27.80	358.00	1750.00	200.00	250.00	250.00	250.00
KJ-2	27.80	358.00	1750.00	200.00	250.00	250.00	250.00
KJ-3	34.00	328.00	1750.00	200.00	250.00	250.00	250.00
KJ-4	34.00	328.00	1750.00	200.00	250.00	250.00	250.00
KJ-5	33.60	355.00	1750.00	200.00	250.00	250.00	250.00
KJ-6	33.60	325.00	1750.00	200.00	250.00	250.00	250.00
KJ-7	50.00	333.00	1750.00	200.00	250.00	250.00	250.00
KJ-8	40.40	340.00	1750.00	200.00	250.00	250.00	250.00
KJ-9	39.80	333.00	1750.00	200.00	250.00	250.00	250.00
KJ-10	39.70	333.00	1750.00	200.00	250.00	250.00	250.00
KJ-11	26.80	333.00	1750.00	200.00	250.00	250.00	250.00
KJ-12	27.70	333.00	1750.00	200.00	250.00	250.00	250.00
KJ-13	36.90	333.00	1750.00	200.00	250.00	250.00	250.00

3.1.4 Angelakos (2000) [38]

The half-scale two dimensional models of the upper story of twenty stories moment resisting space frames were observed. Sixteen experimental specimens divided into five groups were observed. The geometric dimensions of the structural members are shown in Table 3.3. The main reinforcement bar of the beam and column terminated in the knee joint with the standard reinforcement hook of 90 degree except KJ14, KJ15, KJ16. For the specimen KJ15, straight anchorage of the column reinforcement bars in the joint region is documented. The specimen of KJ 15 had a large number of the small diameter reinforcement bars as compared to the other specimens. Both KJ 14 and KJ 15 had a 90-degree hook for the beam longitudinal reinforcement. Specimen KJ16 had headed bars with the T-head anchored within the joint region. For measuring the concrete compressive strength, a concrete cylinder of $150mm \times 300mm$ is used.

Table 3.3:Experimental details of structural members Angelakos (2000)

Specimen ID	f_c' (MPa)	f_{yb} (MPa)	L_b (mm)	b_b (mm)	b_c (mm)	h_b (mm)	h_c (mm)
Angelakos (2000)							
KJ-1	45.70	448.00	1400.00	280.00	400.00	400.00	400.00
KJ-2	49.70	448.00	1400.00	280.00	400.00	400.00	400.00
KJ-3	45.00	448.00	1400.00	280.00	400.00	400.00	400.00
KJ-4	45.60	448.00	1400.00	280.00	400.00	400.00	400.00
KJ-5	31.50	461.00	1400.00	280.00	400.00	400.00	400.00
KJ-6	33.00	461.00	1400.00	280.00	400.00	400.00	400.00
KJ-7	32.90	461.00	1400.00	280.00	400.00	400.00	400.00
KJ-8	36.30	461.00	1400.00	280.00	400.00	400.00	400.00
KJ-9	38.50	461.00	1400.00	280.00	400.00	400.00	400.00
KJ-10	37.90	461.00	1400.00	280.00	400.00	400.00	400.00
KJ-11	35.00	461.00	1400.00	280.00	400.00	400.00	400.00
KJ-12	32.90	461.00	1400.00	280.00	400.00	400.00	400.00
KJ-13	31.70	461.00	1400.00	280.00	400.00	400.00	400.00
KJ-14	33.60	448.00	1400.00	280.00	400.00	400.00	400.00
KJ-15	36.90	434.00	1400.00	280.00	400.00	400.00	400.00
KJ-16	37.20	487.00	1400.00	280.00	400.00	400.00	400.00

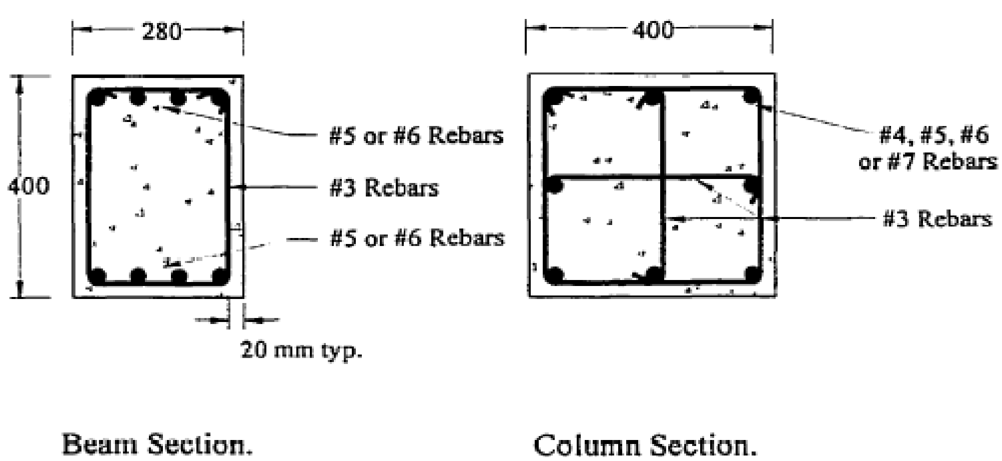

Figure 3.3: Detailing of Specimen Tested by Angelakos (2000)

3.1.5 Zhang (2017) [39]

To investigate the behavior of RC knee joint under seismic load, a ten large scale knee joints were carried out under the reverse cyclic loading. A significant effect of variable geometric and material properties was investigated. The joint specimens were tested for different configurations i.e. different beam depth, columns width and detailing technique of reinforcement. All the specimens were designed according to the ACI 318-14 and ACI 352-02 except KJ-NS specimen, which is non-seismically designed.

Furthermore, all the knee joint specimens were designed to fail in the joint core rather than the adjacent structural member, in order to investigate the seismic performance of the knee joint particularly. To ensure this behavior of the assembly, the nominal shear strength of joint should be kept less that the shear strength of the connecting element.

The experimental specimens were divided into four group based on different geometric and material properties. To apply a reverse cyclic load, a servo-controlled actuator was connected to the beam and the column tip, which produce the opening and closing behavior in the knee joint. The details of the test specimens are tabulated in Table 3.4.

Table 3.4: Experimental details of structural members Zhang (2017)

Specimen ID	**f_c' (MPa)**	**f_{yb} (MPa)**	**L_b (mm)**	**b_b (mm)**	**b_c (mm)**	**h_b (mm)**	**h_c (mm)**
Zhang (2017) and Zhang (2017)							
KJ-NS	38.40	500.00	1800.00	300.00	300.00	300.00	300.00
KJ-F	36.50	500.00	1800.00	300.00	300.00	300.00	300.00
KJ2-H12V10	29.30	520.00	1800.00	300.00	300.00	300.00	300.00
KJ3-H10V12	32.20	500.00	1800.00	300.00	300.00	300.00	300.00
KJ-H8V10	35.40	500.00	1800.00	300.00	300.00	300.00	300.00
KJ-BD500	30.90	500.00	1800.00	300.00	300.00	500.00	300.00
KJ-CW430	30.80	500.00	1800.00	300.00	430.00	300.00	300.00
KJ-BD700	32.50	500.00	1800.00	300.00	300.00	700.00	300.00
KJ-CD500	32.30	500.00	1800.00	300.00	300.00	300.00	500.00
KJ-CW600	33.20	500.00	1800.00	300.00	600.00	300.00	300.00

3.1.6 Mogili and Kuang (2018) [40]

A total number of nine knee joints were tested numbering from KJ1 through KJ2, to study the effect of shear stress of knee joint under reverse cyclic loading. The specimens were divided into further three group based on different joint geometry and joint aspect ratio. However, the joint geometry was constant in each group. The geometric properties of the subassemblies were tabulated in Table 3.5. In all the three group the it has been observed that the opening shear stress were lower than the corresponding closing shear stress.

Table 3.5: Experimental details of structural members Mogilli and Kuang (2019)

Specimen ID	f_c' (MPa)	f_{yb} (MPa)	L_b (mm)	L_c (mm)	b_b (mm)	b_c (mm)	h_b (mm)	h_c (mm)
Mogili and Kuang (2018)								
KJ-NO	37.60	526.00	1800.00	1800.00	300.00	300.00	300.00	300.00
KJ-N1	36.80	526.00	1800.00	1800.00	300.00	300.00	300.00	300.00
KJ-F0	34.50	560.00	1800.00	1800.00	300.00	300.00	300.00	420.00
KJ-F1	29.20	560.00	1800.00	1800.00	300.00	300.00	300.00	420.00
KJ-S0	27.80	560.00	1800.00	1800.00	300.00	300.00	420.00	300.00
KJ-S1	26.80	560.00	1800.00	1800.00	300.00	300.00	420.00	300.00

3.2 Parameters Affecting the Shear Strength of Knee Joint

This section includes the understanding of the parameters that effect the principal tensile strength of joint zone when subjected to reverse cyclic loading. The behavior of principal tensile stresses corresponding to different effecting parameter is shown, using scatter plots. A database is established from the previous literature and this will serve as primary parameter for the statistical analysis.

3.2.1 Compressive Strength of Concrete

The compressive strength of concrete is an important parameter in providing the resistance to the shear failure of the RC joint. For evaluating the principal tensile stresses in the knee joint, both concrete compressive and square root of concrete compressive stress are considered. Fig 3.1 and Fig 3.2 shows, the relationship of nominal principal tensile stress with the concrete compressive stress. The value of concrete compressive stress for the previous experimental results ranges from 26.80 MPa to 50 MPa. Well, a very different influence of concrete compressive strength is observed on principal tensile of knee joint under opening and closing moment. The main reason behind this is the formation of concrete strut which is also likely different under opening and closing behavior of RC knee joint. In opening moment, it is observed that concrete strut tends to become narrow and not well supported at the end. On the other hand, the concrete strut under closing moment is strong bottle shaped and well supported at the ends. The variation of the concrete compressive strength under opening and closing moment is clearly shown in Fig 3.1 and Fig 3.2.

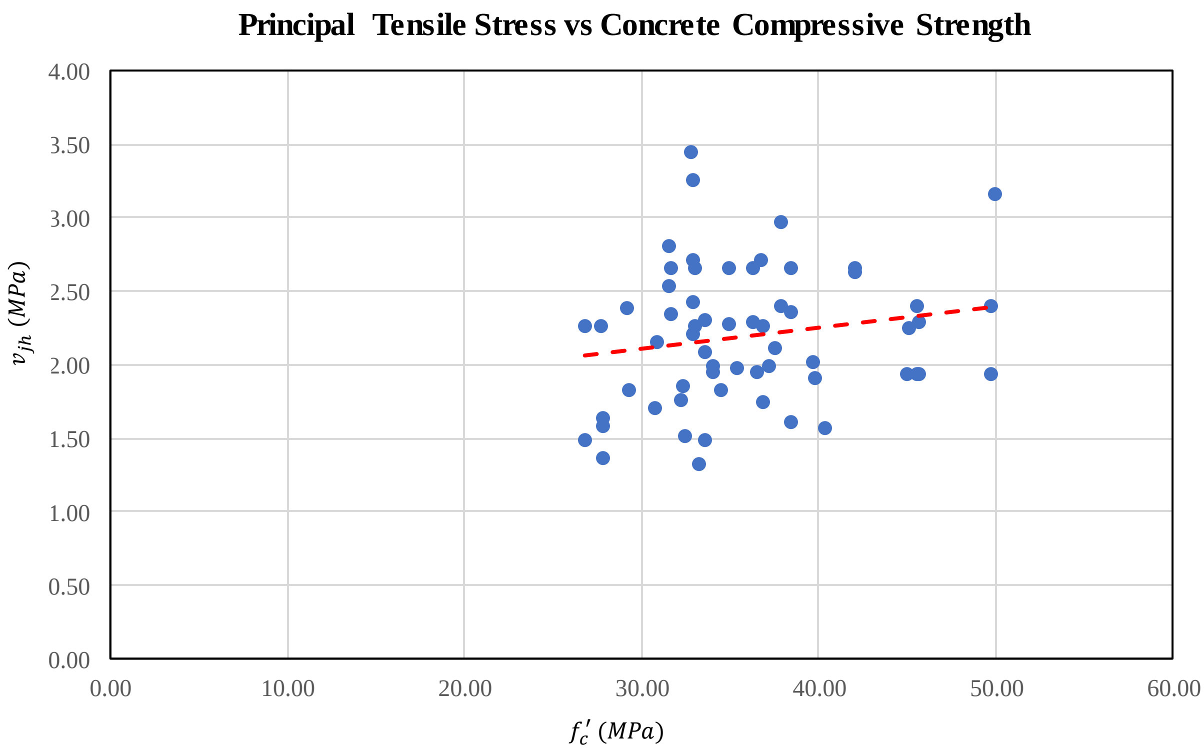

Figure 3.4: Principal Tensile Stress vs. Concrete Compressive Strength under closing behavior

Fig 3.1 and Fig 3.2 shows the negative-positive correlation of concrete compressive stress with the principal tensile stresses when the knee joint is subjected to the opening moment and positive correlation when subjected to closing moment. Fig 3.1 and Fig 3.2 also indicate that principal tensile stress of the knee joint is not only dependent on the compressive shear strength of RC knee joint.

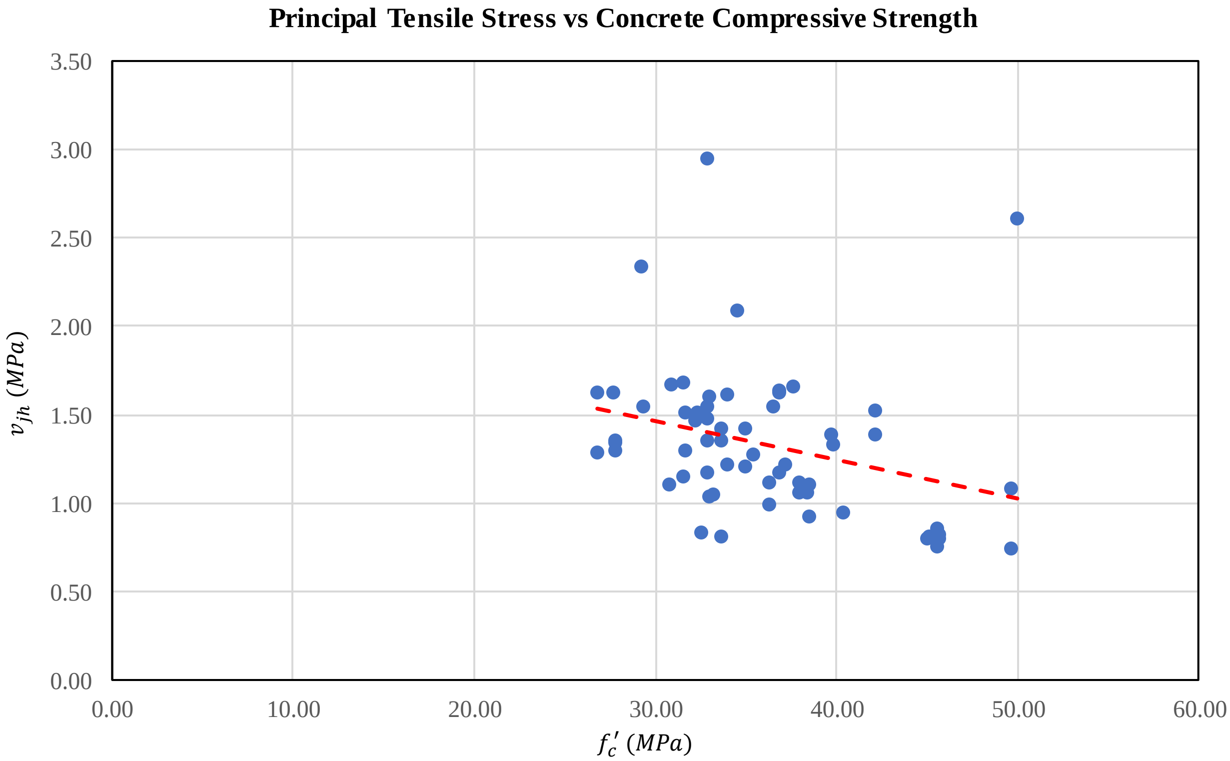

Figure 3.5: Principal Tensile Stress vs. Concrete Compressive Strength under Opening behavior

3.2.2 Longitudinal Reinforcement Ratio

The longitudinal reinforcement of flexural members adjacent to the knee joint shows an impact on the principal tensile stress of the knee joint. It is evident from the past research that the increase in the longitudinal reinforcement tends to increase the shear strength of knee joint both under the opening and closing moment. The trend of longitudinal reinforcement with normalized principal tensile stress for both opening and closing moment is shown in Fig 3.3 and Fig 3.4. In the current study the longitudinal reinforcement ration varies form 0.001-0.012 in opening moment and from 0.005-0.020 in closing moment. For the sake of dimension less quantities the normalized value of principal tensile stresses and beam longitudinal reinforcement is taken in to account during analysis.

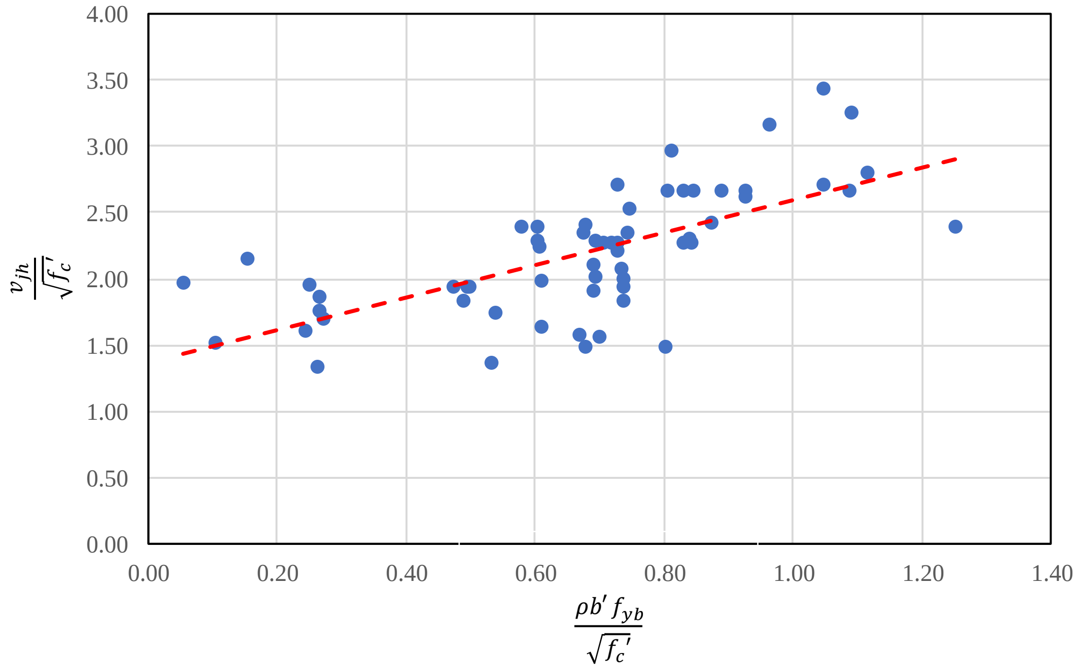

Figure 3.6: Principal tensile stress vs Longitudinal tensile reinforcement under closing behavior

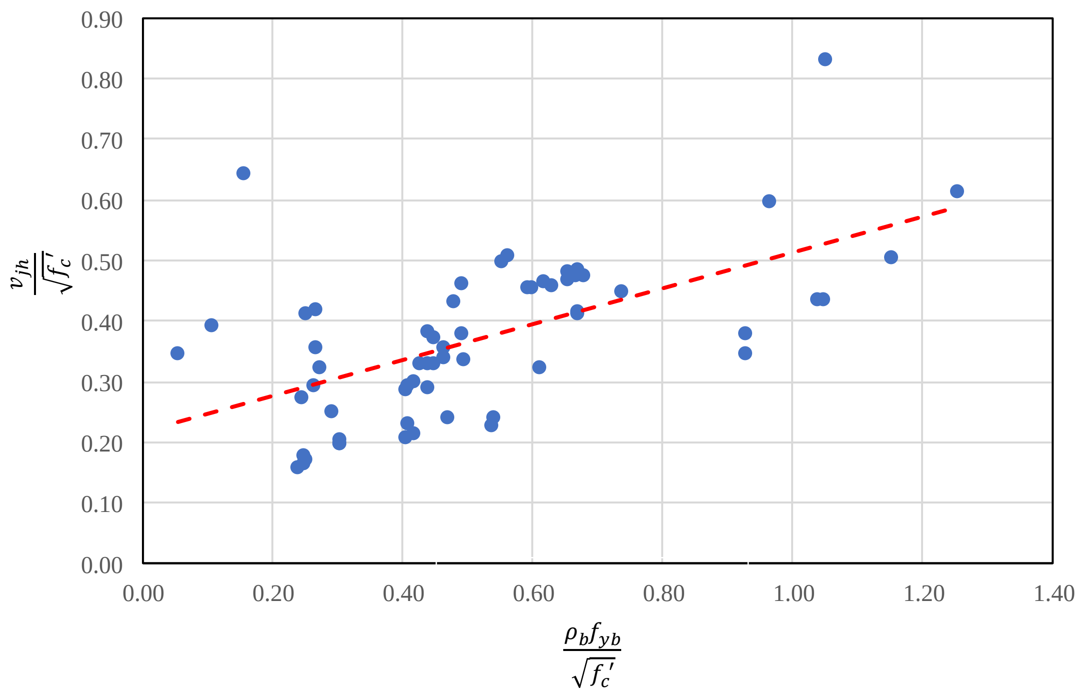

Figure 3.7: Principal tensile stress vs longitudinal tensile reinforcement under opening moment

3.2.3 Beam to Column Depth Ratio

The beam to column depth ratio influences the shear capacity and principal tensile stress of the knee joint. However, this factor has not been incorporated by any of the design code which leads to the wrong prediction of the RC knee joint. The parametric study from different experimental data, which consist of a set of beams to column depth ratio ranges from 0.63-2.33.

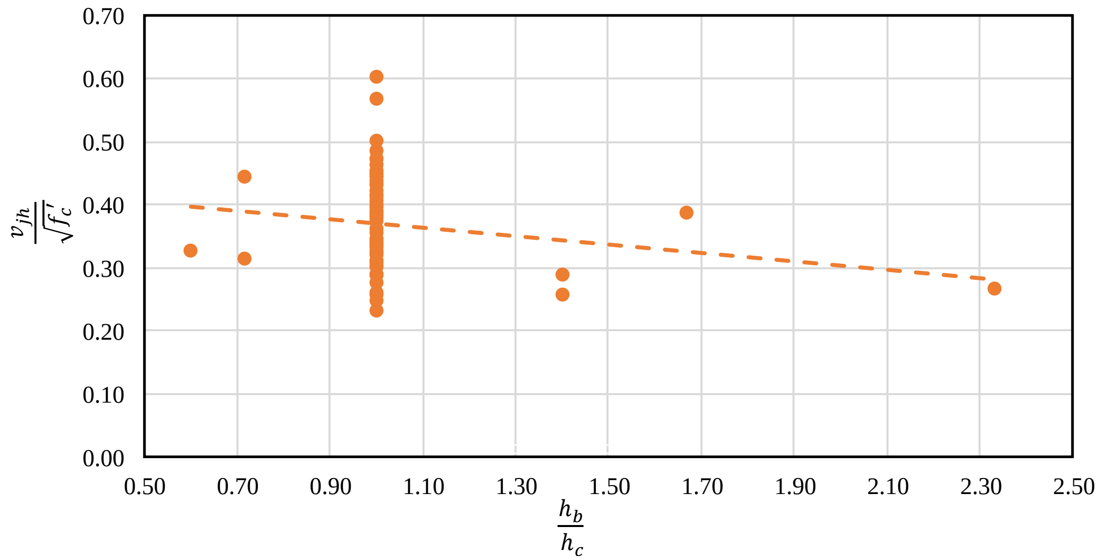

Figure 3.8: Principal tensile stress vs beam-to-column depth ratio under closing behavior

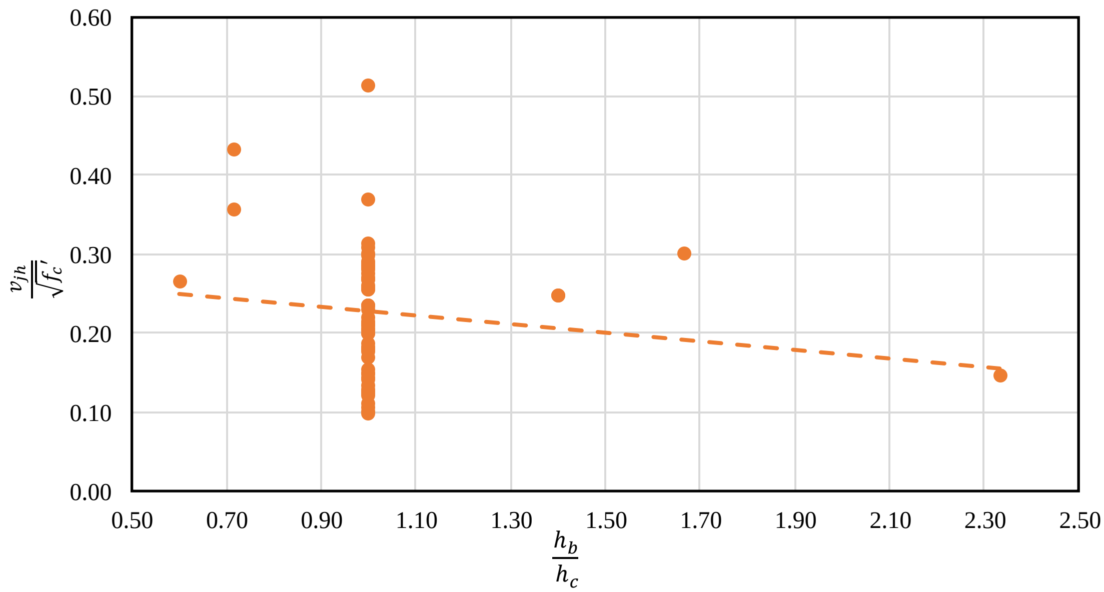

Figure 3.9: Principal tensile stress vs beam-to-column depth ratio under opening behavior

From Fig 3.5 and Fig 3.6, it is evident that the value of normalized principal tensile stress is changing dramatically as the beam-column depth ratio varies.

In closing behavior, when the beam-to-column depth ratio is less than one, the value of principal tensile stress dramatically increases 0.33-0.60. Similarly, a same behavior is observed for opening behavior. For beam-to-column depth ratio less than 1, the value of principal tensile stress increases from 0.27-0.51.

For beam-to-column depth ratio greater than 1, the value of principal tensile stress decreases dramatically. In closing behavior, the principal tensile value decreases from 0.60 to 0.27. Similarly, in case of opening behavior the value the principal tensile stress decreases from 0.51 to 0.15.

This variation of the principal tensile stress with beam-to-column depth ratio indicates that this parameter is important in calculating the shear strength of RC knee joint. However, this important is normally neglected in all the design building codes which leads us to estimate the unrealistic value shear strength of knee joint.

3.2.4 Joint Width Ratio

From the past experimental data, it is observed that width of RC joint also effects the shear stress of RC knee joints. In the codes of practice this factor is also not included which can leads to the unrealistic value of the shear strength of knee joint. It has been observed that the shear resistance of the knee joint increase drastically, when the joint width ration is one.

Much variation of the joint width ratio has been observed from the Fig 3.7 and 3.8. These variations indicate that this factor plays an important role in the principal maximum tensile stress which leads to the variation in the shear stress. Fig 3.7 and 3.8 both indicate the positive correlation of normalize principal tensile stress with the joint width ratio. The joint width ratio from the past experimental results varies form 0.71-1.50. However, the principal tensile stress varies from 0.16-0.83 in case of opening moment and 0.37-0.97 in case of closing moment. Design code provision lack the factor of joint width ratio when calculating the shear capacity of RC knee joint under reverse cyclic load. This clearly shows that consideration of this factor is important in estimating the shear strength of RC knee joint.

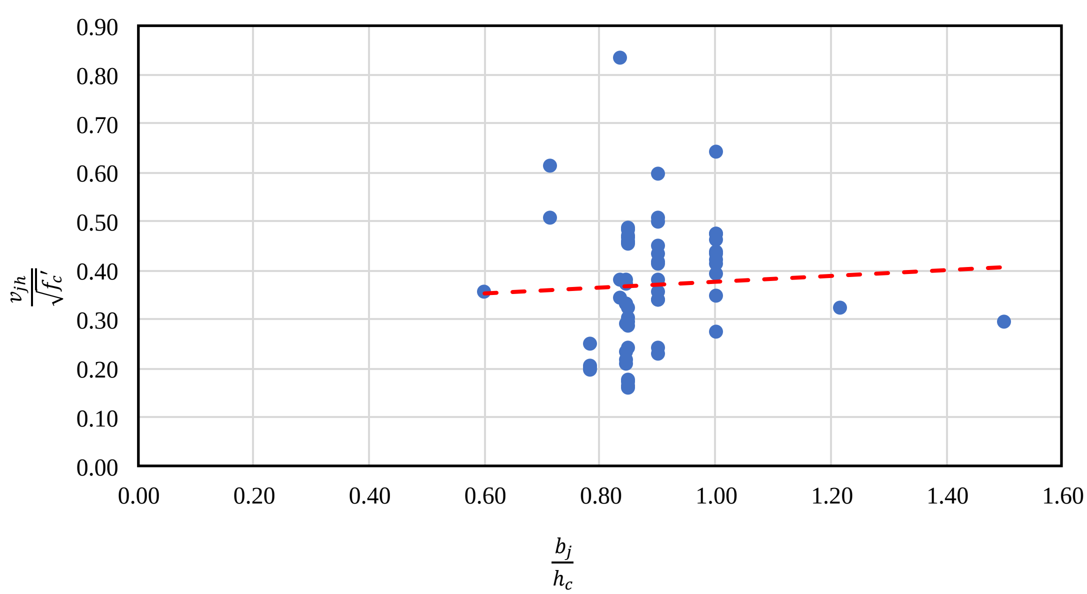

Figure 3.10: Principal tensile stress vs Joint width ratio under opening behavior

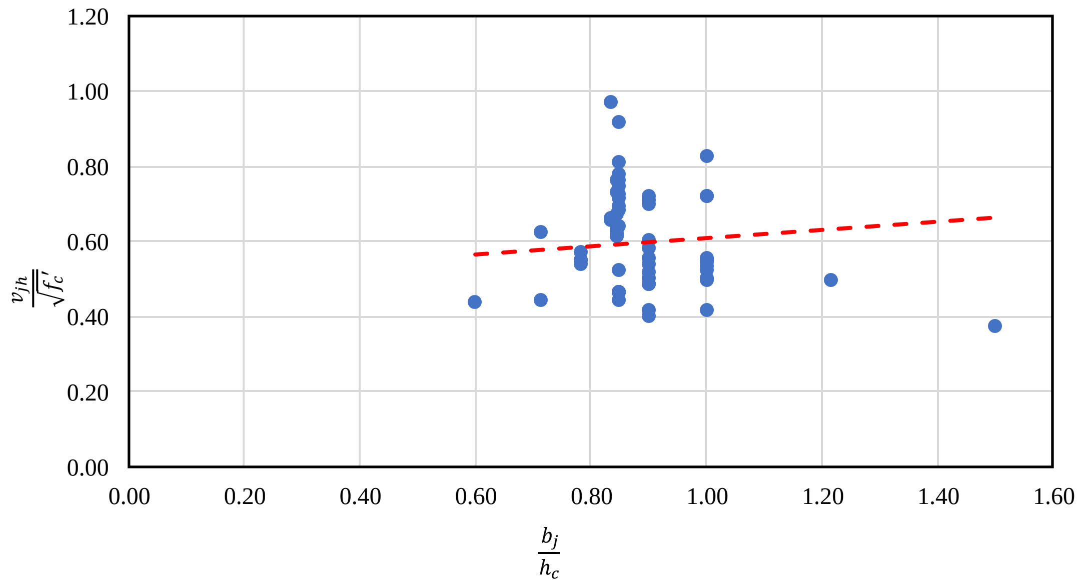

Figure 3.11: Principal tensile stress vs Joint width ratio under closing behavior

3.3 Methodology

This section displays the statistical procedures that was adopted to propose a model for the shear strength of RC knee joint under opening and closing behavior separately. The regression analysis was conducted on the experimental results of the joint mentioned in the literature. The correlations among various affecting parameters were already discussed in the previous sections. Finally, two separate prediction equations for the shear capacity of the knee joint will be presented on the basis of regression analysis.

3.3.1 Data Selection

Various experimental results about the shear strength of knee joint are reported in literatures. It is quite significant to establish a rational equation for predicting the shear strength of the knee joint. This study includes the results of 61 RC knee joint obtained from the previous literature. The era of these testing was from 1991 to 2019. All of the experimental data considered in this study have few common things, including the experimental setup and type of applied loading and type of applied cyclic load. The data opted for the regression analysis includes the geometric and material properties of the knee joint. Since some literature do not provide any significant parameter that will affect the shear strength of the knee joint under opening and closing moment. The study includes more than fifteen parameters which was then reduced to seven based on there correlation with the principal tensile stresses. These factors include the breadth and depth of beam section, breadth and depth of the column section, compression and tension reinforcement of beam, compressive strength of concrete and tensile strength of compression and tension reinforcement. Tabulation form of these factors are given in Table 3.1-3.5 in the aforementioned section.

The scatter plots shown in Fig 3.4-3.11 in the previous section suggest that there is strong relation among the response variables and maximum principal tensile stress. However ever it has been observed that there are some positive as well as negative correlation among some factors. It should be noted that the shear force in unit of joint is taken in kN, then the compressive concrete strength f_c' , tensile reinforcement strength f_y and principal tensile stress is taken as MPa. In all the above plot, the data ranges on the x and y axes which are the minimum and maximum values for each variable included in the regression analysis of the study.

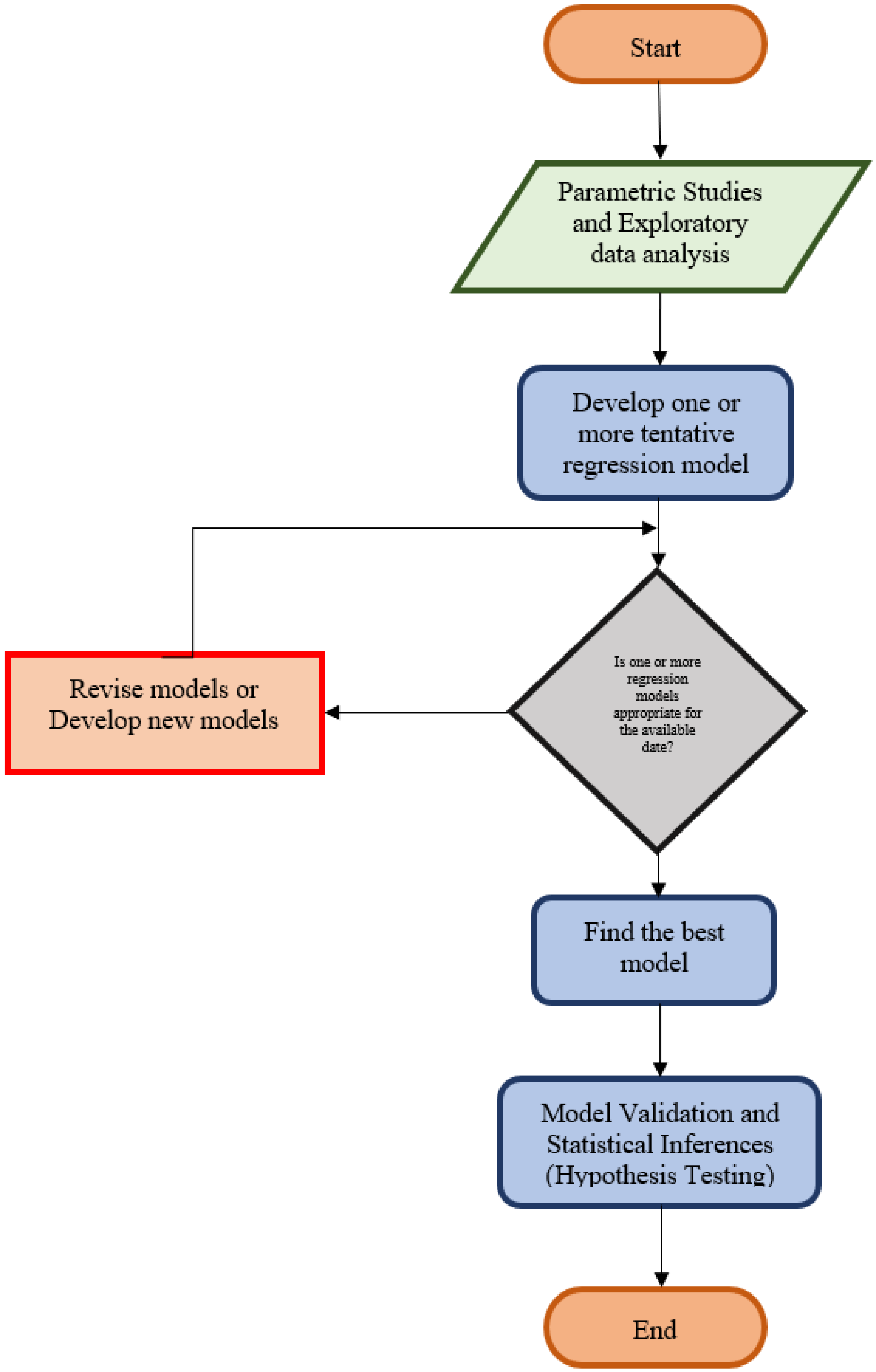

Figure 3.12: Flowchart for developing regression model for RC knee joint

3.4 Simple Linear Regression

Regression is used to investigates the dependence of one variable on one or more variables called independent variable. The process of regression provides an equation that can be used for estimating or predicting the average value of the dependent variable for the know values of the independent variable.

3.4.1 Multivariate Linear Regression

Simple regression is defined as the process for determining the relationship among different variables Multiple linear regression is the type of the simple linear regression that is used to relate the one response variable to two or more predictor variable. In the experimental circumstances where the predictor variable is not controlled by the experimenter, multiple regression is recommended. During the experiments, observer usually consider all prediction variable at the same time. The reason is, because there is more than one significant factor which effect the behavior of the response variable. In such kind of analysis, simple regression is with one predictor variable is not inadequate to accurately estimate the value of the response variable. In order to capture the accurate behavior of the response variable multiple regression procedure is recommended. This multiple regression is also used when the response variable is dependent on various factors. It should be remembered that adding more variables to your regression doesn't means that your regression is model will be more accurate. However, adding more variables may lead to the worse results. Such phenomenon is termed as overfitting. It is also important to understand that, best model can be found when the predictor variables are not correlated to each other but correlated to the response variables. In this particular study, those factors which have some significant effect on the maximum principal tensile stresses of RC knee joint under opening and closing moment were included in the statistical regression analysis to find a new equation. The new equations aim to estimate/predict the principal tensile stresses of the knee joint more accurately, which in turn find the horizontal shear stress. The data is limited to the knee joint subjected to reverse cyclic loading. The final predictor variables include the concrete compressive strength, steel tensile strength, compressive and tensile steel ratio, width and depth of beam and column elements, joint aspect ratio.

3.5 Simple Non-Linear Regression

Two variable having non-linear relationship, and the selection of the appropriate regression and correlation procedure depends on the numerous functional forms. The primary focus of this topic involves the linearization of the non-linear form. This can be done either by the transformation of variables or by creating new variable. The focus is on single technique because of two important reasons:

This method is simple because the liner regression is directly applicable after linearization.

This method is widely applicable because in research most of the time, variable transformation is used to linearized the non-linear relationship.

3.5.1 Variables Transformation Technique

The linearization between two variable having non-linear relation can be done by transforming of the variables (either one or more variable). The examples of the non-linear form, commonly come across in research field, that can be linearized through variables transformation.

$$Y = \alpha\beta^{x} \tag{3.1}$$

The non-linear Eq 3.1 can be linearized by transforming the dependent variable Y to logarithm (log base 10, log Y). Thus, the linear form of Eq (3.1) will be:

$$Y' = \alpha' + \beta' X \tag{3.2}$$

Where $Y' = \log Y$, $\alpha' = \log\alpha$ and $\beta' = \log\beta$

The simple linear regression and correlation procedure can be applied after linearization through variable transformation.

3.6 Multiple Non-linear Regression

Multiple non-linear regression is used to solve the relationship between dependent variable Y and the k independent variables, $X_1, X_2, X_3 \dots \dots, X_k$, where $k > 1$.. Such type of situation can be handled by non-linear multiple regression. Multiple non-linear regression can be used under following conditions described below:

There should be non-linear relationship, in at least one of the independent variables with the dependent variable Y. For two independent variables, say X_1 and X_2 ,there will be non-linear multiple regression if either one or both of the two variables show a non-linear relationship with the dependent variable. For instance, if both of the dependent variable X_1 and X_2 are quadratic, the corresponding non-linear regression equation representing their relationship to Y would be:

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_1^2 + \beta_3 X_1 + \beta_4 X_2^2 \tag{3.3}$$

The independent variables X_1 and X_2, each of which separately linearly affects Y. The non-linear multiple equations for such cases is represented by

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2 \tag{3.4}$$

The main aim to linearized the non-linear regression is to apply the multiple linear regression directly for further evaluation.

$$Y = \alpha \beta_1^{X_1} \beta_2^{X_2} \beta_3^{X_3} \beta_4^{X_4} \beta_5^{X_5} \beta_6^{X_6} \dots \beta_k^{X_k} \tag{3.5}$$

Transforming the non-linear Eq 3.5 to the linear equation, the linear equation will be

$$Y' = \alpha' + \beta_1' X_1 + \beta_2' X_2 + \beta_3' X_3 + \beta_4' X_4 \dots \beta_k' X_k$$

Where $Y' = \log Y$, $\alpha' = \log \alpha$, and $\beta_i' = \log \beta \, (i = 1, \dots, k)$

In this particular type of study, a regression model is based on the Eq 3.5 is used to estimate the principal tensile stress of the RC knee joint, which leads us to estimate the shear stress of RC knee joint for both opening and closing behavior. Keep in view the functional form of previously presented equations, the proposed equation is presented in the same fashion.

$$v_{jh}^{o} = h_b^{\alpha_1} h_c^{\alpha_2} b_b^{\alpha_3} b_j^{\alpha_4} \rho_b^{\alpha_5} f'^{\alpha_6}_{c} f_{yb}^{\alpha_7} \tag{3.6}$$

$$v_{jh}^{c} = h_b^{\beta_1} h_c^{\beta_2} b_b^{\beta_3} b_j^{\beta_4} \rho_b^{\beta} f'^{\beta_6}_{c} f_{yb}^{\beta_7} \tag{3.7}$$

In Eq. 3.6 and 3.7, β and α represent the nondimensional coefficients which will be evaluated using regression analysis.

3.7 New Proposed for Maximum Shear Strength of Knee Joint

The regression coefficient for Eq 3.6 and 3.7 was found using manual calculation or by hit-and-trial method. The process was continued until best regression coefficient were obtained. To make the equation dimensionally homogeneous Eq 3.6 and 3.7 was set in such a way that the dimensionally the equation is compatible.

$$v_{jh}^{o} = \left(\frac{h_b}{h_c}\right)^{\alpha_1} \left(\frac{h_b}{b_b}\right)^{\alpha_2} \left(\frac{b_j}{h_c}\right)^{\alpha_3} \left(\frac{\rho_b f_{yb}}{\sqrt{f_c'}}\right)^{\alpha_4} \left(\frac{f_c'}{f_{yb}}\right)^{\alpha_5} \tag{3.8}$$

$$v_{jh}^{c} = \left(\frac{h_b}{h_c}\right)^{\beta_1} \left(\frac{h_b}{b_b}\right)^{\beta_2} \left(\frac{b_j}{h_c}\right)^{\beta_3} \left(\frac{\rho_b f_{yb}}{\sqrt{f_c'}}\right)^{\beta_4} \left(\frac{f_c'}{f_{yb}}\right)^{\beta_5} \tag{3.9}$$

After a complex process of analysis, the final equation can be written as

$$v_{jh}^{c} = 1.4834 f_c^{X_1} \frac{\left[\left(\frac{h_b}{h_c}\right)^{X_2}\left(\frac{h_b}{b_b}\right)^{X_3}\left(\frac{b_j}{h_c}\right)^{X_4}\left(\frac{\rho_b' f_{yb}}{\sqrt{f_c'}}\right)^{X_5}\left(\frac{f'}{f_{yb}}\right)^{X_6}\right]^{X_7}}{\left(\frac{h_b}{h_c}\right)^{X_8}\left[1-\sqrt{1+4\left(\frac{h_c}{h_b}\right)^{X_9}}\right]\left[-0.566\left(\frac{\rho_b' f_{yb}}{\sqrt{f_c'}}\right)^{X_{10}}+1.47\right]} \quad (MPa) \tag{3.10}$$

$$v_{jh}^{o} = 58.642 f_c^{X_1} \frac{\left[\left(\frac{h_b}{h_c}\right)^{X_2}\left(\frac{h_b}{b_b}\right)^{X_3}\left(\frac{b_j}{h_c}\right)^{X_4}\left(\frac{\rho_b f_{yb}}{\sqrt{f_c'}}\right)^{X_5}\left(\frac{f_c'}{f_{yb}}\right)^{X_6}\right]^{X_7}}{\left(\frac{h_b}{h_c}\right)^{X_8}\left[1-\sqrt{1+4\left(\frac{h_b}{h_c}\right)^{X_9}}\right]\left[-0.672\left(\frac{\rho_b f_{yb}}{\sqrt{f_c'}}\right)^{X_{10}}+1.217\right]} \quad (MPa) \tag{3.11}$$

Where, p_t^o and p_t^c are principal tensile stress under opening and closing behavior, h_b and h_c is depth of beam and column. b_b and b_j width of beam and joint. f'_c is compressive strength of concrete. f_{yb} is the tensile yield strength of reinforcement. ρ_b is the tensile reinforcement ratio.

The regression coefficient for Eq (3.10) and (3.11) are tabulated in Table 3.6.

Table 3.7: Regression coefficients

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}
Closing	0.30	0.23	-0.12	-0.49	0.18	1.00	-0.02	1.00	1.00	1.00
Opening	-0.88	-1.28	-1.57	1.5	0.31	1.00	0.08	1.00	1.00	0.5

3.8 Statistical Parameters for Validation

In this section few statistical parameters are picked to find the accuracy of the proposed equation. Performance factor, coefficient of Variation, coefficient of determination and student two-T test are normally picked to compare the results of shear stress in the knee joint by proposed equation with the previously proposed in the literature. Using these statistical parameters, the proposed equation is also compared with the equation proposed by the structural design codes. Based on these statistical parameters, the accuracy and efficiency of the proposed equation will be accessed.

3.8.1 Performance Factor

The performance factor is generally used to check, how much accurate and efficient the model is to predict the shear strength of RC knee joint. For a model to estimate a good prediction, the net value of the performance factor should be closer to the 1. The value of the performance factor will be equal to 1, Mathematically the performance factor is shown in Eq. 3.14

$$(PF) = \frac{v_{Exp}}{v_{Est}} \tag{3.12}$$

3.8.2 Coefficient of Variation (CoV)

The dispersion of the statistical points in the data sets around the mean is calculated by the coefficient of variation (CoV). It is generally defined as the ratio of the standard deviation to the mean of the total data set. This factor is usually helpful in calculating the degree of variation from one data series to another, even if the mean of the data set is different from each other. The extent of the variability of data in a sample in relation to the mean of the population is shown by the coefficient of variation (CoV). Mathematically the coefficient of variation is defined as

$$Coefficient\ of\ Variation = \frac{Standard\ Deviation}{Mean} \tag{3.13}$$

3.8.3 Coefficient of Determination

Total variation is defined as, the variability among the values of the dependent variable Y and is given by:

$$= \sum(y - \bar{y})^2 \tag{3.14}$$

The expression shown in Eq (3.16) is composed of two parts:

- The one which is explained by regression line i.e. $\sum(\hat{y} - \bar{y})^2$
- The one which regression line fails to explain, i.e. $\sum(y - \hat{y})^2$

$$Total\ Variation = Unexplained\ Variation + Explained\ Variation$$

$$\sum(y - \bar{y})^2 = \sum(y - \hat{y})^2 + \sum(\hat{y} - \bar{y})^2 \tag{3.15}$$

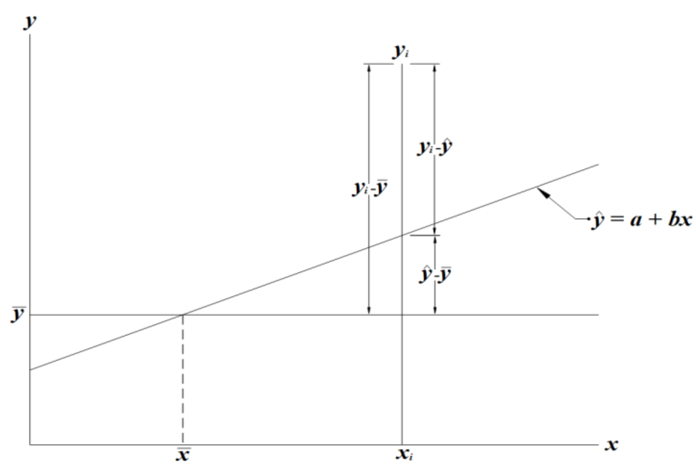

Figure 3.13: Graphical Representation of Coefficient of Determination

The ration of the explained variation to the total variation is termed as coefficient of determination and is represented as R^2. Mathematically, the coefficient of determination (R^2) is given by:

$$Coefficient\ of\ Determination = \frac{Explained\ Variation}{Total\ Variation}$$

$$R^2 = \frac{\sum(\hat{y}-\bar{y})^2}{\sum(y-\bar{y})^2} \tag{3.16}$$

$$R^2 = 1 - \frac{\sum(y-\bar{y})^2}{\sum(y-\bar{y})^2} \tag{3.17}$$

3.8.4 Student's t-Test

Another statistical indicator (t-statistic) is used to compare, whether the model's results are statistically significant at a particular confidence level. The t-statistic was calculated using Eq. 32 [41] and defined as If $\bar{X}$ and s^2 are the mean and variance, respectively, of a random sample of size n taken from population that is normally distributed having the t - distribution with $v = n - 1$ degree of freedom. given as:

$$t = \frac{\bar{X}-\mu}{\frac{s}{\sqrt{N}}} = \frac{\bar{d}-d_o}{\frac{s_d}{\sqrt{n}}} \tag{3.18}$$

Where

$\bar{X}$ = Sample mean

μ = Population mean (The sample mean was tested against a value of zero, i.e. μ=0, assuming no difference between experimental and analytical Joint Shear Stress (MPa)

s = Standard deviation

N = Sample size (number of observations)

v = Degree of freedom

The significant level $\alpha=0.05$ with $\mu=60$ degrees of freedom. The critical t-value is obtained $t_{\frac{\alpha}{2}}$, depends on the level of significance (α) and the degree of freedom ($n-1$). In order for the model's estimates to be judged statistically insignificant at the $(1-\alpha)$ confidence level, the calculated t value must be less than the critical t value. For present study the significance level was chosen to be $\alpha = 0.05$. Paired t-test was performed treating the difference as a random sample with mean $d_o=\mu_D=\mu_1-\mu_2$ i.e. the null and alternative hypothesis stated as H_o:$\mu_D= 0$ i.e. $\mu_1=\mu_2=0$ and $H_1 : \mu_D \neq 0$, respectively.

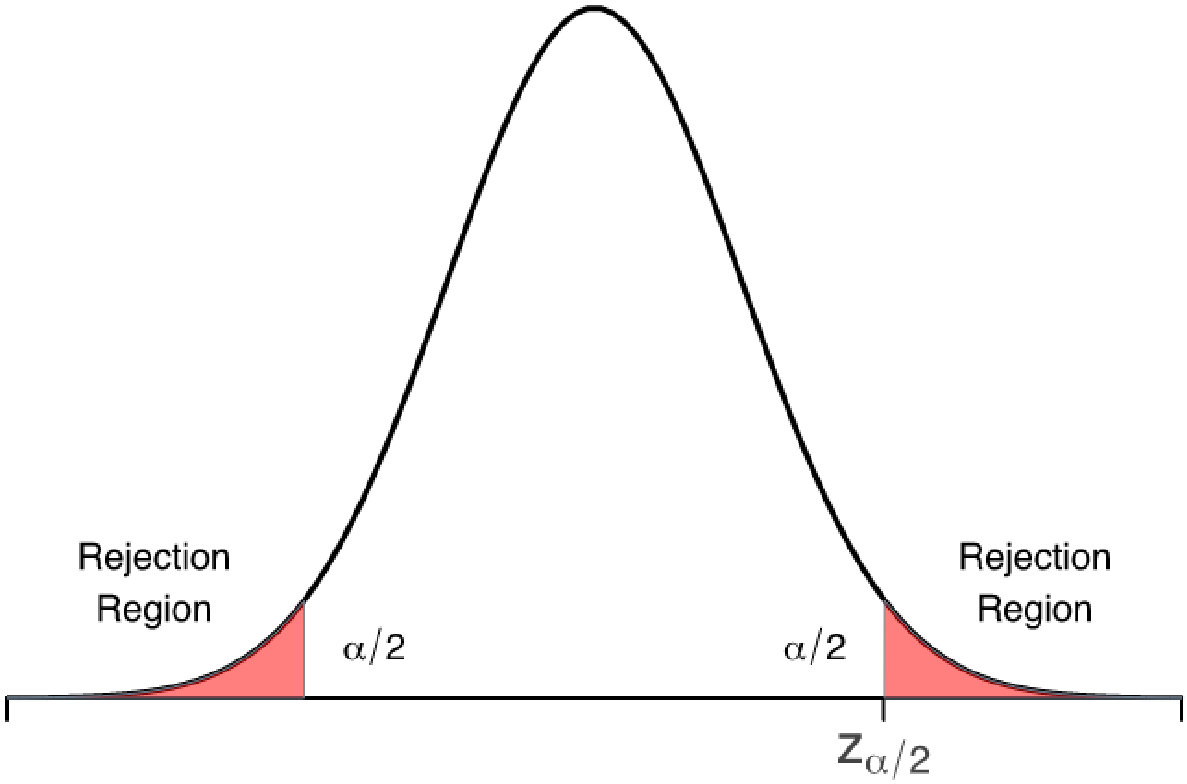

Figure 3.14: Graphical Representation of Student's t-Test

4 RESULTS AND DISCUSSION

4.1 Organization

In this section the proposed model for the opening and closing shear capacity is validated using different statistical tools. The statistical analysis is not only applied on the current model but it is also applied on the previously proposed model to estimate the robustness and efficiency of the current model over the previously proposed models. The two proposed models for opening and closing are also compared with the equation proposed by the different design codes. The variation of results is also represented graphically for better understanding.

4.2 Model Validation

Model Validation is an important step after the selection of the model. This step actually confirms the application of the proposed model on the given set of experimental data. In this research study the model is not only validate with experimental data set but also validate with the previous literature and code provisions.

In most of studies it has been observed that only R^2 is used as statistical tool for the validation of the model. Statistical literature reveals that higher R^2 does not always guarantee that the model will fits the data. It is also observed that a prediction model that does not fit the data points well, cannot give a good estimated result to the underlying engineering questions. Apart from using only one statistical tool for the validation purpose, it is necessary to apply different statistical tools available in the literature, to validate your proposed model. In this research study the statistical tool selected are discussed in detail in section 3.8. Using those statistical tools, a detail statistical analysis is performed. The results obtained from statistical analysis will be discussed in details for both opening and closing behavior.

4.3 Model Validation for Closing Shear Strength of RC knee joint

4.3.1 Coefficient of Determination Under Closing Behavior

The results of the proposed equation for finding the shear strength of RC knee joint under closing behavior is presented in Table 4.1and Fig 4.1-4.9, indicate that the proposed equation is more accurate and precise than the other existing models, as its coefficient of determination $R^2 = 0.98$. Among all the previously proposed models, the equation proposed by Mogili et al. [40] was more accurate than any of the other previous model. However, it's R^2 the value was 0.97. The equation proposed by Zhang [39] for predicting the shear strength of the RC knee joint under closing behavior had coefficients of determination equal to 0.96.

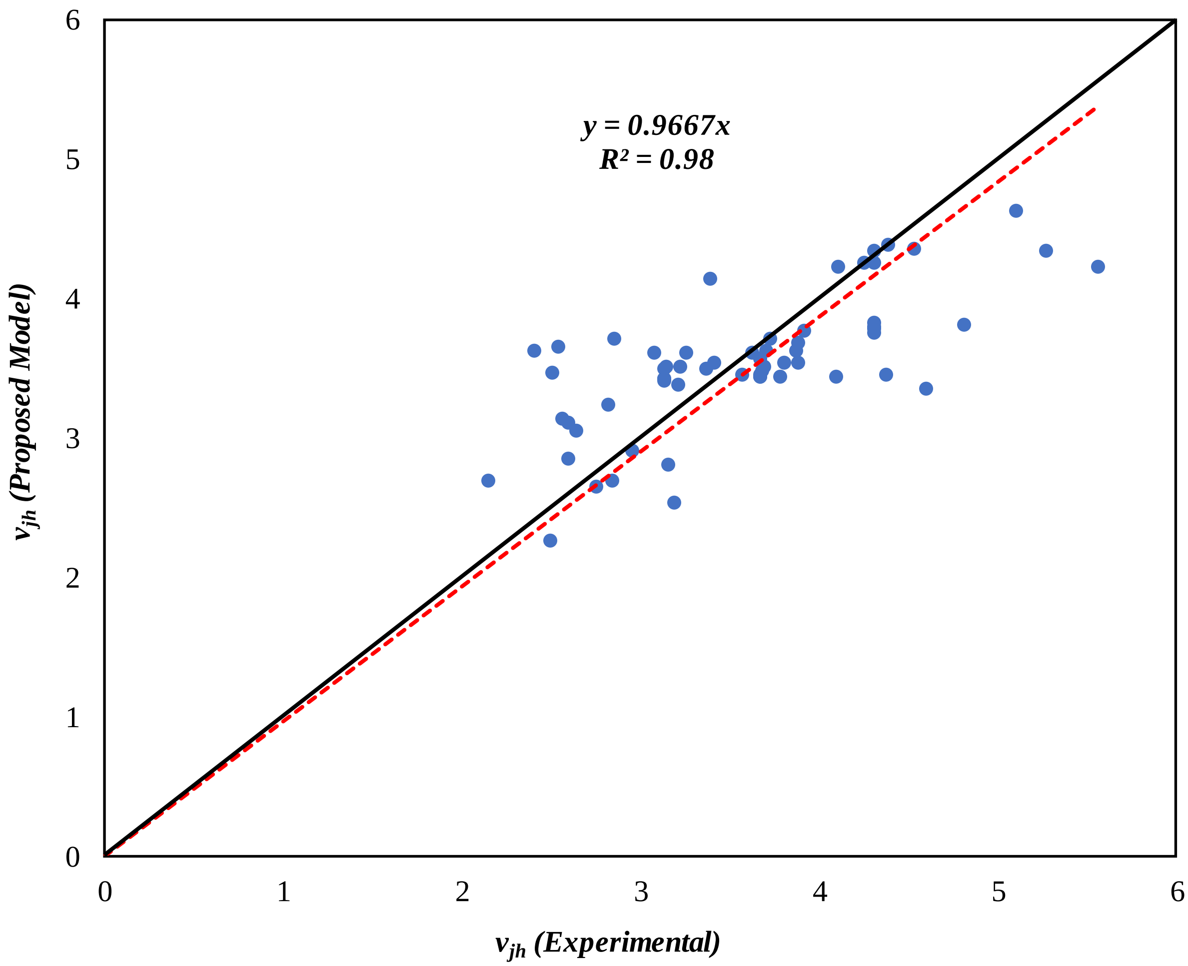

Figure 4.1: R^2 Value for the Proposed Equation

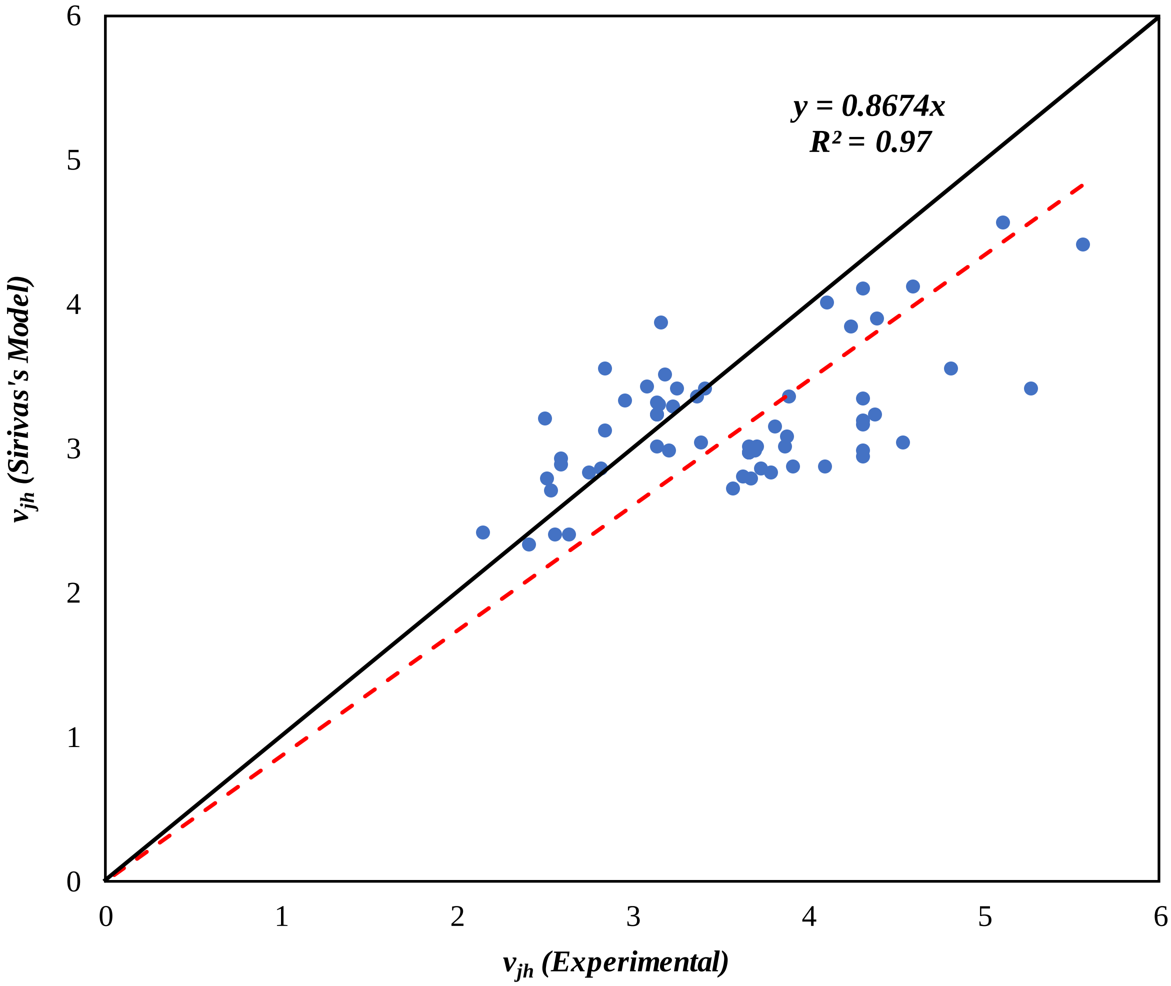

Figure 4.2: R^2 Value for the Mogili's Proposed Equation

4.3.2 Average Absolute Error Under Closing Behavior

The equation proposed in this research for predicting the shear strength of the RC knee joint under the closing moment has the lowest AAE (11 %) than the previously proposed model. The AAE value for the equation proposed by Mogili et al. [40], and Zhang [39] was 15% and 17%, respectively. The AAE and R^2 for the equation proposed are much better than other building codes equations as shown in Table 4.1-4.2

4.3.3 Performance Factor of Proposed Model Under Closing behavior

The average Performance factor (PF) obtained from the proposed equation is 1.01, which is much closer to 1. However, the average PF value obtained from the equation proposed by Mogili et al. [40], and

Zhang [39] was 1.13 and 1.04, respectively. The average performance factor for ACI [33], Eurocode [7], NZ3101:2006 [8], and GB50010 [16], are quite less than 1, however for AIJ, PF value is 0.98.

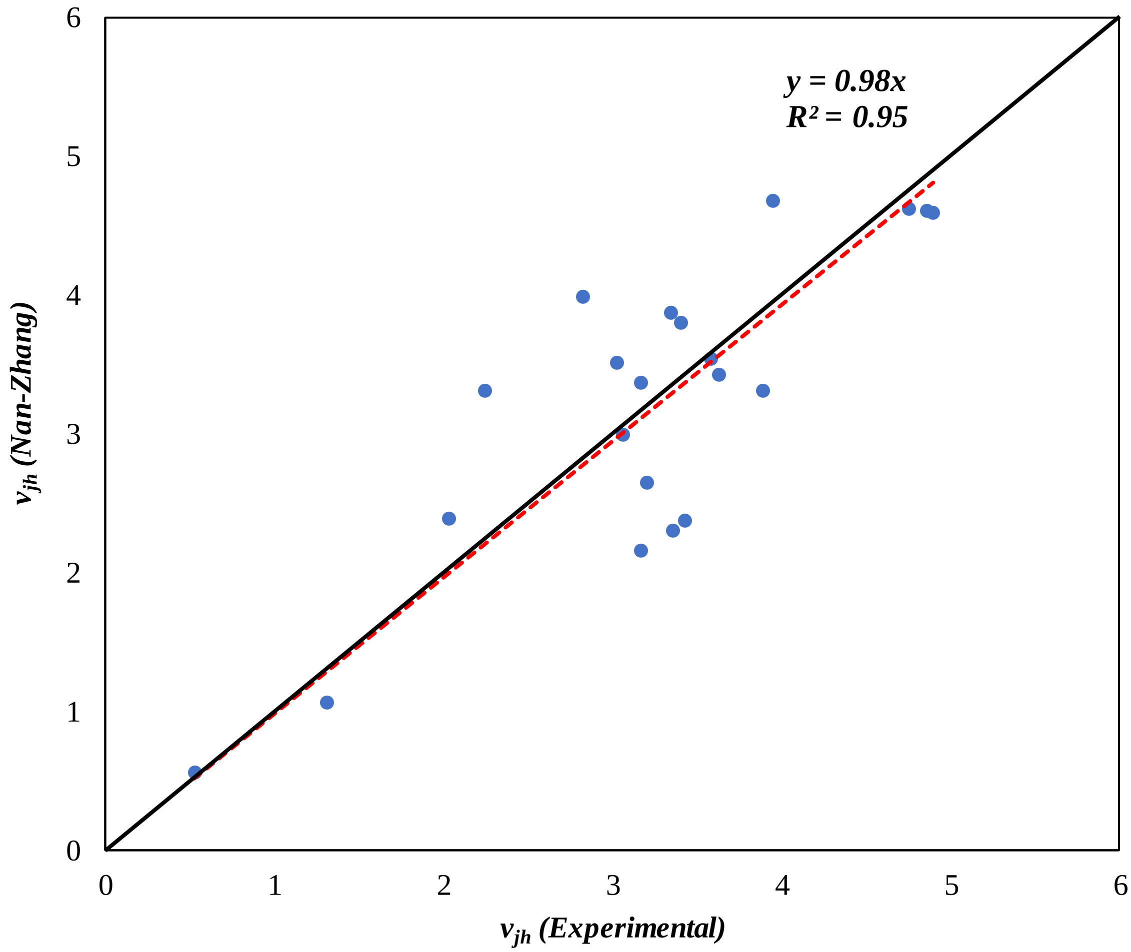

Figure 4.3: R^2 Value for the Zhang's Proposed Equation

4.3.4 Coefficient of Variation of Proposed Model Under closing moment

The *CoV* for the equation proposed in this research is 0.17, which is less than *CoV* obtained from the equation of Mogili et al. [40], and Zhang [39]. The *CoV* obtained from the AIJ [9] equation is less than the other codes equation. Hight *CoV* of ACI [33], Eurocodes [7], NZ 3101:2006 [8], and GB50010 [10] indicate a widespread in its results, making them more inaccurate for predicting the shear strength of the RC knee joint under closing behavior.

4.3.5 Student's t-Test Under Closing behavior

The $t_{Calculated} < t_{(0.025\,,\,60)}$ i.e., 0.60782 < 2.0002 for closing stress with degree of freedom $(v) = 60$ as shown in Table 4.3. Therefore, we do not reject the null hypothesis and accept the analytical model results at 5% level of significance

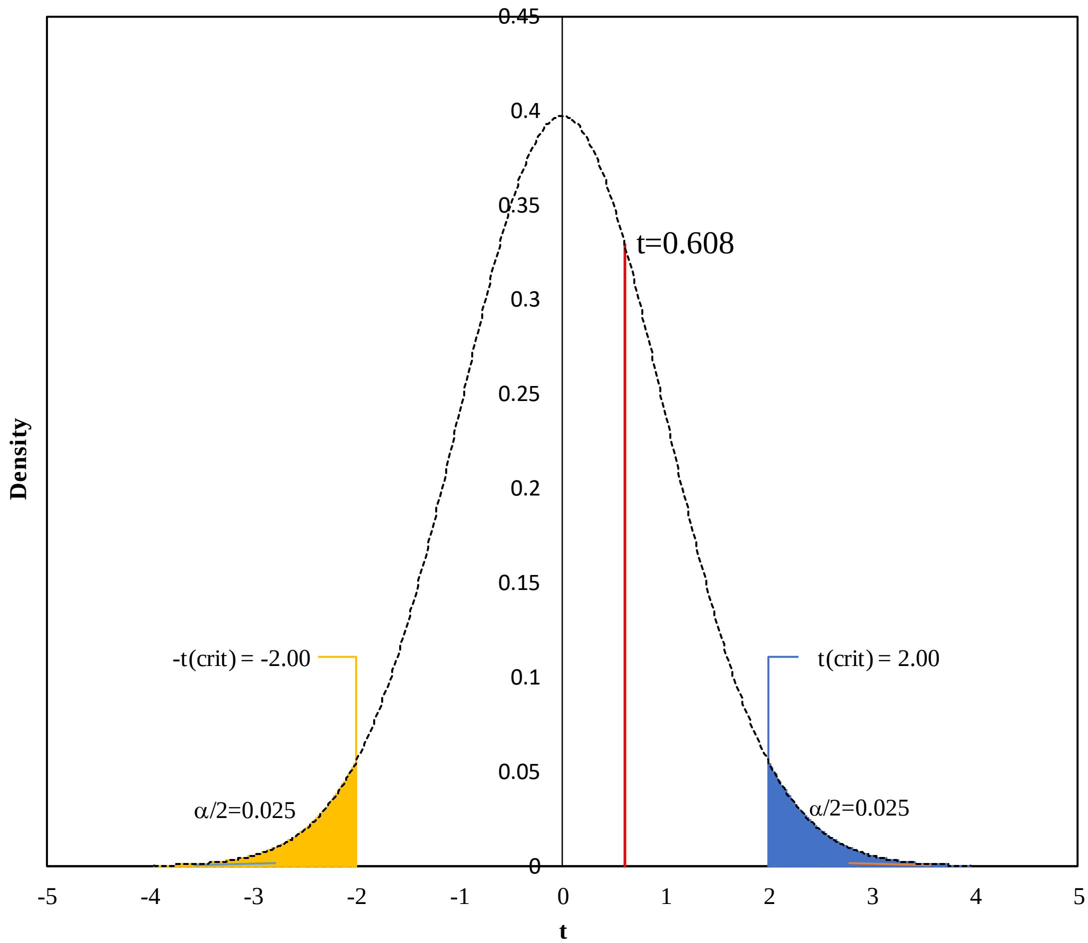

Figure 4.4: Student's t-test for shear strength of the knee joint Under Closing Behavior

4.4 Comparison of Proposed Model with Structural Design Codes for Closing Behavior

The Proposed Model is not only compared with the past literature models but also compared with the different models proposed in the structural design codes. The structural design codes picked for this study includes ACI [33], Eurocodes [7], NZS 3101:2006 [8], GB50010 [10] and AIJ [9]. One of the major differences between the proposed model and design code models is that, codes equation is only dependent on compressive strength of concrete while on the other hand the proposed equation is dependent on the variety of corelating factors.

4.4.1 Comparison of Proposed Model with ACI 352R-02 [33] Model

The statistical analysis revels that the ACI model slightly overestimated the shear capacity of the knee joint under closing behavior. It has been observed that the statistical parameters are not giving efficient results using ACI 318-14 proposed equation for estimating the nominal shear strength of RC knee joint under closing moment.

Fig 4.5 generally shows that ACI model for finding the shear strength of RC knee joint give result with average relative error of 0.22. On the other hand, the proposed model is giving results having the AAE value 0.11. It is also evident that the prediction of ACI is not on the conservative side.

4.4.2 Comparison of Proposed Model with Eurocode [7] Model

A huge over estimation is observed by the statistical comparison of the proposed model with the Eurocode. The average absolute error using this model comes out to be 1.42 which is much more than the average absolute error of proposed model 0.11. Fig 4.6 clearly shows that the Eurocode prediction for shear capacity of RC knee joint is away from the benchmark line of 45 degree.

4.4.3 Comparison of Proposed Model with NZS 3101:2006 [8] Model

A huge over estimation is observed by the statistical comparison of the proposed model with the New Zealand code. The average absolute error using this model comes out to be 1.08 which is much more than the average absolute error of proposed model 0.11. Fig 4.7 clearly shows that the NZS 3101:2006 prediction for shear capacity of RC knee joint is largely deviated from the benchmark line of 45 degree.

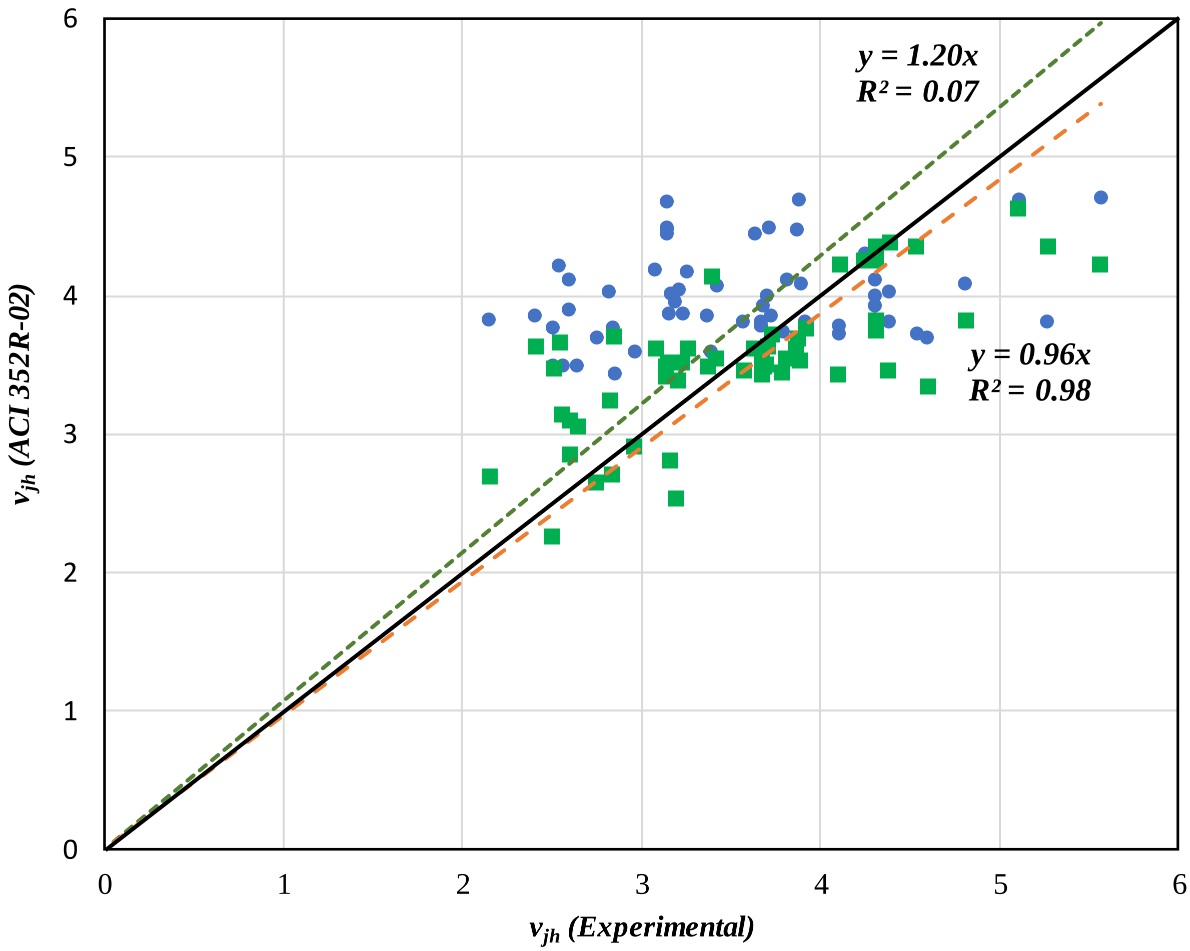

Figure 4.5: Comparison of ACI and Proposed Model for knee joint

4.4.4 Comparison of Proposed Model with AIJ [9]

The statistical analysis revels that the ACI [33] model slightly overestimated the shear capacity of the knee joint under closing behavior. It has been observed that the statistical parameters are not giving efficient results using AIJ [9] proposed equation for estimating the nominal shear strength of RC knee joint under closing moment.

Fig 4.8 generally shows that AIJ model for finding the shear strength of RC knee joint give result with average relative error of 0.19. On the other hand, the proposed model is giving results having the AAE value 0.11.

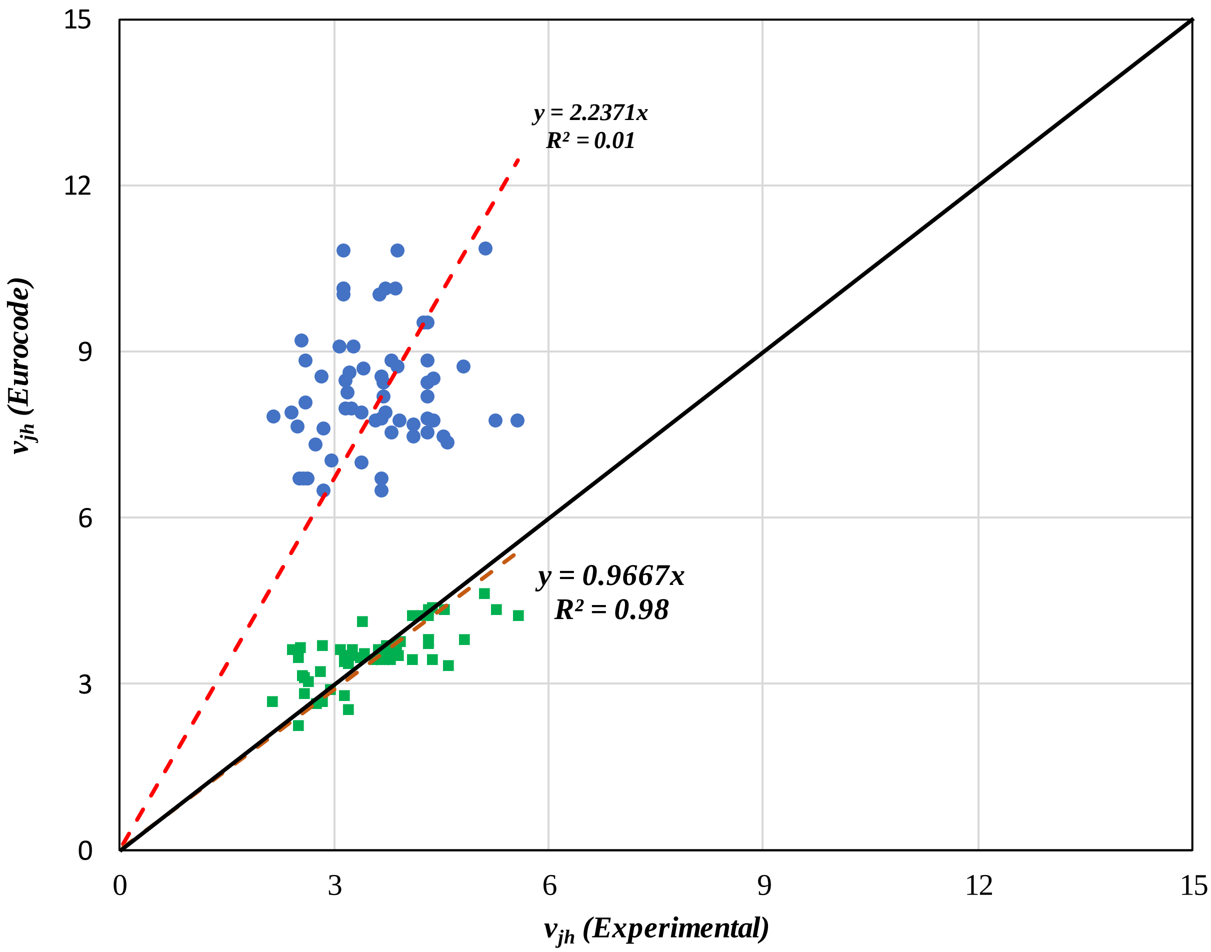

Figure 4.6: Comparison of Eurocode and Proposed Model for the knee joint

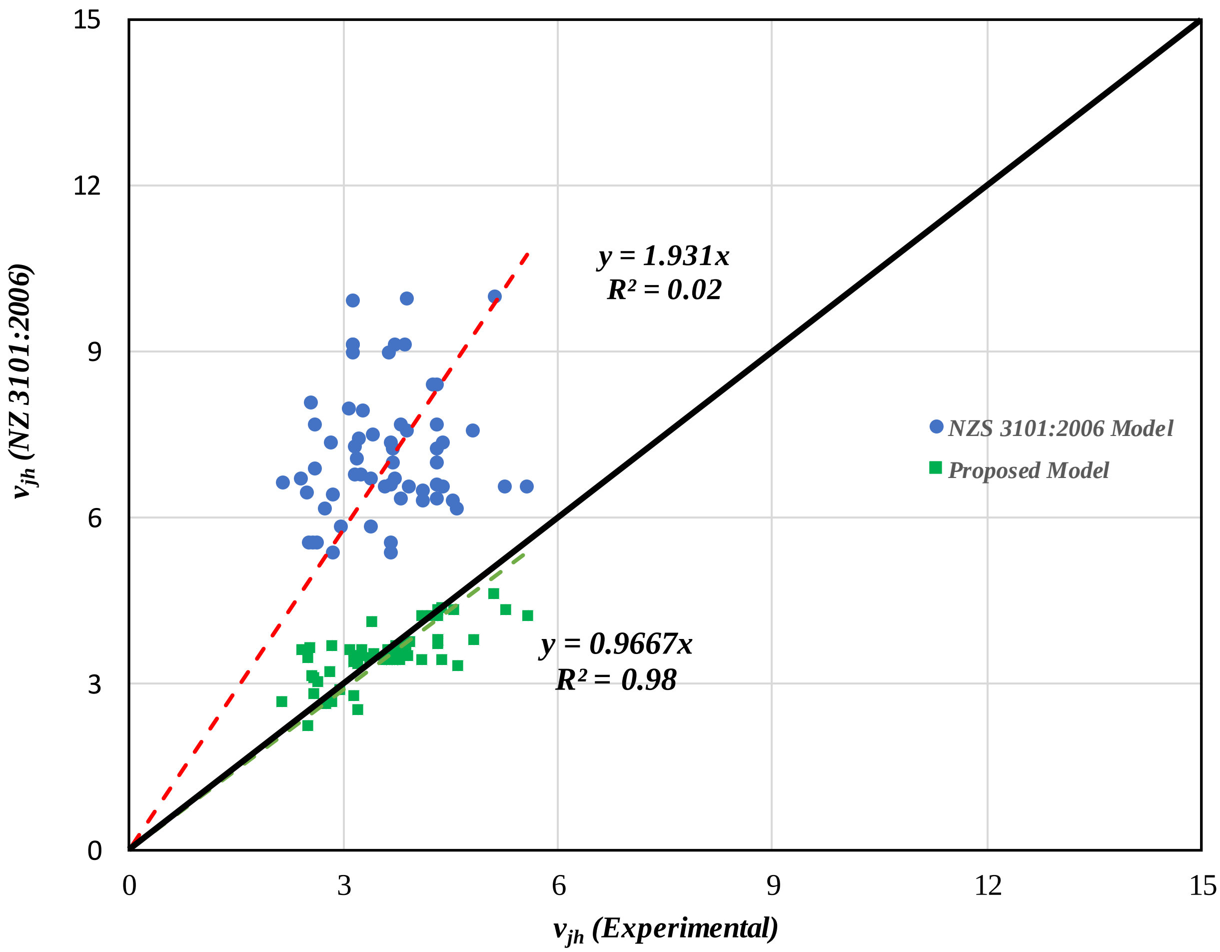

Figure 4.7: Comparison of NZS3101-2006 and Proposed Model for the knee joint

4.4.1 Comparison of Proposed Model with GB50010 [10]

A huge over estimation is observed by the statistical comparison of the proposed model with the Chicness structural design code model. The average absolute error using this model comes out to be 2.126 which is much more than the average absolute error of proposed model 0.11. Fig 4.9 clearly shows that the GB50010 [10] prediction for shear capacity of RC knee joint is largely deviated from the benchmark line of 45 degree.

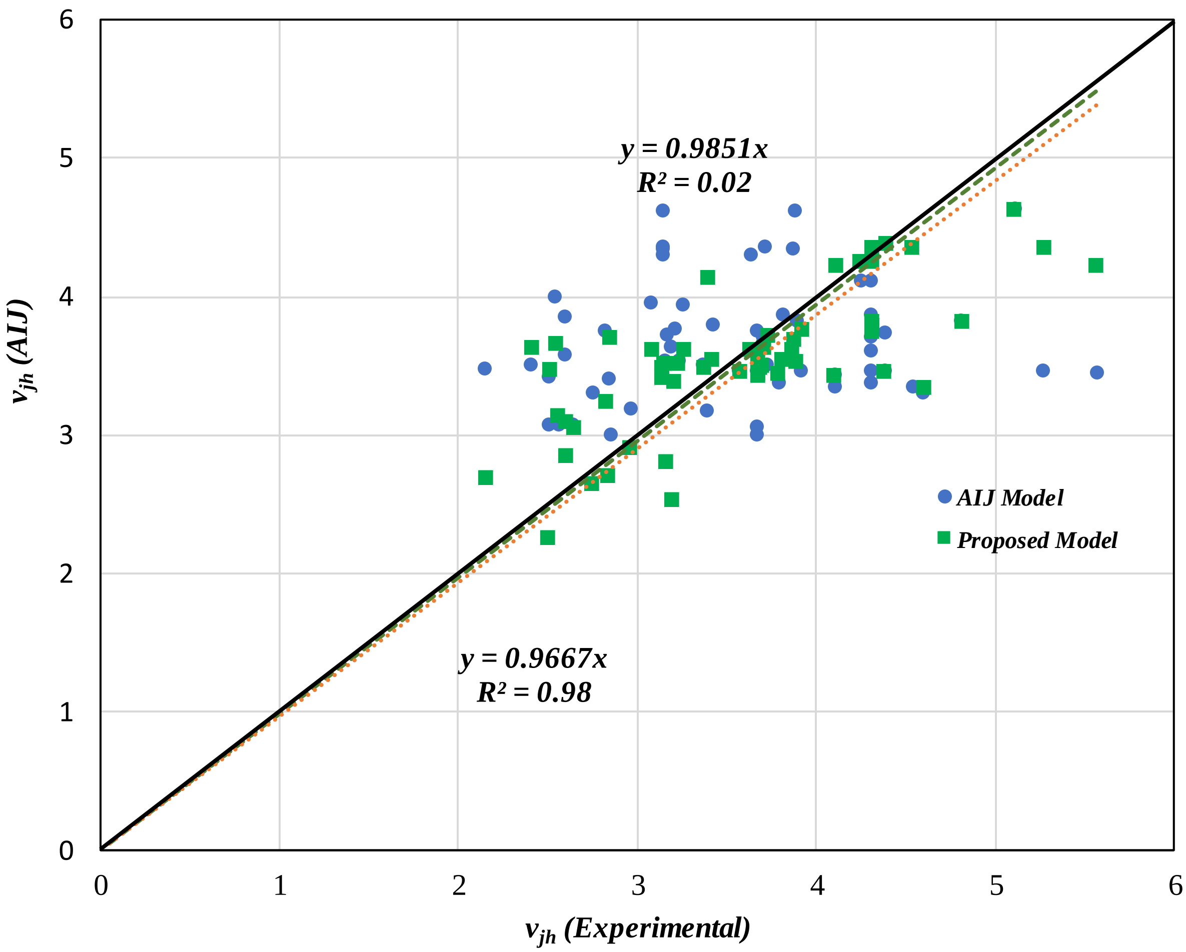

Figure 4.8: Comparison of AIJ and Proposed Model for the knee joint

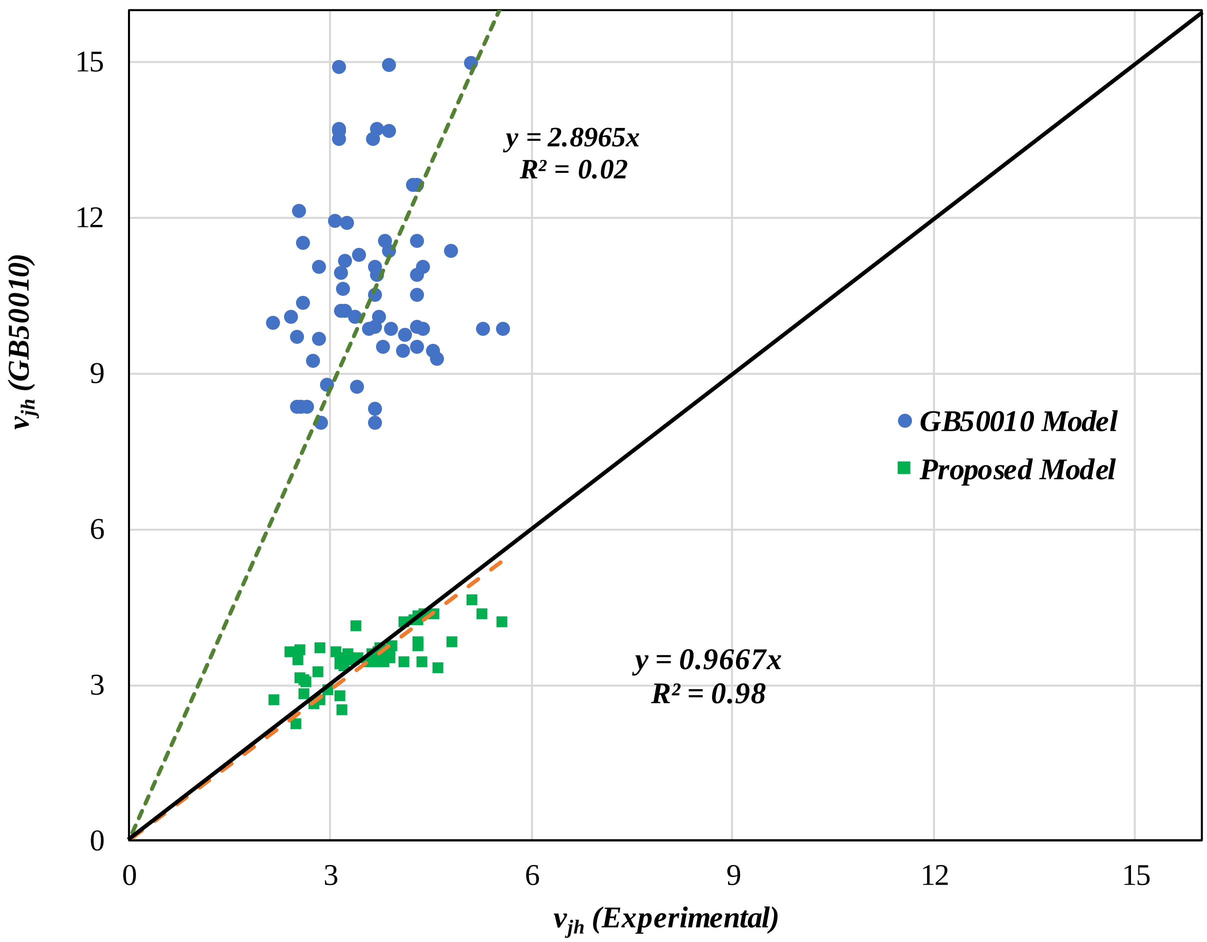

Figure 4.9: Comparison of GB50010 and Proposed Model for the knee joint

4.5 Model Validation for Opening Shear Strength of RC knee joint.

4.5.1 Coefficient of Determination Under Opening Behavior

By analyzing the results presented in Table 4.1-4.2 and Fig 4.10-4.18, it can be noticed that the proposed equation for predicting the shear strength of the RC knee joint under opening behavior is more accurate and precise than any of the other equation previously investigated. The coefficient of determination R^2 for the proposed model is 0.97 and superseded those of the previous models. The equations proposed by Mogili et al. [40] predicted the shear strength of RC knee joint better than any other previously proposed model with R^2 value 0.95. The R^2 proposed by different building codes is very low, which makes them less reliable to predict the shear capacity of the RC knee joint under opening behavior.

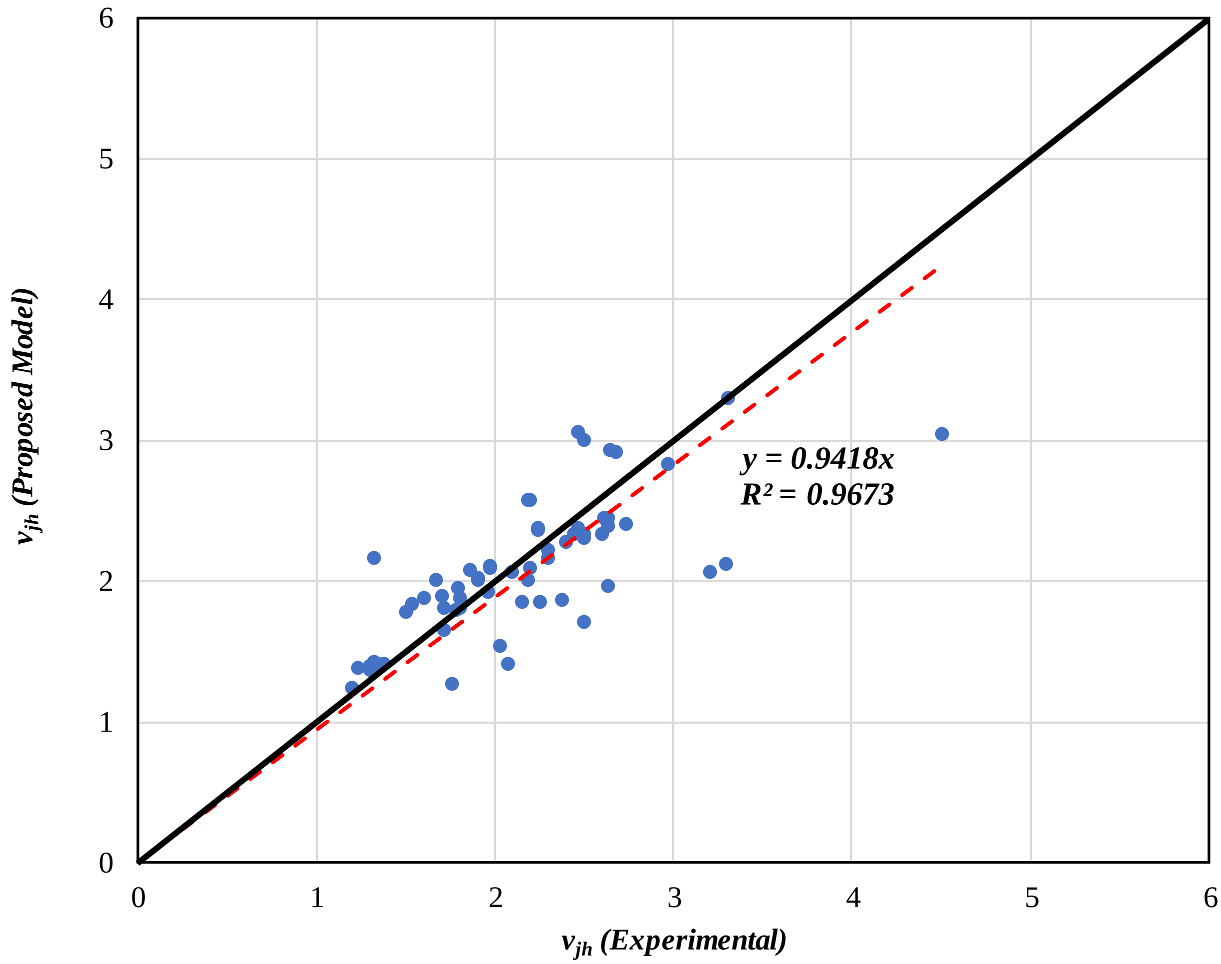

Figure 4.10: R^2 value for the proposed model

4.5.2 Average Absolute Error [AAE] Under Opening behavior

The equation proposed in this research has the lowest AAE value of 12.5%. Prediction of RC knee joint shear capacity using Mogili et al. [40] and Zhang [39] equations gives AAE value 18% and 37%, respectively. Shear strength prediction equations proposed by different building codes gives a high value of AAE and overly estimate the shear capacity of the RC knee joint under opening behavior as shown in Fig. 4.14-4.18

4.5.3 Performance Factor of Proposed Model Under Opening Behavior

The average performance factor of the equation proposed in this research for predicting the shear strength under opening behavior is 1.04. The equation proposed by Mogili et al. [40] and Zhang [39] has an average performance factor of 0.98 and 0.85, which are also close to 1. The average performance factor for ACI [33], Eurocode [7], NZ3101:2006 [8], and GB50010 [10], are much less than 1, which indicates their low performance in the prediction of shear strength of knee joint.

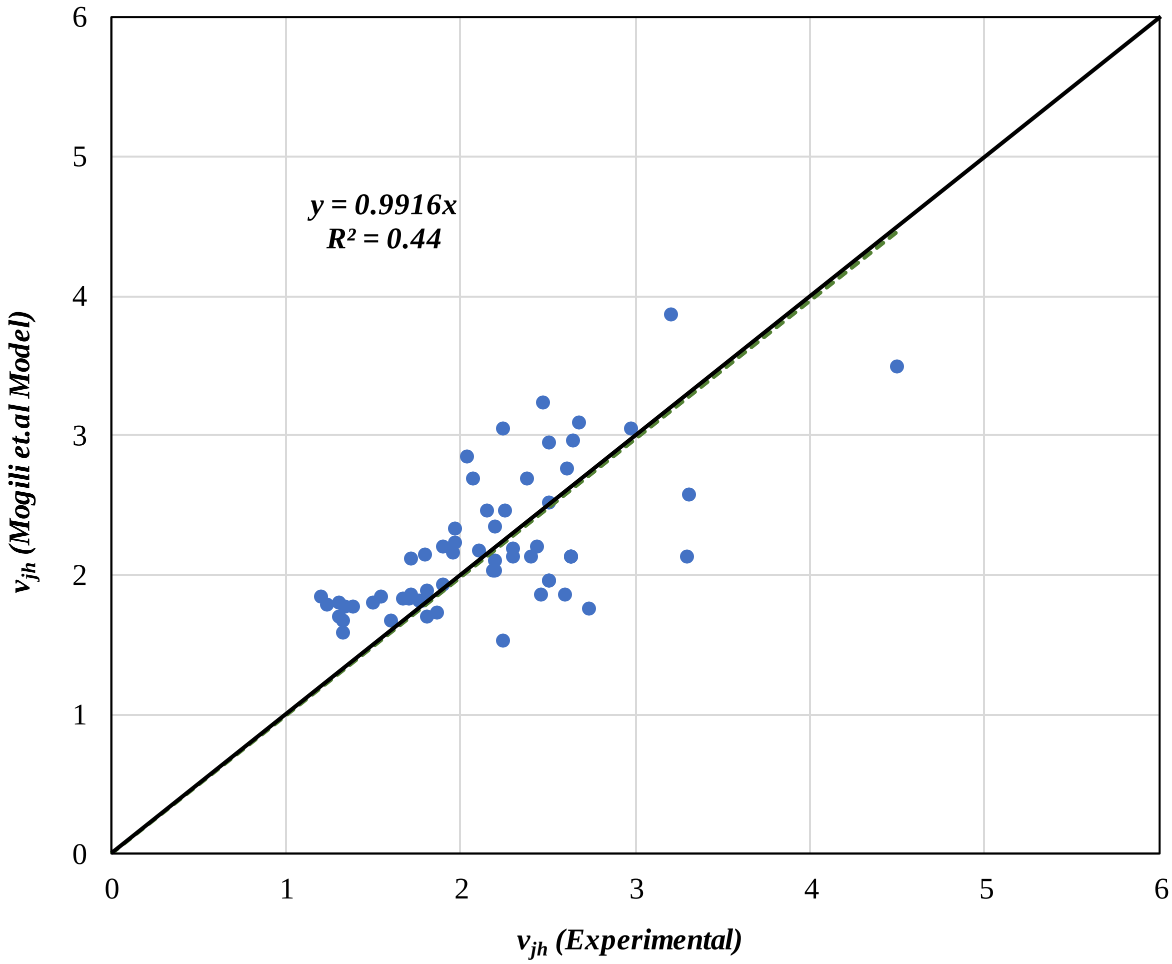

Figure 4.11: R^2 Value for the Mogili's Proposed Equation

4.5.4 Coefficient of Variation of Proposed Model Under Opening Behavior

The *CoV* for the proposed equation is 0.18. The model proposed by Mogili et al. [40] gave 0.22 *CoV*. The equation proposes by Zhang [39] has *CoV* equal to 0.31 and show more scatter results.

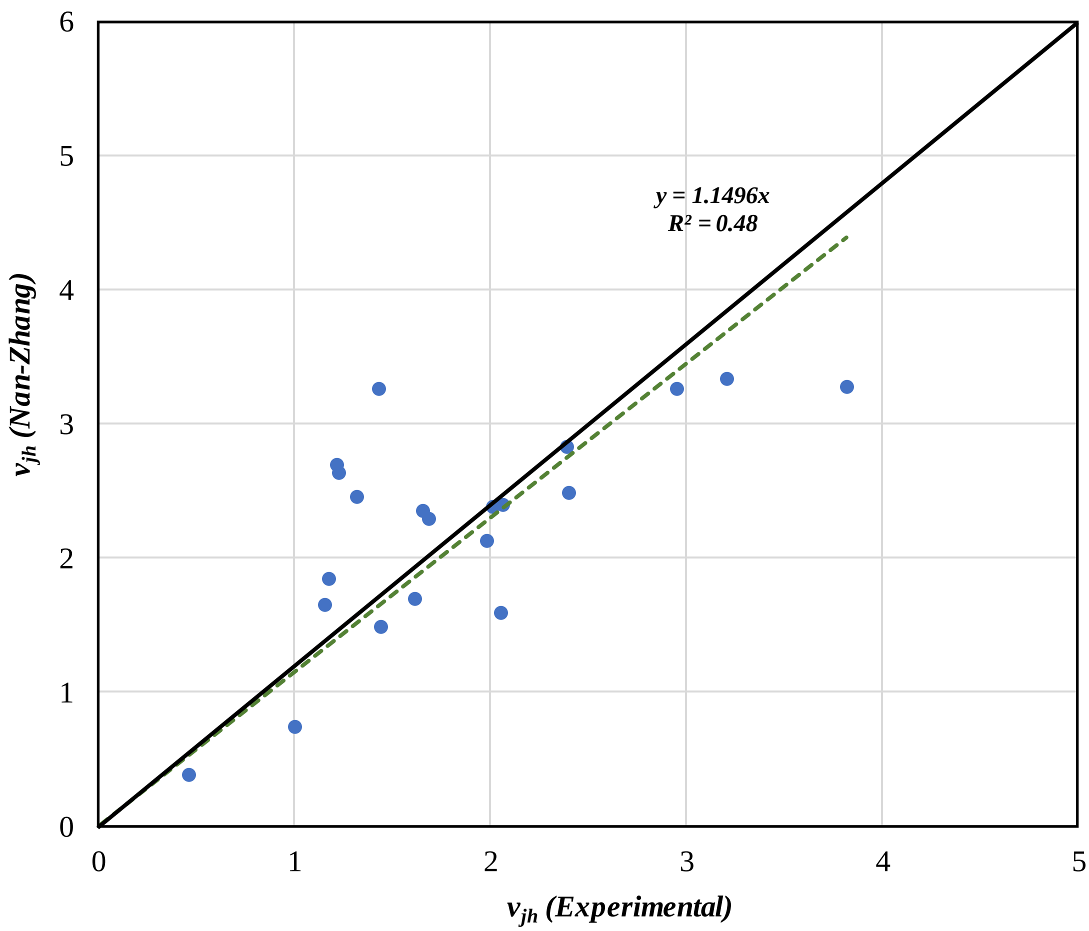

Figure 4.12: R^2 Value for the Zhang's Proposed Equation

4.5.5 Student's t-Test Under Opening Behavior

The $t_{Calculated} < t_{(0.025\,,\,60)}$ i.e. $-0.2811 < 2.0002$ for RC knee joint under opening behavior with degree of freedom $(v) = 60$ as shown in Table.4.3. Therefore, we do not reject the null hypothesis and accept the analytical model results at 5% level of significance.

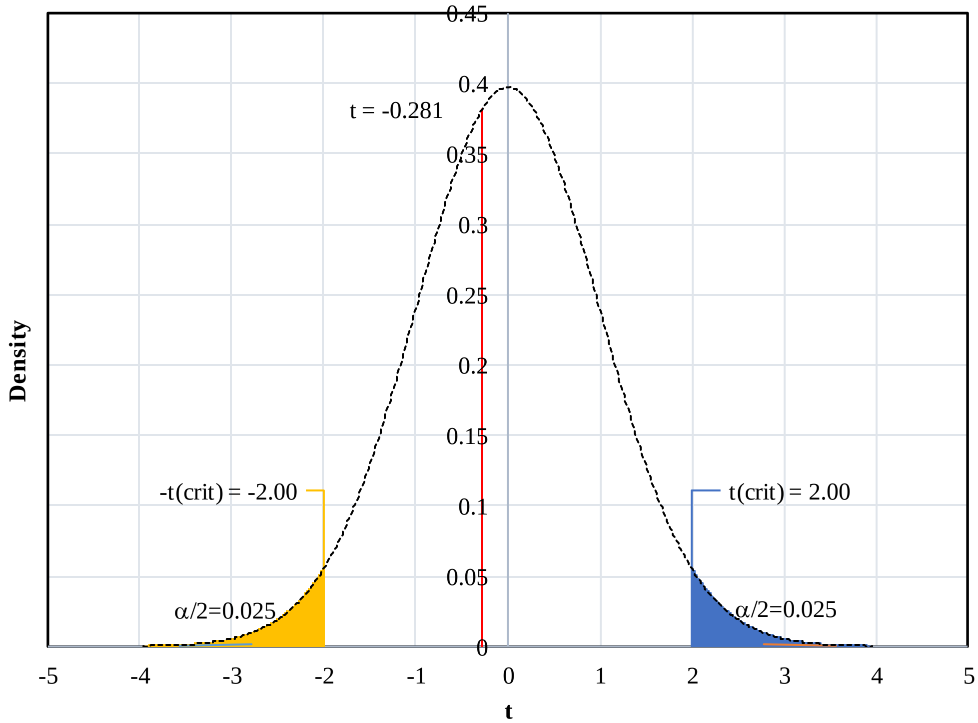

Figure 4.13: Student's t-test for shear strength of the knee joint Under Closing Behavior

4.6 Comparison of Proposed Model with Structural Design Codes for Opening Behavior

The Proposed Model is not only compared with the past literature models but also compared with the different models proposed in the structural design codes. The structural design codes picked for this study includes ACI [33], Eurocodes [7], NZS 3101:2006 [8], GB50010 [10] and AIJ [9]. One of the major differences between the proposed model and design code models is that, codes equation is that, they only depend on compressive strength of concrete while on the other hand the proposed equation is dependent on the variety of corelating factors.

4.6.1 Comparison of Proposed Model with ACI 352R-02 [33] Model

The statistical analysis revels that the ACI model largely overestimated the shear capacity of the knee joint under opening behavior. It has been observed that the statistical parameters are not giving efficient results using ACI [33] proposed equation for estimating the shear strength of RC knee joint under opening moment.

Fig 4.14 generally shows that ACI model for finding the shear strength of RC knee joint give result with average relative error of 1.01. On the other hand, the proposed model is giving results having the AAE value 0.12. It is also evident that the prediction of ACI [33] is not on the conservative side.

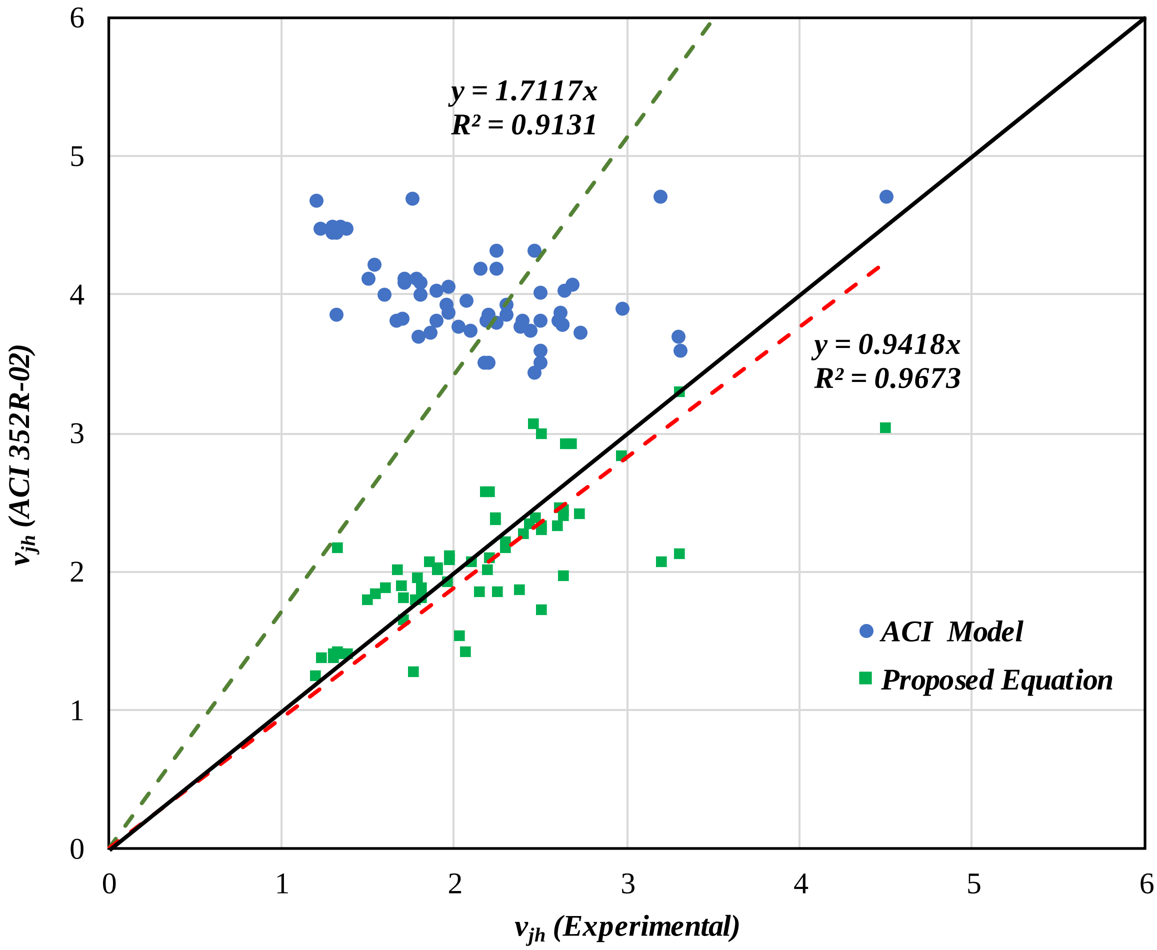

Figure 4.14: Comparison of Proposed Model with ACI Model

4.6.2 Comparison of Proposed Model with Eurocode Model

A huge over estimation is observed by the statistical comparison of the proposed model with the Eurocode, under opening behavior. The average absolute error using this model comes out to be 3.25 which is much more than the average absolute error of proposed model 0.126. Fig 4.15 clearly shows that the Eurocode prediction for shear capacity of RC knee joint is away from the benchmark line of 45 degree.

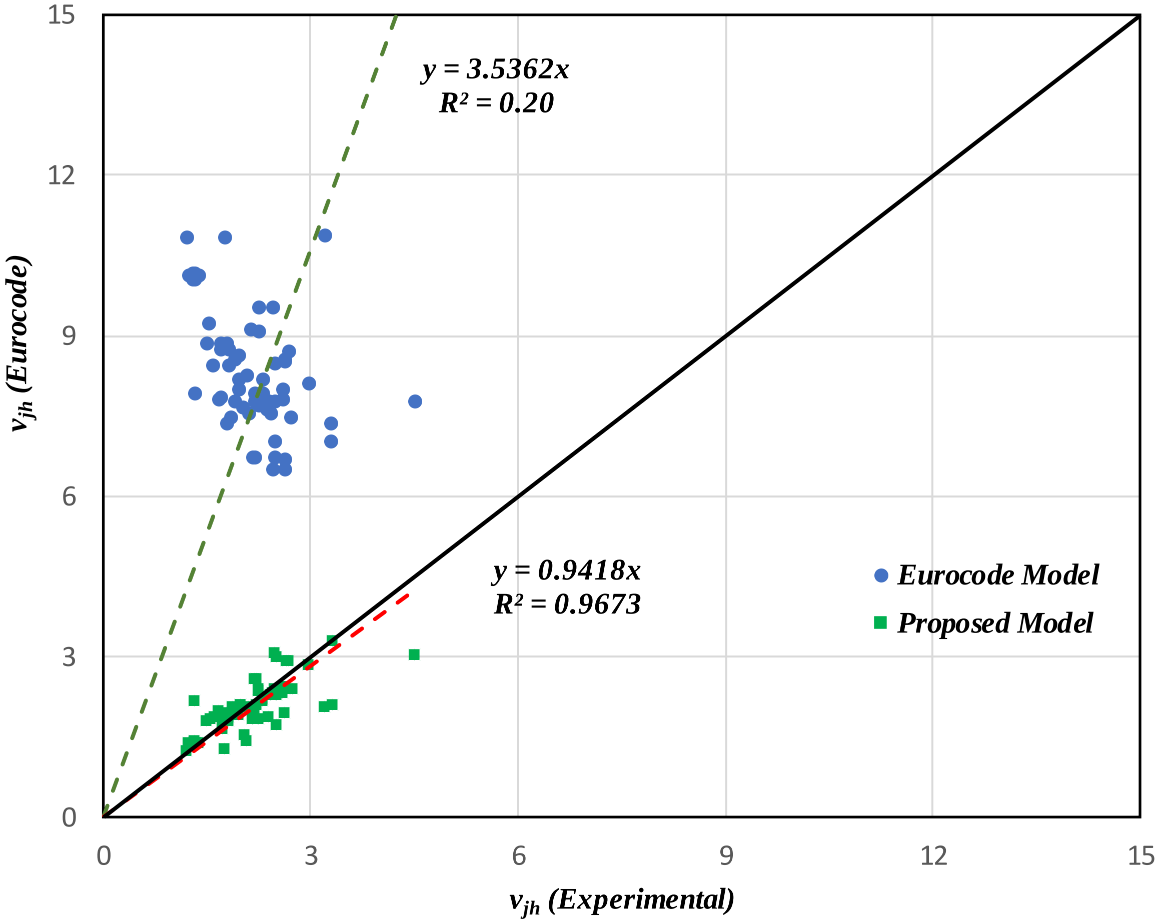

Figure 4.15: Comparison of Proposed Model with Eurocode Model

4.6.3 Comparison of Proposed Model with NZS 3101:2006 [8]

A huge over estimation is observed by the statistical comparison of the proposed model with the New Zealand code. The average absolute error using this model comes out to be 1.08 which is much more than the average absolute error of proposed model 0.126. Fig 4.16 clearly shows that the NZS 3101:2006 prediction for shear capacity of RC knee joint is largely deviated from the benchmark line of 45 degree.

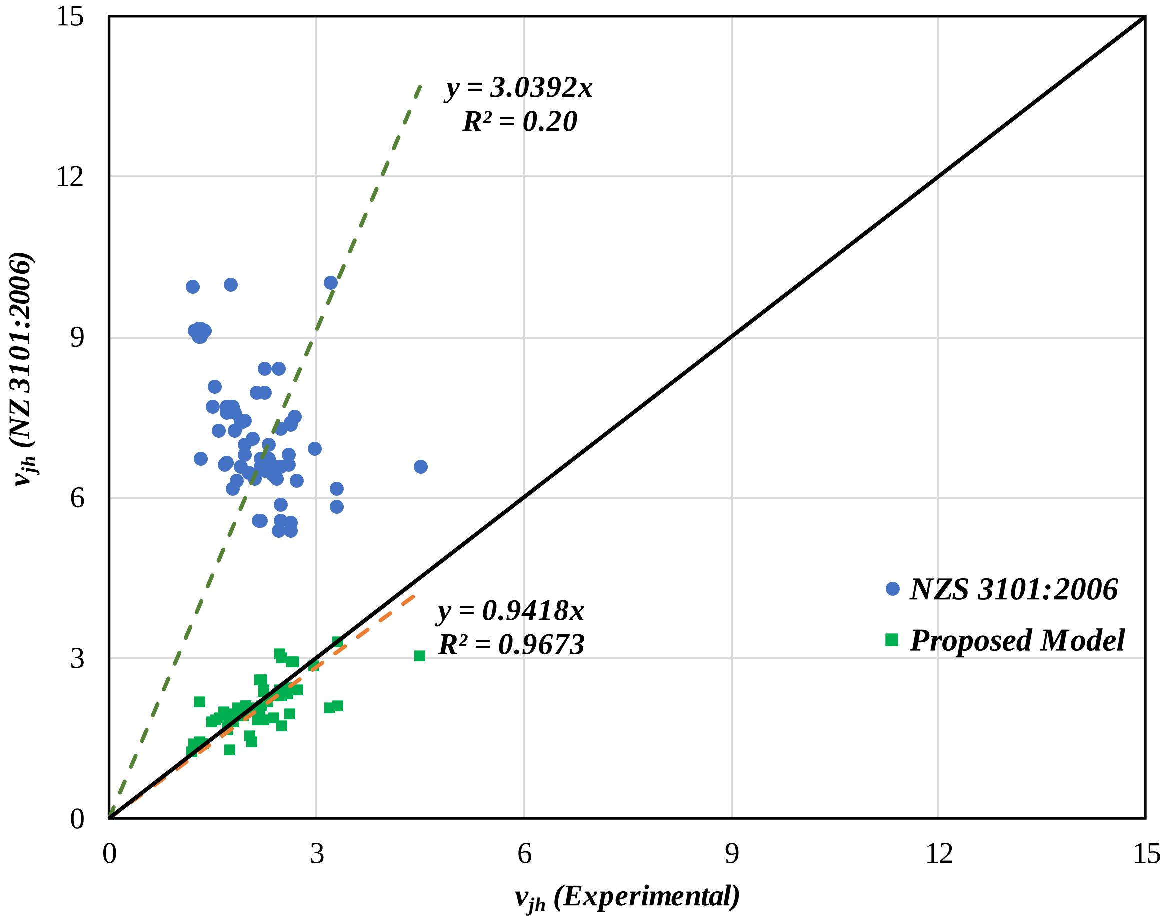

Figure 4.16: Comparison of Proposed Model with NZS 3101:2006

4.6.4 Comparison of Proposed Model with AIJ [9]

A huge over estimation is observed by the statistical comparison of the proposed model with the Japanese code. The average absolute error using this model comes out to be 0.19 which is more than the average absolute error of proposed model 0.126. Fig 4.17 clearly shows that the AIJ [9] prediction for shear capacity of RC knee joint is largely deviated from the benchmark line of 45 degree.

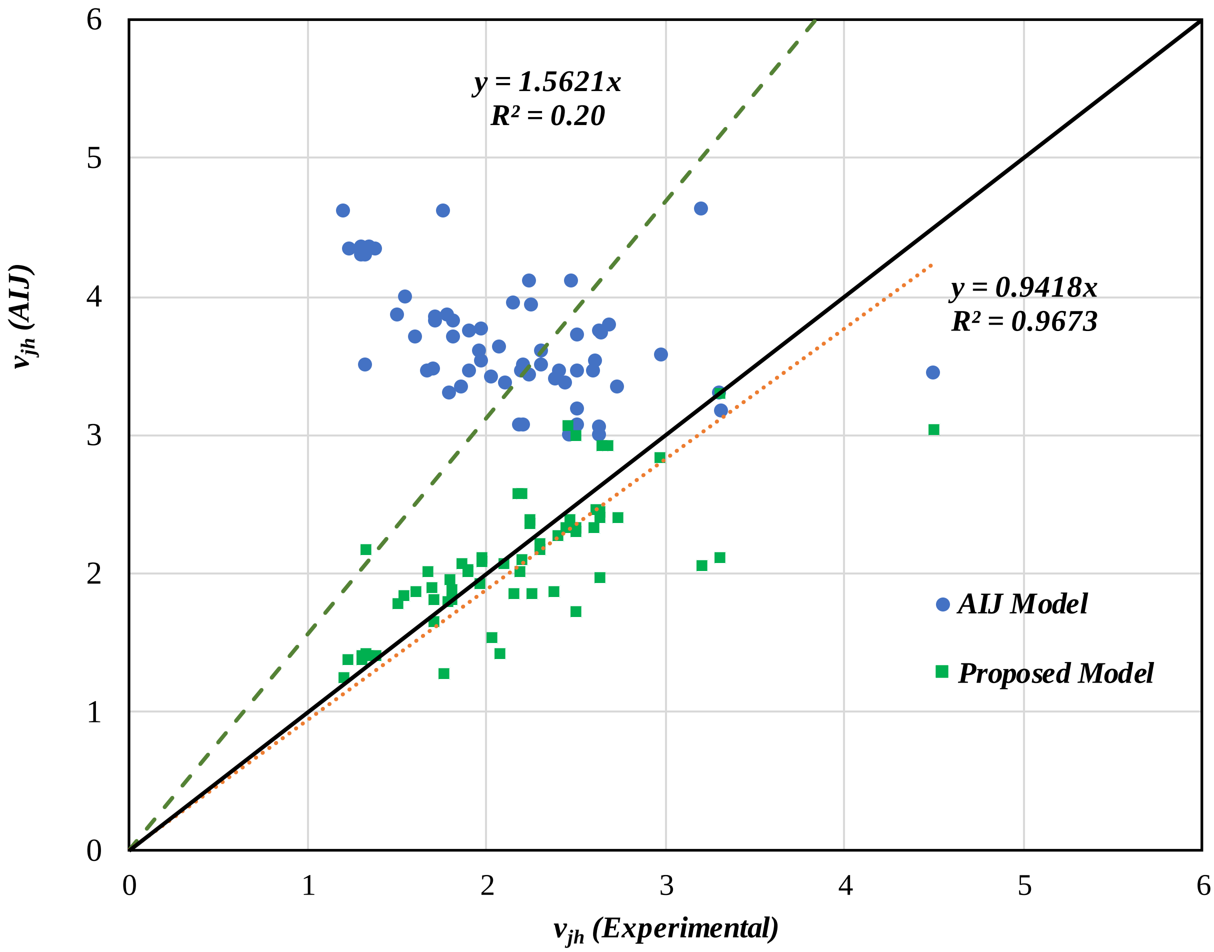

Figure 4.17: Comparison of Proposed Model with AIJ

4.6.5 Comparison of Proposed Model with GB50010 [10]

A huge over estimation is observed by the statistical comparison of the proposed model with the Chinese code. The average absolute error using this model comes out to be 4.50 which is much more than the average absolute error of proposed model 0.125. Fig 4.7 clearly shows that the GB50010 [10] prediction for shear capacity of RC knee joint is largely deviated from the benchmark line of 45 degree.

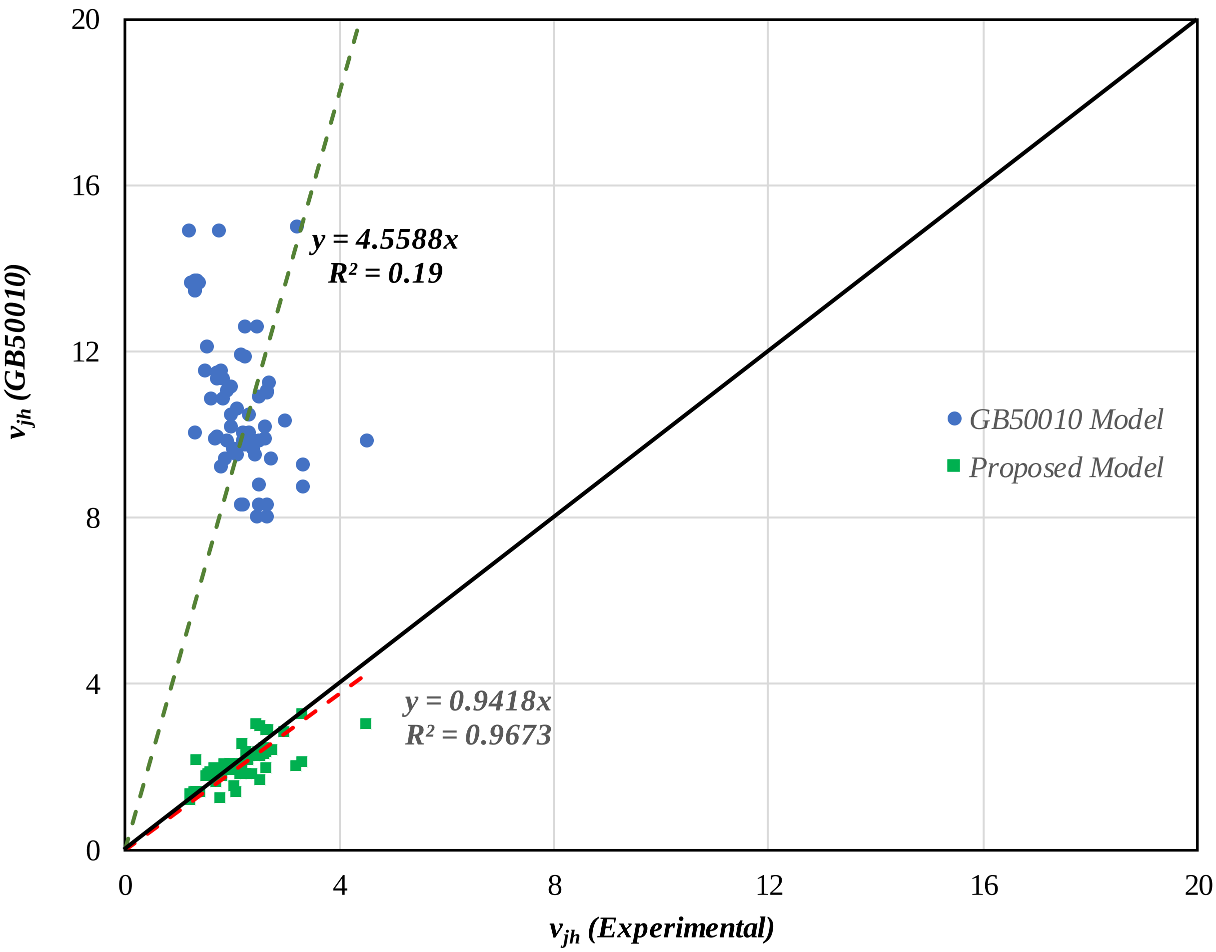

Figure 4.18: Comparison of Proposed Model with GB50010

Table 4.1: Statistical analysis of shear strength prediction of RC knee joint under opening moment

Author	$PF = \frac{v_{jh}^{Exp}}{v_{jh}^{Est}}$ ***Mean***	***Std. Deviation***	***COV (%)***	***AAE (%)***	R^2
Mogili et al.	0.98	0.210	22.0	18.0	0.44
Zhang	0.85	0.260	31.0	38.0	0.48
ACI 352R-02	0.55	0.160	29.0	101.0	0.06
EN 1998-1-2004	0.27	0.097	36.0	323.0	0.20
GB 50010-2011	0.21	0.079	37.0	450.3	0.19
NZS 3101-2006	0.31	0.113	36.0	266.8	0.20
AIJ (1999)	0.61	0.200	33.0	87.3	0.20
Proposed	1.04	0.230	22.0	12.6	0.97

Table 4.2: Statistical analysis of shear strength prediction of RC knee joint under closing moment

Author	$PF = \frac{v_{jh}^{Exp}}{v_{jh}^{Est}}$ ***Mean***	***Std. Deviation***	***COV (%)***	***AAE (%)***	R^2
Mogili et al.	1.13	0.190	17.3	15.0	0.34
Zhang	1.04	0.230	22.0	17.0	0.69
ACI 352R-02	0.90	0.180	20.0	22.0	0.07
EN 1998-1-2004	0.44	0.101	23.0	141.8	0.01
GB 50010-2011	0.34	0.083	24.5	212.6	0.02
NZS 3101-2006	0.51	0.125	24.5	108.4	0.02
AIJ (1999)	0.98	0.210	23.0	19.7	0.02
Proposed	1.01	0.146	14.6	11.7	0.98

Table 4.3: Student's t-Test under results for opening and closing

Description	***Opening***		***Closing***	
	v_{jh}^{exp} ***(MPa)***	v_{jh}^{Est} ***(MPa)***	v_{jh}^{exp} ***(MPa)***	v_{jh}^{Est} ***(MPa)***
Mean	2.16	2.17	3.58	3.54
Variance	0.38	0.38	0.56	0.23
Observations	61	61	61	61
Pearson Correlation	0.76		0.73	
Hypothesized Mean Difference	0.00		0.00	
df	60	60	60	60
t-Stat	-0.28		0.61	
t-Critical two-tail	2.00	2.00	2.00	2.00

4.7 Discussion

To predict the shear strength of the RC knee joint, a regression analysis was performed using the data presented in Table 2 and Table 3. The findings were compared to those derived from the experiments available in the literature to validate the accuracy of proposed equations for predicting the shear strength of the RC knee joints under opening and closing behavior.

Table 2 and Table 3 represents the closing and opening shear strength estimated according to the analytical model along with concrete strength and experimental shear strength by various researchers. The collected data sets contain specimens with varying reinforcement configuration and joint dimensions. The ratio of observed shear strength and predicted shear strength is termed as strength ratio. Fig 8 represents the strength ratio under opening and closing action. In closing and opening behavior of the RC knee joint, the shear strength estimation showed a satisfactory correlation with the experimental dataset, with a mean strength ratio of 1.00 and 1.01 under the opening and closing behavior, respectively, representing the accuracy.

From the statistical analysis discussed in section 12.2, it was determined that the equation proposed in this study for the shear strength prediction of the RC knee joint under the opening and closing behavior produced more accurate results as compared to any other previously proposed equations. The proposed models were also able to predict the shear strength of the RC knee joint better than any of the other previously proposed equations.

The equations proposed in this study for different geometric properties of the RC knee joint under the opening and closing behavior can produce more accurate results and those of previous equations since this study considers some more and different parameters. The shear strength prediction equations proposed in this research have a high coefficient of determination as compared to those previously presented, which implies the reliability of the proposed equations.

The equations proposed by different building codes overestimate the shear strength of the RC knee joint under the opening and closing behavior. Such overestimation can be dangerous for designers as the amount of shear reinforcement needed to prevent shear failure contains much more uncertainty. Shear strength overestimations, as in the case of some of the previously proposed model for RC knee joint, cannot be used in practice unless a proper safety factor or reduction factors are incorporated with the equations.

The proposed equation estimates for joint Shear Stress (MPa) for opening and closing are statistically non-significant i.e. there is no difference between experimental and analytical joint shear stress at 95 percent of confidence level. It specifies that the proposed equation can be safely used.

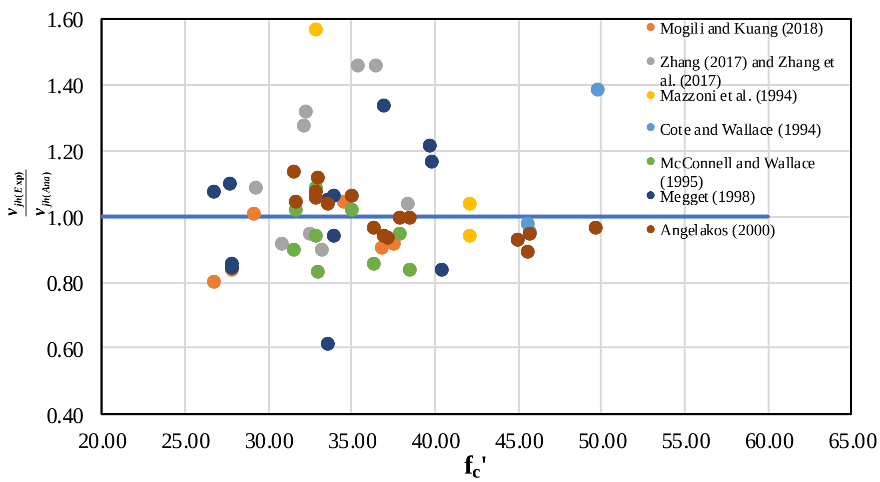

Figure 4.19: Strength ratio variation in RC knee joint under Opening behavior

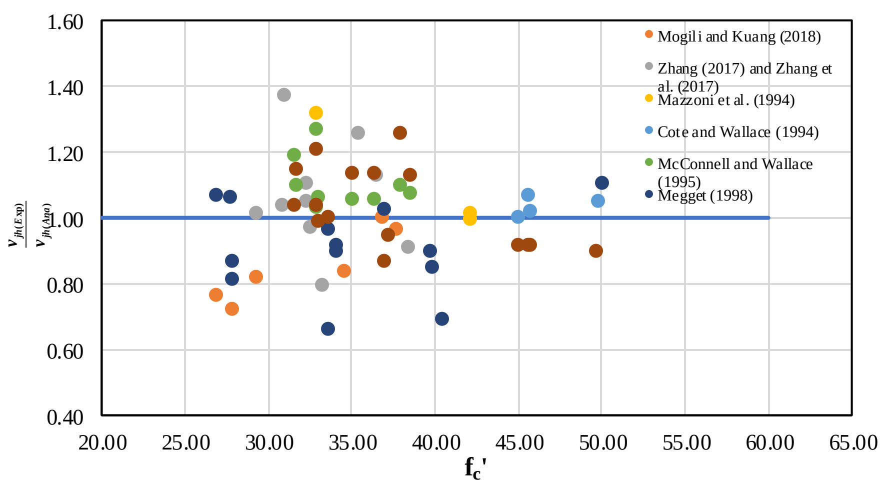

Figure 4.20: Strength ration variation in RC knee joint under closing behavior

5 CONCLUSION AND RECOMMENDATION

Shear behavior of the RC knee joint has not been fully understood because of several reasons. The assembly of the RC knee joint is different from that of the interior and exterior joints. The RC knee joint is subjected to reverse cyclic load, has two distinct behavior, i.e., opening and closing behavior. It is essential to understand better and predict the shear capacity of the RC beam-column knee joint for its broader application in the construction industry. Many researchers have developed analytical and numerical tools for predicting the shear strength of the RC knee joint. Developing such a model is a challenging task as there are several parameters such as concrete compressive strength, joint aspect ratio, steel tensile strength, and quantity of longitudinal and shear reinforcement. This research utilized previous experimental data to develop an equation for predicting the shear strength of the RC knee beam-column joint under the opening and closing behavior using regression analysis.

Several equations were developed to predict the shear strength of the RC knee joint based on concrete compressive strength, joint aspect ratio, and characteristics of longitudinal and shear stirrups, which were found to produce good results. In this study, the equation developed for the RC knee joint using regression could predict the shear strength of the RC knee joint with accuracy than any of the other previous models.

The equation proposed in this study for different configurations of RC knee joints can produce more accurate results than those of previous equations by different researchers. The coefficient of determination for the proposed equations is higher as compared to those previously predicted, which implies the reliability of proposed equations.

5.1 Recommendations

Extensive experimental investigations are required to evaluate the RC knee joint with more variability in the identified parameters that affect their shear strength. This will help to develop a better and more precise numerical tool considering an extensive database. Further research work will pave the path of the RC knee joint as a strong candidate in the construction industry. Such enhancement will reduce the failure risk and improve the capacity assessment of the RC beam-column knee joint.

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