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Original Article

Design of Reinforced Concrete Beam-Column Joint

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Abstract — *In general, Reinforced Concrete (RC) plays a significant role in the construction industry. A concrete devoid of reinforcement is weak in tension; thus, RC is highly significant. As a result, when the tensile stress goes beyond, the concrete is utilised with reinforcement, which augments the Tensile Strength (TS). This concrete can be constructed in numerous varied shapes and sizes, from a simple rectangular column to a slender curved dome or shell, as it is a robust construction material. In RC, the steel's TS and the concrete's Compressive Strength (CS) work jointly to permit the member to uphold the stresses over substantial spans. Therefore, the RC Beam-Column (RCBC) joints' design should be valued in-depth necessarily. Subsequently, the shear forces acting on joints, the methodologies utilised in shear forces acting on joints, the Shear Resisting Mechanism (SRM), systems utilised in SRM, along the RCBC joint's design specifications are reviewed in this work. Furthermore, the TS between Natural Aggregate Concrete (NAC) and Recycled Aggregate Concrete (RAC), the CS between NAC and RAC, and the reinforcing bar's tensile development length are also reviewed in this paper.*

Keywords — *Reinforcement, Beam column joint, Design, Shear resistance, Shear force, Beam column, Model, and Tensile.*

I. INTRODUCTION

RC is an adaptable composite with the most extensively utilised materials in modern construction. RC is also termed Reinforced Cement Concrete (RCC), a composite material. The concrete's lower TS or ductility is reimbursed by adding reinforcement possessing larger TS or ductility. All the sectors utilise RC in the capital amenities [1]. Better fire resistance, higher CS, lower maintenance, higher water resistance, and longer service life are the benefits of utilising this concrete [2]. The RC framed structures' performance highly relies on the Beam-Column Joint (BCJ).

The region of connection of beam along with columns is termed as joint. The column part is the most significant of the beams and columns [3]. The BCJs are categorised into '3' types in the RC structures: interior, exterior, and knee joints. The BCJ's reinforcement details devoid of sufficient Shear Reinforcement (SR) are explained in figure 1. The RC structures' design and construction are the '2' vital phases [4]. BCJs are the RC structures' significant part. RC is concrete in which the steel is inserted so that the '2' materials act jointly in resisting forces. For RC structures, concrete cracking and the interaction between concrete and reinforcement play a crucial role [5]. In the evaluation, it is estimated that the joints of the RC moment-resisting frames

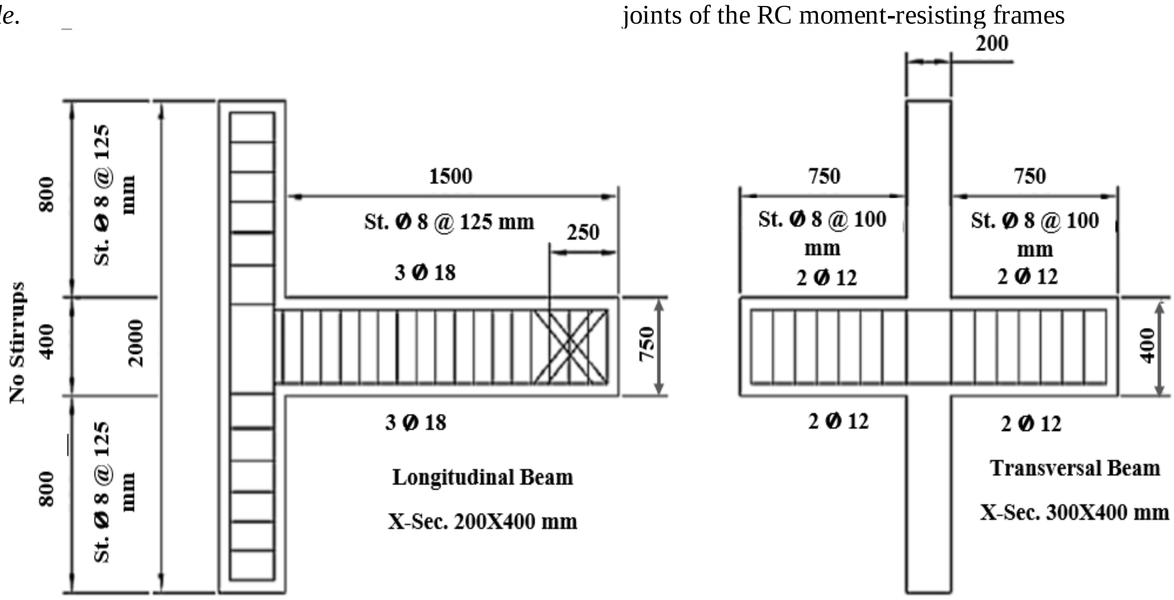

Fig. 1 Example for reinforcement details of a beam-column joint without adequate shear reinforcement

In RC structures, during the making of BCJ, there occurs a failure in a beam frequently. The cause behind the critical activities of the joint is the unexpected change in the geometry along with the complexity of stress distribution [7]. Following are the challenges faced by RCBC joints.

- ✓ Applying forces larger than the design load is an issue in BCJ.
- ✓ The cyclic load is marked by the amalgamation of diagonal tension, large shear forces, and higher bond stress in the reinforcement bars.
- ✓ Insufficient Transverse Reinforcement (TR), along with a deficiency in anchorage capacity in the joint, is the reason for the insufficiency of joints.

Nevertheless, under seismic conditions, to stimulate real RC frame buildings, there is a shortage of research in the behaviour of full-scale retrofitted BCJs [8]. A comparison is conducted between the behaviours of the strengthened joints and the control models. Under cyclic loading, a brittle failure is faced by the joints devoid of SR. However, their ductility is also increased [9]. Several experimentations showed that compared with joint specimens devoid of Partially Debonded Longitudinal Rebars (PDLRs) in the beams and columns, the joint specimens with PDLRs have smaller stiffness, lesser seismic damage, and the energy dissipating ratios, along with better ductility [10].

In the research, along with the construction industry, the design of RCBC joints has turned into a most demandable and promising field. Numerous researchers have evaluated the RCBC joint, but merely a few researchers explore ideas on the design of RCBC joints. Consequently, models on SRM and the RCBC joint's design specifications are being reviewed in this paper.

II. LITERATURE REVIEW

The SRM influences the RC beam section since it has been estimated that the RC beam's Shear Strength (SS) is decreased by the shrinkage of high-strength concrete than the low-shrinkage concrete. Therefore, it is effortless to study the design of RCBC joints whilst explicating the SRM. Thus, in this study, the shear mechanisms to the resistance of BCJ is illustrated in section 2.1; the shear forces acting on joints are proffered in section 2.2; the RCBC joint's design specifications are explicated in Section 2.3, and finally, the results along with the conclusion are given in section 3.

A. Shear Resisting Mechanism

The shear and bond mechanisms control the response of joints. These mechanisms display the worst hysteretic properties, so the joints should be considered inappropriate for energy dissipation [11]. The following are the '4' mechanisms that contributed to the BCJs' resistance.

- ✓ The strut mechanism
- ✓ The truss mechanism
- ✓ The confinement
- ✓ The bond in longitudinal confinement

B. Strut Mechanism

The diagonal concrete compression force in the joint leads to the formation of this mechanism. The vertical and horizontal compression stresses and the shear stresses on concrete at the beam and column are the reason for the generation of this force. The contribution of the horizontal or vertical reinforcement is not needed for the system to be equilibrium. This model is termed the strut mechanism [12]. This mechanism relies on the concrete's CS. The strut mechanism is explicated in figure 2.

Ho Choi et al. [13] examined the URM wall infilled RC frame's diagonal strut mechanism for numerous bays. It designed two ¼ scale model frames and the experiential parameter of the spans. The outcomes displayed that a diagonal compressive strut was formed by the two-bay specimen as the one-bay specimen in every infill wall. However, a better agreement with the overall lateral strength was not shown by the RC columns' summation and the CB's shear force.

Chuang Shi et al. [14] illustrated the cable-strut tensioned antenna mechanism's design along with multi-objective comprehensive optimisation. A new type of cable-strut tensioned antenna mechanism was implemented then subjected to multi-objective optimisation. The outcomes displayed that this mechanism with similar diameter's basic frequency values were 10.967, 12.258, and 15.574 Hz. However, detecting the relationship between the input structural parameters and output fundamental frequency.

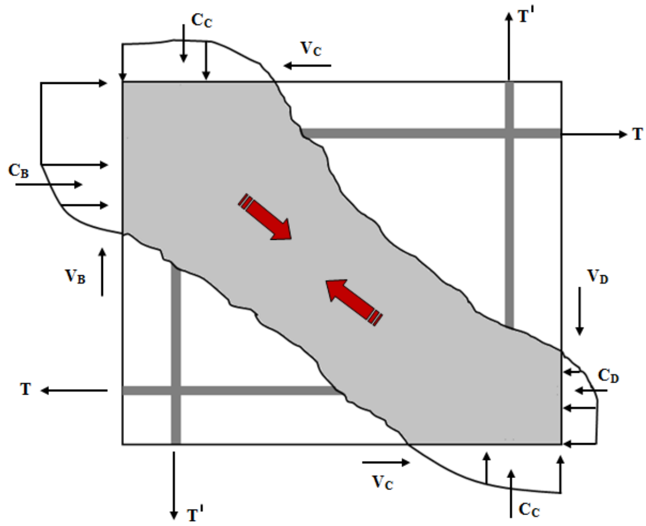

Fig. 2 Mechanism of strut

C. Truss Mechanism

The amalgamation of the bond stress transfer with the beam and longitudinal column reinforcement, the lateral reinforcement's tensile resistance, and compressive resistance of uniform diagonal concrete strut in the joint panel results in the formation of the truss mechanism. This mechanism relies on the lateral reinforcement's tensile yield strength crossing the failure plane. The truss mechanism is demonstrated in figure 3.

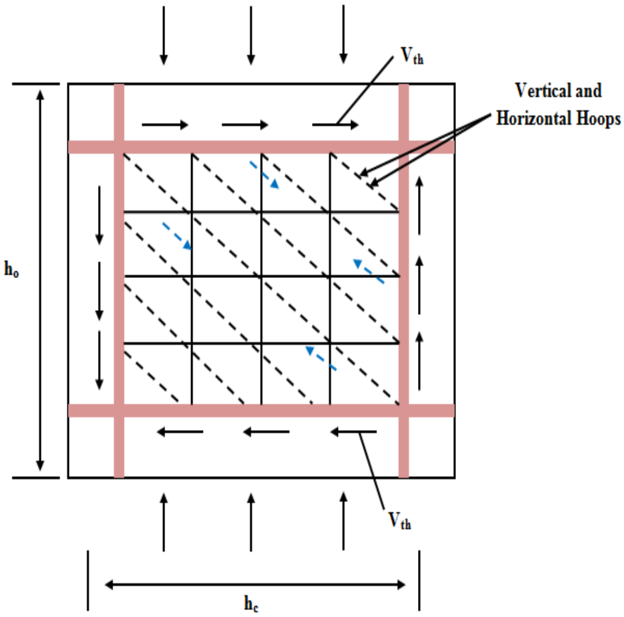

Fig. 3 Mechanism of truss

Rongfu Lin et al. [15] explicated the family of legged landers' topological design regarding the truss mechanism transformation methodology. Designing legged mobile landers was highly significant. The outcomes displayed that the TMT methodology was efficient for the robots' topological design to alter truss mechanisms. However, whilst attaining the extreme point, the links couldn't interpret in one direction; similarly, for '2' links linked by the R joint, the '1' link couldn't rotate if it was locked by the locking device being appended.

Liangliang Chen et al. [16] illustrated the deployable mechanisms' type synthesis for the truss antenna utilising accumulating constraint chains. The outcomes displayed that the mechanism's simulation model was developed utilising ADAMS; likewise, by including the appropriate '7' actuators, the fully unfolded, half-folded, and the fully folded states were achieved, which were appended at joints R17, R27, R37, R39, R14, R24, and R34. However, the nodes on the bottom face couldn't reach the required attitude adjustment since the 3R-3RRR mechanism had no DOFs.

D. Confinement

The concrete resistance dominates the strut resistance, whilst the TR provides the confinement. The following are the reasons for strut failure: when compression or tension occurs in the concrete of a joint; when the joint stirrups reach the ultimate strain. Beam longitudinal bar slippage occurs due to loss of bond; however, it doesn't cause any joint failure. Maintaining the joint concrete's integrity, reducing the stiffness rate, enhancing the joint concrete toughness, and strengthening deterioration are the joint core's confinement objectives. The '3' major factors served by the confining reinforcement are,

- ✓ It offers shear resistance to the member.
- ✓ The ultimate strain of the concrete is increased by limiting the concrete core; thus, a concrete cross-section is provided by greater ductility.
- ✓ The compression reinforcement is provided with the lateral restraint against buckling. The experiential outcomes displayed that the external beam-columns seismic capacity is enhanced significantly by using rectangular spiral reinforcement. The joint's confinement is explicated in figure 4.

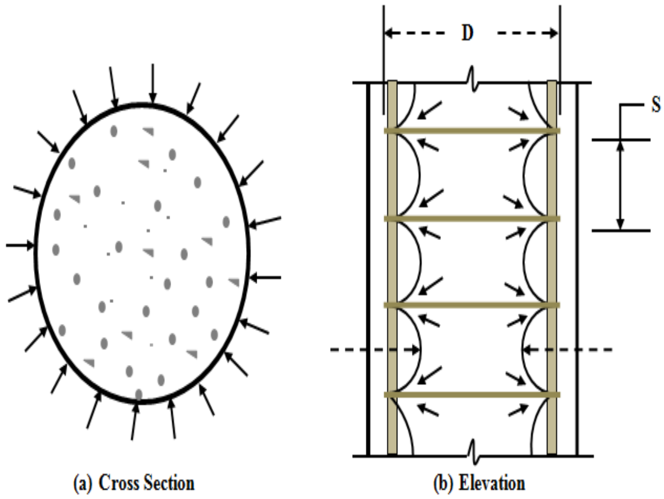

Fig. 4 Confinement of the joint

N. Subramanian et al. [17] explicated RC columns' confinement reinforcement design. The TRs performed a significant role in protecting the columns. The outcomes displayed that the ACI allowed crossties to use 135 ^{o} hook at one end and 90 ^{o} hook at the other end. IS 13920 persisted both the ends of crossties to have 135^{o} only. As recommended in the ACI code, the arrangement was effortless to adopt at the site.

E. Bond in Longitudinal Reinforcement

The design load is transferred into the structural member from the anchors by utilising the Reinforcement (ACI 318-14). The inception of yielding in the beam will go through the column region if special actions are considered to transfer the plastic hinge area away from the column's face. Because of this, the key puts forward that the lesser half of the column depth or 10 times the bar diameter should reduce the anchorage length of beam bars anchored within the column region in external joints described. The bond in the longitudinal reinforcement is explicated in figure 5.

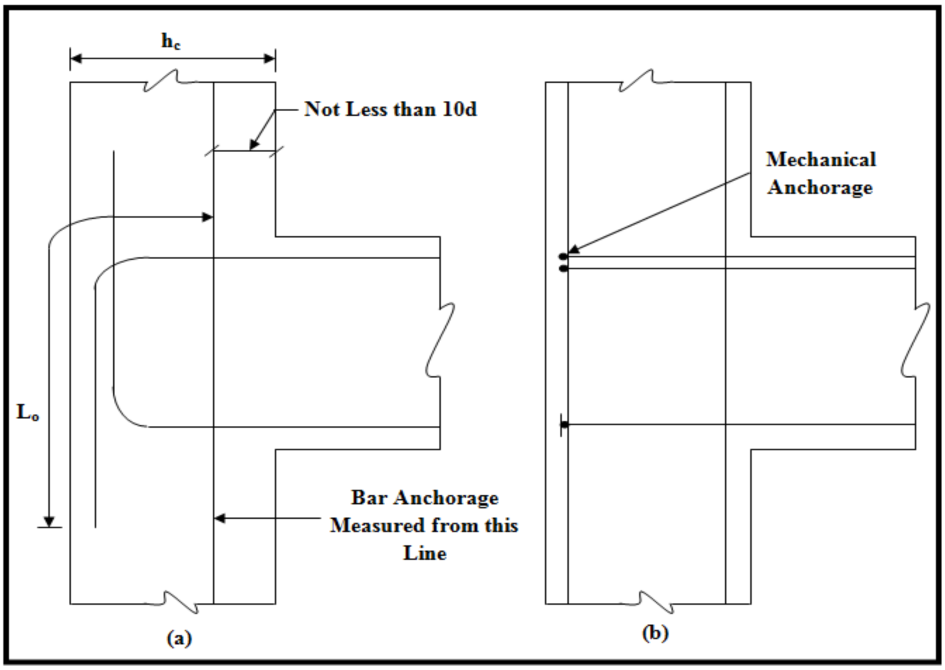

Fig. 5 Bond in the longitudinal reinforcement

Joakim Jeppsson et al. [18] examined the RC's behaviour with loss of bond at longitudinal reinforcement. The loss of bond was created by enclosing the longitudinal reinforcement with the plastic tubes by leaving short bond lengths. The outcomes displayed the significance of the number of bonds existing. To what limit the load-carrying potency was reliant on the contribution as of the stirrups was also indicated by this. The bond determination was highly complicated; the distribution was extremely large.

Nik Farhanim Binti Imran et al. [19] illustrated the longitudinal reinforcement's tensile force along with bond stress in the heavy RC beam. The ratio of longitudinal and SR was included in the test variables. The outcomes displayed that the over-reinforced beam's concrete attained the ultimate stress. Nevertheless, the yield strain was not attained by the steel. The over-RC beam achieved a reinforcement ratio of 3%. The augmentation in the moment resistance was not balanced to the augmentation in the tensile reinforcement region; thus, the over-reinforced section was too costly.

F. Shear forces acting on joint

Shearing forces are unaligned forces in which the body's one part is pushed in one direction, and the other part is pushed in the opposite direction. The strength comes as of the friction between the materials bolted together whilst working with a riveted or tensioned bolted joint [25]. The shearing force working on the joint can be estimated by utilising the equilibrium conditions. The horizontal shear force across the joint is also attained [26]. The horizontal shear in an Exterior Joint is illustrated in figure 6.

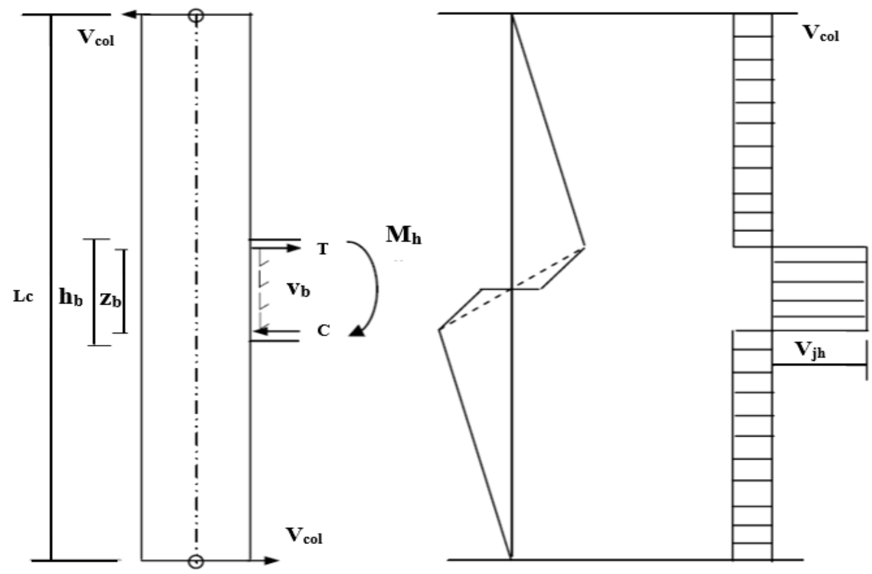

Fig. 6 Horizontal shear in an exterior joint

The column shear V_{col} in an exterior joint is specified as,

$$V_{col} = \frac{M_h}{l_c} \quad (1)$$

The joint shear V_{jh} is signified as,

$$V_{jh} = T - V_{col} \quad (2)$$

Assuming $C_b = T_b$, the column shear, V_{col}, as of the above forces is computed from equilibrium conditions as h_c

$$V_{col} = \frac{2T_b z_b + V_b h_c}{l_c} \quad (3)$$

$$V_{col} = \frac{T_b z_b + V_b \frac{h_c}{2}}{l_c} \quad (4)$$

By taking the moment gradient within the joint core into consideration, the horizontal shear force V_{jh} is formulated as,

$$V_{jh} = V_{col}\left(\frac{l_c}{z_h} - 1\right) - V_b\left(\frac{h_c}{2z_h}\right) \quad (5)$$

The hogging moment is specified as M_h; the columns' centre-to-centre height is signified as l_c; the tensile force is denoted as T_b; the column depth is represented as h_c and the lever arm is expressed as z_b.

Jadhav. H .S et al. [27] described the shear force bursting stress in BCJ, which was evaluated and structured as per Indian Standards. In the BCJ, the forces and the moments over the stresses were evaluated incorrectly than the ones derived at the time of seismic loading. The outcomes displayed a differentiation in the BCJ's behaviour regarding the location accompanied by the configuration. The hinge formation technique demonstrated the building frame's ductile behaviour via the pushover evaluation. Mostly, the issues that occurred were highly complicated, so they were unable to solve by conventional analytical methodologies.

G. Models used in shear forces acting on joint

Numerous methodologies are utilised in shear forces working on joints. A SS condition, along with the associations between stresses and displacements in the normal and shear directions, is incorporated in this model [28].

Shyh-Jiann Hwang et al. [29] described the analytical model for forecasting the exterior RCBC joints' SSs for seismic resistance. This model was centred on the strut-and-tie idea. In general, only the equilibrium criteria were satisfied by the strut-and-tie model implemented to the joint. The outcomes displayed that the cracked RC's force equilibrium, constitutive laws, and strain compatibility were satisfied. Determining the specific joint details affecting the SS was highly complicated for the designers.

Tung M. Tran et al. [30] illustrated the RC exterior joint's SS model under cyclic loading. In this, merely a tiny quantity of this force was forwarded into the joint core; whilst the remaining was transferred into the neighbouring column. The outcomes displayed that the assumption implemented, including the column axial stress and the joint SR, was vindicated. The model was reliant on the assessment of the diagonal strut's width. However, the estimation with accurateness was difficult.

Kanak N. Parate et al. [31] elucidated the simplified empirical model for the SS of RCBC joints. It detected together with analysed the governing parameters influencing the joint SS. The outcomes displayed that the beam, column, joint SR together with the column axial were considered by the model being implemented. The deviation of the model's prediction was extremely lesser than the other models. However, the model was reliant on the communication of several parameters; thus, the prediction of joint SS accurately was a complicated task.

III. DESIGN SPECIFICATIONS OF REINFORCED CONCRETE BEAM-COLUMN JOINT

The joint, particularly the beams or columns, must be stronger than the neighbouring hinging members is the fundamental need of design specification. The column or beam size might require adjustment to satisfy the specifications for joint strength; thus, it is necessary to ensure that the joint size is apt in the design process. The following steps are included in the BCJs' design contract globally by several codes and authors.

- ✓ Appear at the preliminary size for members centred on anchorage needs for the selected longitudinal bars [32].
- ✓ To attain the required beam yielding mechanism, sufficient column Flexural Strength (FS) is secure [33].
- ✓ The TR is utilised for confinement in which the shear actions are resisted [34].
- ✓ Offered sufficient anchorage length for the reinforcement that passes via the joint [35].
- ✓ The sheer force is measured by the overall FS of adjacent beams and internal forces via equilibrium [36].
- ✓ The dimensions of neighbours members must compute the effective joint shear area [37].

To discuss in-depth, the points are expanded.

A. Development Length of Anchorage and Flexural Strength Ratio

The bond strength provides concrete and steel's composite action in RC structures [38]. The desired bond strength is obtained by offering an adequate development length [39]. The expensive fabric materials. the needed cross-sectional region is reduced, or better structural performance is provided by a proper anchorage system regarding the augmentation in the fabrics reinforcement ratio [40]. In the joint, the bars anchorage and the development length are mentioned based on the significant section positioned at a distance from the column face. Table 1 illustrates the relevant expressions recommended by several codes regarding the development length. Table 2 explicates the relevant expressions recommended by several codes regarding the FS of ration.

Table 1. Code provisions of development length

Parameters	Development length of exterior joint
ACI 352:2002 [41]	$l_d = \left(\frac{\alpha f_y d_b}{6.2\sqrt{f'_c}}\right)$
EN 1998-1:2004 [42]	$\frac{d_b}{h_c} \leq \frac{7.5 f_{ctm}}{\gamma_{Rd} f_{yd}}(1 + 0.8 f_s)$
IS 13920:2016 [43]	$L_d = \frac{\phi\ \sigma_s}{4\ \tau_{bd}}$

Table 2. Code provisions of flexural strength Ratio

Parameters	Development length of exterior joint
ACI 352:2002 [41]	$\frac{\sum M_c}{\sum M_b} \geq 1.2$
EN 1998-1:2004 [42]	$\frac{\sum M_c}{\sum M_b} \geq 1.3$
IS 13920:2016 [43]	$\frac{\sum M_c}{\sum M_b} \geq 1.4$

B. Confinement factor

Beam confinement is nothing but the BCJs restricted by the beams. The beam confinement's efficiency relies on the beams that congregate at the joint [46]. It has a benefit that the confinement factor is lesser sensitive to the alloy composition of the waveguide along with cladding layers, which is highly significant for ultraviolet.

The '4' possible beam configurations of confinement are explicated in figure 7. The containment factor (λ) in the codes ACI 318, CSA A23.3, and AIJ considered the joint containment's effect owing to the neighbouring beams. Additionally, several concepts have displayed that lateral beams augment the joint shear's strength on both sides of the joint. The confinement factor owing to beam confinement is demonstrated in table 3.

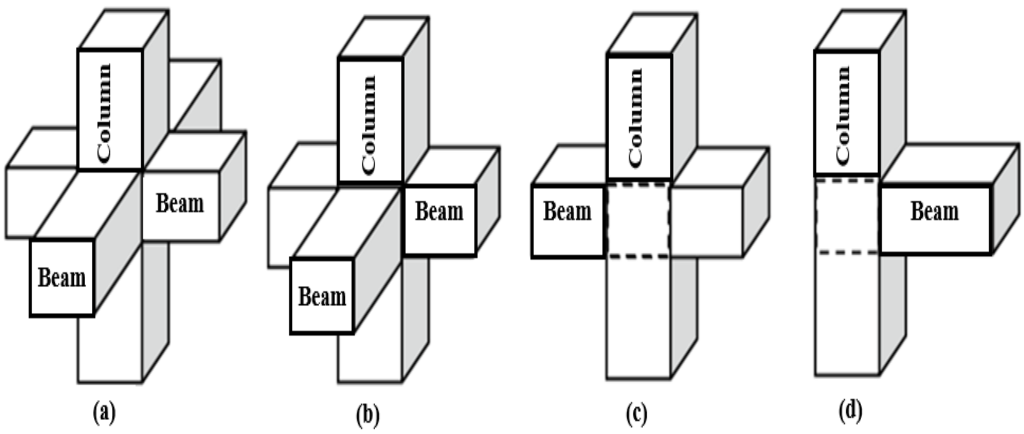

Fig. 7 Confinement of beam in the joint (a). All four sides (b) three sides (c) two sides (d) one side

Table 3. Confinement factor due to beam confinement in the codes

Codes	All four sides	Three/two sides
ACI 318 [47]	1.70	1.20
CSA A23.3 [48]	2.20	1.60
AIJ [49]	1.00	0.85

C. Transverse Reinforcement of Beam-Column Joint

To retain the longitudinal reinforcement and capture the shear, the SR is generally structured in stirrups [50]. The core exposed to a complex state of stress is confined by the TR instead of just resisting shear or enhancing the deformability under axial compression. At the time of SRM, the intermediate column bars are exposed to tension, along with the bars that would possess adequate strength to hold tensile stresses.

Sang Whan Han et al. [51] examined the influence of TR on the seismic behaviour of Diagonally RC Coupling Beams (DRCB). The outcomes displayed that for limit states, the model parameters, strength equations, along with limiting values, are modified by utilising the DRCB specimens with $L_n/h \geq 2$. However, placing the reinforcing bars in DRCB was highly complicated due to reinforcement congestion and interference.

Abolfazl Nouri et al. [52] elucidated the assessment of BCJs made of HPFRCC composites to mitigate TRs. The outcomes displayed that to mitigate the number of TRs and damage index; in addition, to augment the load-carrying capacity, damping percentage, energy dissipation, along with stiffness of members, the HPFRCC materials were utilised in joints. Without utilising the TR, the joint zone's strength was not offered perfectly; similarly, a concrete crush was caused due to TR's non-existence in the joint zone.

Andri Setiawan et al. [53] described the punching of RC slabs devoid of TR aided on lengthened columns. For TR, the joint shear model was utilised. The outcomes displayed that an accurate and constant output was produced for cmax/d ranging from 3 to 10. The shear redistribution should be restricted around the control perimeter for $c_{max}/d > 10$. The model displayed supportive criteria as rigid to spring with higher compressive; however, it also displayed lower tensile stiffness.

IV. RESULTS AND DISCUSSION

The CS between NAC and RAC, TS between NAC and RAC, and the reinforcing bar's tensile development length are explicated in this portion. The material's ability to uphold loads apt to decrease size is termed CS [54]. The correlation between the traditional concrete's CS and RAC at 7, 14, and 28 days is demonstrated in figure 8.

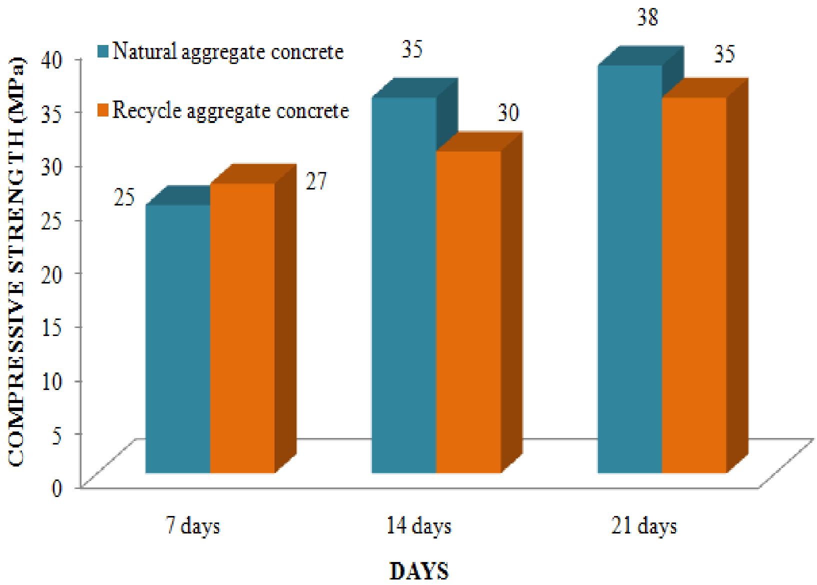

Fig. 8 Comparison between compressive strength of conventional concrete and recycled aggregate concrete at 7, 14 and 28 days

The values produced a better agreement for the '2' types of concrete. Therefore, it is confirmed that an identical or a higher CS could be attained with the concrete mixture utilising RAC to substitute the NAC. The utmost quantity of tensile stress consumed by a material before failure is termed TS. The TS of a specific material contains a greater numerical value [55]. The TS between NAC and RAC is demonstrated in figure 9.

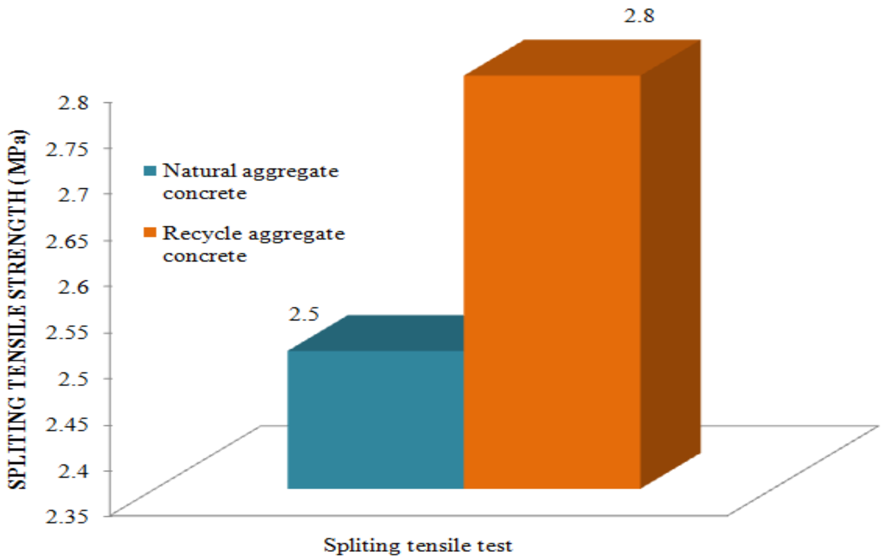

Fig. 9 Tensile strength between natural aggregate concrete and recycled aggregate concrete

In accordance with the outcome, higher TS are attained by RAC than the NAC. Thus, a better CS along with TS is possessed by RAC. The bar's minimum length is called the tensile development length. It must be inserted in the concrete ahead of any portion to obtain its full strength. In the case of axial tension or axial compression, it is termed as anchorage length; similarly, in the case of flexural tension, it is termed as development length. The reinforcing bar's tensile development length is demonstrated in figure 10.

The design codes CEB-FIP Model [56], ACI [57], BNBC [58], IS [59], EURO Code 2 [60], and AASHTO [61] are utilized in the reinforcing bar’s tensile development length. In correlation with the other codes, a larger value of development lengths is recommended by the BNBC.

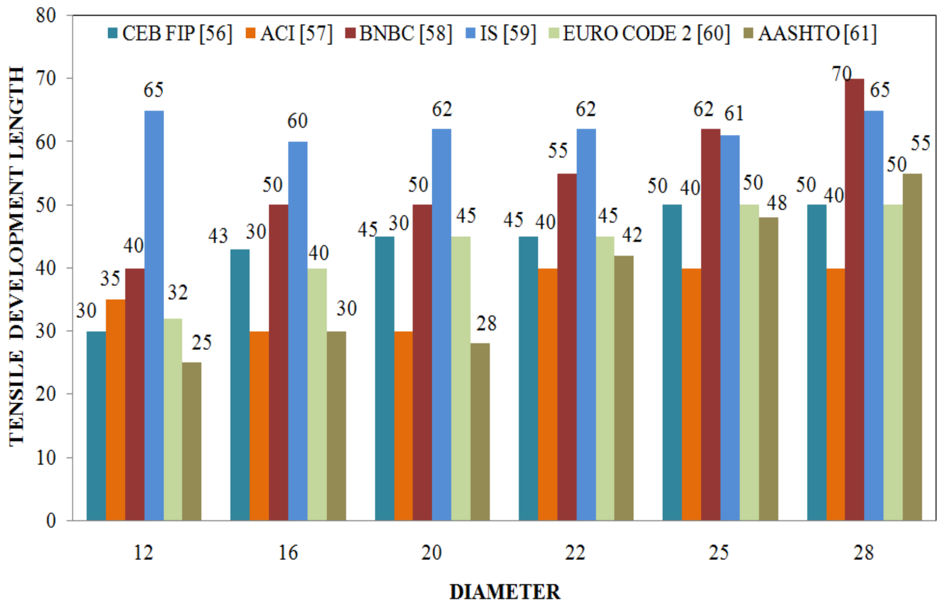

Fig. 10 Tensile development length of reinforcing bar

In BNBC, the modification factors utilised for tensile development length are substantial. It is concluded that in BNBC, this large modification factor might be a worry for more significant tensile development length.

V. CONCLUSION

RC structures are also the famous structures amongst the popular structure systems. Numerous architecture projects utilise RC structures because of their designs. However, owing to the design ideas with limited knowledge about RC design, the buildings being designed are structurally questionable in numerous cases. Concrete devoid of reinforcement is feeble in tension. The concrete's TS are around 10% of its CS.

Consequently, when the tensile stress goes beyond, the concrete is utilised with reinforcement, which augments the Tensile Strength (TS). The TS between NAC and RAC, CS between NAC and RAC, and the reinforcing bar's tensile development length with various design codes like BNBC, ACI, AASHTO, IS, CEB-FIP and EURO code 2 are assessed in this paper. In the upcoming future, heavy congestion can be prevented with specific alterations in the design codes. For example, the design codes with columns and beams of the same width or continuous reinforcement with a large amount lead to heavy congestion.

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