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PARAMETRIC STUDY ON HEADED ANCHORAGE SYSTEM IN R/C BEAM COLUMN JOINTS

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Abstract*— Congestion of reinforcement and constrained geometric conditions are often imposed design limitations and constructability issues in R/C beam column joints. The seismic conditions of beam column joints exhibit complex force transfer mechanism than any other part of structural system. Research studies identified that detailing aspects and configuration of joint reinforcement will significantly influencing both strength and ductile performance of beam column joint. Use of headed bar anchorage system provides a viable solution than conventionally used hooked bars in R/C beam column joints. Headed bar facilitate ease of fabrication, placement, and reduce reinforcement congestion in the integrated joint system. This paper comprehensively discussed about headed bar anchorage mechanism and associated parametric influence in beam column joints under quasi static and dynamic loads. Further this study promoted the usage of headed bar anchorage system in high strength conditions of concrete, as the literature expressed deficiency of joint strength. The strength of joint is not at par with its connecting members in integrated joint system.

***Keywords:* Headed bar, anchorage mechanism, parametric influence, beam-column joint, detailing provisions.**

I. INTRODUCTION

Failure of R/C beam column joints are mainly attributed to critical transfer of forces in joint element. Transfer of forces in joint are in the form of shear and bond through anchorage of reinforcement bars. Insufficient anchorage and poor detailing of reinforcement and compaction of concrete in unconfined state are major influential factors for brittle failure of a joint Mechanical anchorage of reinforcement bars in the form of hooks or heads provide viable solution when straight anchorage of reinforced bars not able to meet the anchorage requirements of full yield strength of rebar. In design of beam column joints, the primary size of discrete joint system is based on prevailing stress conditions and anchorage requirements. The hooked bar anchorage system in congested reinforcement location of joints often cause fabrication problems and constructability issues. Studies made by Shao.Y (2016)[2] and Sung Chul et al.,(2009) [9] expressed that the performance of headed anchorage system is superior than hooked bars during monotonic and cyclic load conditions and its identity is more vigilant in discrete joint conditions. As per the shear cone theory, provision of headed bars effectively reduced the development length (L_d) than hooked bars.

The current design practice of R/C constructions, utilisation of high strength materials (concrete, steel) expanded to limits. But limited research work done on strength and anchorage improvements of joints during high strength materials (concrete: fck>40Mpa ,steel: fy>415 Mpa) used in R/C beam column joints. The deliverables of past experimental studies identified that increase of shear and bond strength of joints are deficient and not at par with the member strength when using high strength concrete. Also the contribution of concrete strength, during high shear conditions ($V_c > 0.4\sqrt{fck}$) is less than the predicted values mentioned in the design codes. The authors, Arthur.H and David Darwin et al., expressed that the strength reduction factor of high strength concrete in joint core is influenced by tensile stresses developed in the concrete.

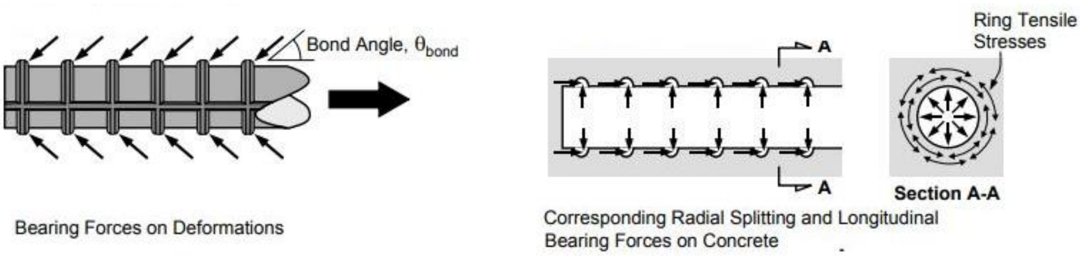
Referring the above conclusions, the current practice of beam column joints are executing less conservative design approach with high strength concrete. It is worth mentioned that, an efficient performance of joints with high strength concrete is quite essential and the designer should not sacrifice structural safety through integrity of joints. The efficient seismic performance of headed bar anchorage system in terms of energy dissipation, ductility, lateral drift and extent of damage was experimentally demonstrated by Thomas H et al.,(2008)[11]. Headed anchorage provides minimum slip and more accurate dimensions of reinforcement fabrication or caging than hooked bars. Hence the usage of headed bar system is a viable solution to satisfy strength requirements and fabrication issues of integrated beam column joints.

II. SIGNIFICANCE OF THE STUDY

The current design practice of beam column joints are unable to establish its full strength during high shear and high concrete strength conditions .The improvement of joint strength is not at par with its connecting members during high strength concrete used in structural system. Hence less conservative designs established for joints. Headed bar anchorage system provides viable solution to meet high strength conditions of R/C beam column joint. A comprehensive study on headed bar mechanism and parametric influence on its anchorage system will helps to meet the design requirements and constructability issues .The study helps to establish high strength conditions in R/C beam column joints.

III. BOND STRENGTH AND DEVELOPMENT LENGTH OF ANCHORAGE SYSTEM

Bond strength is an interaction between steel reinforcement and surrounding concrete that allows transfer of tensile stress from steel to concrete. Bond stress mechanism allowed by anchorage of reinforcement influence important features on stiffness and crack control of concrete. Bond can fail in multiple ways. If longitudinal bond stresses exceeds shear strength of concrete, then the keys between ribs and bar can pull free. This is referred to as "pullout" failure. More commonly though, splitting cracks will propagate from the bar to the surface of the concrete and the cover will spall off. Splitting failure occurred in unconfined concrete is governed by bar spacing and cover dimensions of concrete. But limitless cover does not provide limitless bond and beyond a certain level of splitting resistance, pullout failure will govern. The development length of straight anchored reinforcement bar (Ld) is based on average bond stress over its embedment length (L). A single bar embedment in mass concrete need not require great development length, but row of bars in mass concrete create a weak planes of longitudinal splitting along the plane of bars. This anchorage system is more critical in congested reinforcement where the section imposed by constrained area.



Bond and splitting components of rib bearing stress

ACI-318 Proposed standard expression for development length (Deformed bars in Tension) : Ld

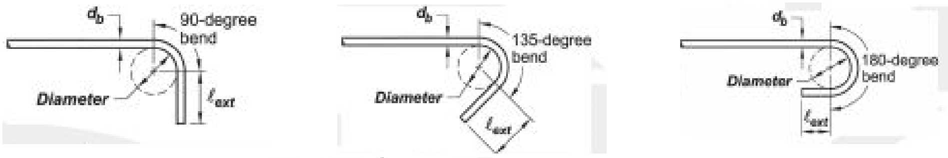
$$\ell_d = \left(\frac{f_y}{1.1\lambda\sqrt{f'_c}}\frac{\psi_t\psi_e\psi_s}{\left(\frac{c_b+K_{tr}}{d_b}\right)}\right)d_b$$

where: Confinement factor ϕ: $\left(\frac{c_b+K_{tr}}{d_b}\right)$

If $\phi < 2.5$ splitting failure likely to occur
If $\varnothing > 2.5$ pullout failure likely to occur

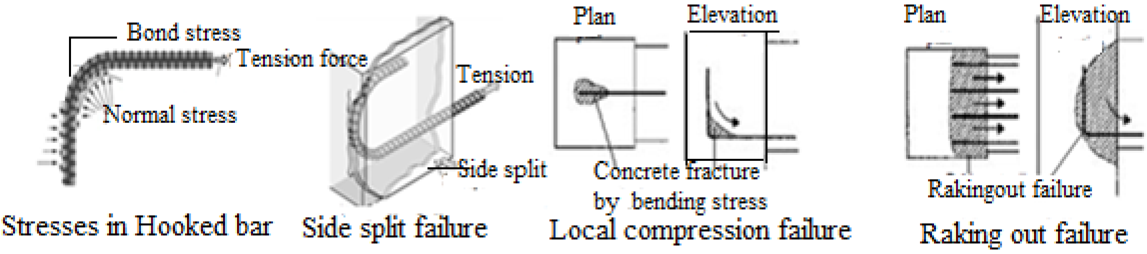
The contribution of Concrete cover (C_b), Confinement reinforcement (Ktr), across potential slipping plane, and anchored bar diameter (d_b), significantly influence development length of bars under tension. ACI equation for development (Ld), put limitations on strength of concrete (fc) as $\sqrt{f'_c} < 8.30$ MPa, and restricted the influence of high strength concrete (fck >70MPa) on anchorage requirements of straight bar. Researchers suggested that brittle anchorage failure of concrete joints often happened in high strength concrete conditions due to inadequate transverse reinforcement. Provision of transverse reinforcement will improve the ductile anchorage behaviour [23]. But ACI code is unable to address the basic requirements of transverse reinforcement in the direction of tension development or splice length. Design codes of ACI/NZS/EURO established design guidelines on applicability of headed bars in beam column joint system. But the codes are less addressed about influence of confinement, size and configuration of bars. Also the code put limitations on strength of concrete and reinforcement in headed anchorage of joint core. In this context shear capacity and bond strength of joints are improperly designated.

IV. ANCHORAGE PERFORMANCE IN HOOKED BARS



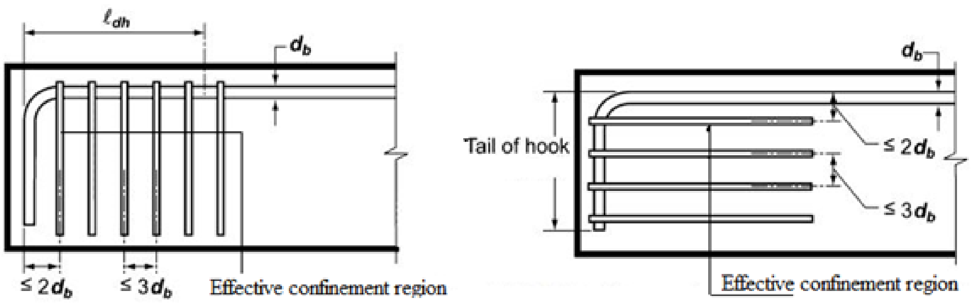
Different shapes of Hooked bars in anchorage system

Transfer of forces in hooked bar anchorage system is in the form of bond stress and normal stress. The development length of standard hooked bars in tension ranges approximately between 30%-50% of straight bar anchorage .However the tail extension and bends often cause reinforcement congestion due to sufficient radius for bending of bars should be allowed against streamline of normal stresses and bond stresses. This makes it difficult to place the hooked bars in congested joint regions[11]. The code ACI 318-14 suggested that the hooked bars do not effectively contribute during compression action of forces which is more often happened under reverse cyclic loading. They are susceptible to splitting failure due to absence of minimum clear cover requirements (both in-plane or out-plane of hook). Researchers established the influence of column axial load (P) on usage of hooked bars in beam column joints. If P < 0.3fck , there is no influence of axial load on bond strength and if P < 0.5fck, then no influence of axial load on shear strength of joint. Failure of hooked bars in beam column joints are associated with (i) Side split failure, (ii) Local compression failure and (iii) Raking out failure



Modes of failure in hooked bar anchorage system

Side split failure of concrete located in adjacent side of bent portion is fractured with split due to insufficient thickness of concrete cover. The splitting failure occurred if both concrete side cover in the direction of normal plane of hook and both top and bottom cover in the direction of plane of hook are insufficient. Local compression failure of concrete located inside the bent portion is fractured by bearing stress due to the bent radius of reinforcement is not enough large against smooth transfer of in-plane stresses of bar. As a result, slip of bars at facing of joint occurred. Raking out failure of concrete located in front of bent portion if it is raked out as one body. The anchorage mechanism of hooked bar depends on embedment length, strength of concrete, lateral confinement, amount of transverse reinforcement, concrete cover to reinforcement in joint panel [17]. The current ACI 318 code restricted the design provisions of anchorage system when strength of concrete strength is more than 70MPa. Special confinement reinforcement (as shown in figure) needed in the form of ties or stirrups when small concrete cover used in anchorage of reinforced bars.



Provision of confinement in Hooked bar anchorage (Ref.ACI 318-14)

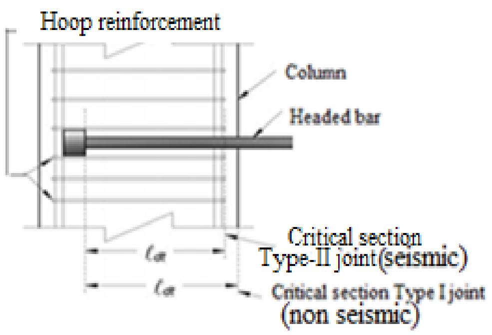
V. ANCHORAGE PERFORMANCE OF HEADED BARS

The heads are fabricated by attachment of plate or nut at the end of reinforcement to provide large bearing area of anchorage against tensile forces developed in the bar . As per the studied literature, the state of headed anchorage system is well supported by strut and tie method (STM). STM offers safe and lower bound design philosophy under non linear stress conditions and failure modes of beam column joints. The beam column joints are accompanied by analysis under discrete conditions and headed anchorage system is more compatible with the present conditions. The resistance provided by headed bar is in the combination of bond resistance of ribs and bearing resistance of head. Studies made by Devries.R et al.,(1999),[20] concluded that headed bars can provide efficient anchorage system to accommodate tensile force of R/C beam column joint. The successive researchers established that headed bars provide 62%-80% of development length of straight bar anchorage system [15]. The influence of head size and shape mentioned by the previous researchers (Ref: Wallace et al:1998, Thompson et al:2002, Chun et al:2007) on anchorage capacity and development length was well established. But ACI:318 code does not consider this influence.

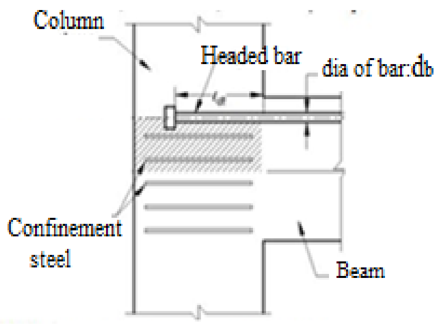
As per ACI 318 code, the placement of transverse reinforcement for confinement of headed bar is ineffective and not improved its anchorage capacity (except limit the splitting tensile cracks). Also the confinement factor of joint concrete (φ) as stated earlier for development of hooked bars was not considered in ACI code. The researcher Choi et al., (2006)[13] has shown that, anchorage strength of headed bars in presence of confinement reinforcement parallel to the bars will improve the anchorage strength of bar (18% to 32%) than without confinement and the presence of vertical confinement shows less significance.

(i) Brief review on experimental studies

Thompson et al. (2005, 2006) studied about anchorage behaviour of headed bars at compression-compression-tension (CCT) nodes of deep-beams. The test parameters included bar size ,strut angle (30°, 45°, 55°), head size (net bearing area A_b ranging from 1.2 - 10.4) and head orientation (horizontal or vertical orientation of longer sides of rectangular heads).Confining reinforcement provided within the nodal zone under medium concrete strength conditions. An increase in contribution of bond of about 46% to anchorage strength was observed in specimens with confinement reinforcement, while the contribution from bearing on the head decreased by about 21%.Thompson suggested that this increase is due to the stirrups restrained splitting of concrete, and prevented a decrease of bond along the bar, and also that stirrups provide alternate paths to carry out the load through multiple compression struts.

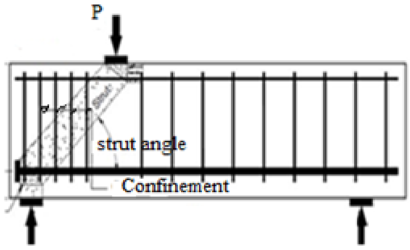


Lateral confinement of Headed bar (Ref: Choi et al)

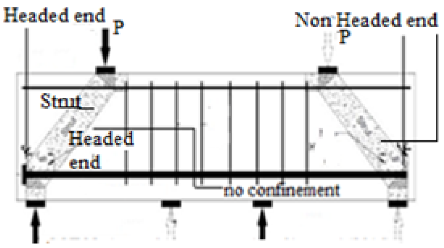


Confinement of Headed bar (Ref:Shao et al)

Shao.Y et al.,(2016)[2] proposed headed and non-headed end anchorage at unconfined conditions. The test results concluded that headed end shows 40% greater anchorage strength than non-headed end[2]. He further concluded that the net bearing area of a head with an obstruction be definedas the gross area of head minus the area of the obstruction adjacent to the head and be at least 4Ab (A_b: Area of bearing). Bashandy.T (1996)[22] expressed that anchorage strength of the headed bars increased with increase in embedment length, confining reinforcement, head size, and concrete cover. But the bar size did not shows significant influence on anchorage strength of headed bar.



CCT Node proposed by Thompson et al (2002)

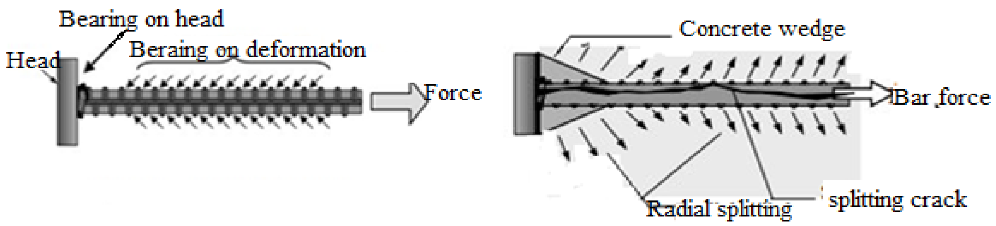


CCT Node proposed by Shao et al (2016)

Experimental studies made by Sung Chul Chun et al(2009) [9] established that, when proper embedment and geometry of headed bar provided in beam column joint, that will encourage shear failure .The results stated that the approximate contribution of head bearing is 60% and bond is 40% against anchorage strength of headed bar in R/C beam column joint. Dahl (1995) produced some evidence on contribution of strength in headed bars .Accordingly 75% of the load is taken through bearing of head and 25% through conventional bond strength in headed anchorage system.

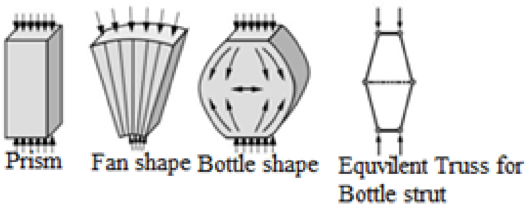
(ii) Force transfer mechanism in headed anchorage system

Transfer of forces in headed bar anchorage system to concrete is in the form of bearing force at head and bond force along the length of bar. The contribution of bearing and bond strength of headed bar against anchorage strength was well established by Sung chul chun et al., (2009)[9]. Accordingly the initial anchorage is carried by bond and as tensile load increased then head bearing starts to contribute only after bond contribution reaches to maximum value. Once head participation started, the peak bond stress is slightly reduced, and bearing stress of head increased increases until it failure. The head bearing contribution is proportional to embedded depth and normalized by column depth. Force transfer mechanism of headed bars are expressed in terms of CCT node conditions by strut and tie method (STM). The CCT node denotes two compressive forces and one tensile force acting at node in equilibrium condition.

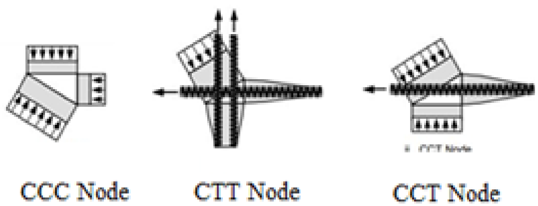


Transfer of forces in Headed anchorage system

Strut and tie method (STM) was derived from lower bound theory of plastic analysis where the strain capacity of material is fundamental requirement. A properly detailed and confined concrete may represent the plastic stress strain condition which is ductile in nature. The STM involves formation of truss mechanism composed with the formation of concrete strut, tension steel and nodes which represent localized stress conditions where the tensile forces transferred to concrete through anchorage and strut forces to tie. Longitudinal bond splitting cracks occurred when the bond along the deformed bars deteriorated and stresses are transferred to the heads.



Typical shapes of strut formation in STM



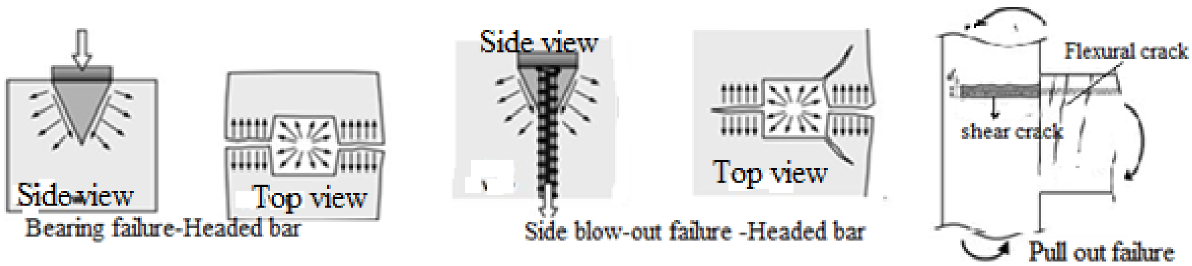
Typical cases of Nodes formation in STM

STM allows several different types of struts and nodes. Figure shows some possible formation of strut types. The most likely strut type is Prism strut with constant cross-sectional shape all along its length. Fan type strut is likely to occur in deep beams, where the diagonal shear struts converge to a single node. The Bottle-shaped strut is likely to occur when large amount of surrounding concrete allow the compression stresses to bulge outward in the middle of the strut. The spreading within a Bottle-shaped strut produces tension stresses that may require transverse reinforcement. The Bottle shaped strut may be reduced to an equivalent truss for a better understanding on transfer of forces. The failure of STM is defined by yield of ties or excess stress produced within struts or by anchorage failure of reinforcement at nodes. When the elements are properly detailed, then except yield failure, rest of the failures may obviate. The choice of adoptable stress levels in concrete will prevent local crushing or splitting failure in struts and nodes, which basically depends on good confinement of concrete.

Formations of three basic nodes of truss elements in STM are shown in the figure. The CCC node represents Compression-Compression-Compression node which is an intersection of three compression struts. The CTT node represents Compression-Tension-Tension which is an intersection of one compression strut and two tension ties. The CCT node represents Compression-Compression-Tension, which is an intersection of two struts and one tension tie. Both CCT and CTT nodes have generally lower strengths than CCC nodes due to disruption by splitting stresses associated with bond anchorage of the reinforcement bars. Headed anchorage mechanism well connected with CCT node conditions of STM. In order to apply STM to structural concrete members, it is convenient to delineate disturbed regions (D-regions) from the other parts of the structure that will follow plane section material behaviour under conventional beam analysis (Bernoulli's theorem).The selection of D-region boundary is based on St. Venant's theorem and the transition of local stress fields into full section stress fields.

(iii) Failure modes in headed anchorage system

The failures of headed bars in beam column joints are associated with (i) Bearing failure, (ii) Pullout failure and (iii) Side blowout failure. Bearing failure in joints occurs when the head is not enough to transfer the bearing stress of tensile forces. ACI 352-02R specify the minimum diameter of head to fulfil the bearing stress as $4d_b$(db: dia of bar). Concrete pull-out failure happened when the net head area is less than 4 times bar cross sectional area. Concrete breakout failure is rare combination when effective depth of beam is 1.5 times embedment length of headed bar. Side face blow out failure is associated with inadequate side cover of concrete. As per ACI 352-02R minimum concrete cover $2d_b$ is necessary to avoid the failure.



Failure modes in Headed bar anchorage system

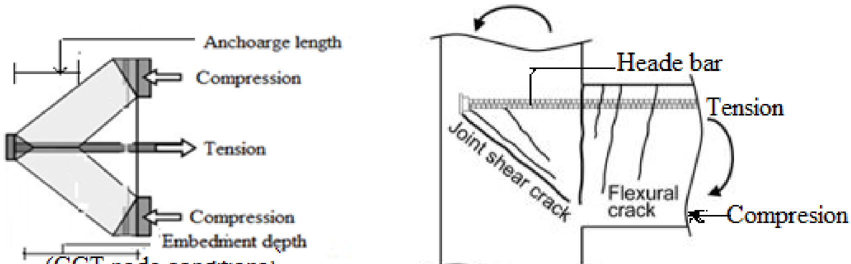
R/C beam column joints exhibit complex interaction between shear and bond in the presence of headed bars. The bond performance of anchored headed reinforcement influences the shear resistance mechanism. The bond deterioration initiated at column face when yield penetration occurred and results development of splitting cracks .This results complete loss of flexural strength of connecting beam. Headed bars offers good anchorage system and is suitable for both non cyclic and cyclic loading conditions.

(iv) Anchorage strength of headed bar

The length of anchorage (La) in headed bar is defined as length measured along the bar from the bearing face of the head (or the end of a straight bar) to the point of peak bar stress (as per STM).The point of peak bar stress (or anchorage point) is generally coincides with intersection of bar and the leading edge of the strut of bar anchors. Embedment depth (Ld) is the length measured along the bar from the bearing face of the head (or the end of a straight bar) to the surface of the member in which the bar is anchored. The anchorage length is generally shorter than the embedment depth. STM is necessary to determine the available anchorage length based on CCT node conditions (CCT: compression-compression-tension).The anchorage strength of heads depends on classification its CCT node conditions.

CCT node formation in headed anchorage system is classified under (i) Surface nodes, (ii) Interior nodes. The surface CCT nodes formed in the locations of concentrated load point (corbel, dropped beam) where the load is indirect contact with headed bar .The interior nodes formed inside the members of (corner / external) beam column joint and headed bars hanging in deep beams. The strength of surface CCT nodes are higher than interior CCT nodes due to following reasons.

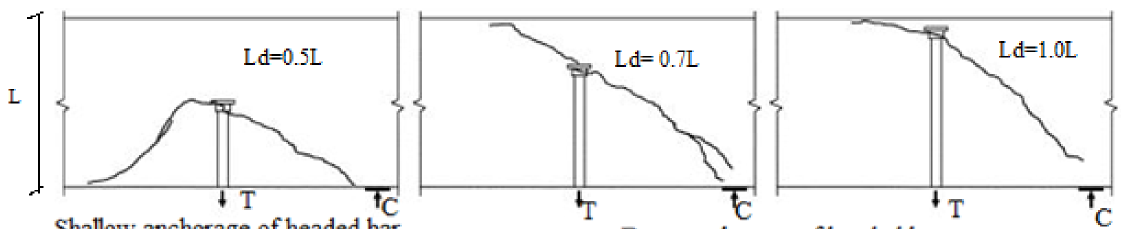
- Surface CCT node provides more restraint against transverse deformation of concrete in presence of bearing plate.
- The dimensions of bearing plate decide the dimension of CCT node in the surface nodes,, and the state of internal stress field decide the dimension of CCT node in the interior nodes,.
- The bond created outside the nodal zone may lost at ultimate state in surface CCT node ,due to development of cracks near the nodal zone.



(CCT node conditions)
Anchorage length in Headed bar

External beam column Joint failure

In the absence of local failure of headed bars, joint failures are mainly attributed to formation of diagonal cracks under shear. These cracks are mainly due to failure of compressive strut in joint core. This failure initiated at bearing head of bar and ends at compression zone of beam .The initial crack occurred due to loss of bond around the bar and propagated towards the head. Then diagonal cracks anticipated between the head and compression face of beam. The increase of column reinforcement delayed the formation of diagonal crack. In shallow anchorage system, the cracks are radiated on both faces of column and results cone shaped concrete breakout, which is referred as concrete break-out failure. In deep anchorage system, the diagonal shear crack occurred between the head and compression face of beam. Headed anchorage strength depends on length of embedment (Ld) and direction of applied loads. Accordingly headed anchorage system classified under (i) Shallow embedment (ii) Deep embedment



Shallow anchorage of headed bar (concrete break out)

Deep anchorage of headed bar (Shear failure of joint)

C: compression
T: tension

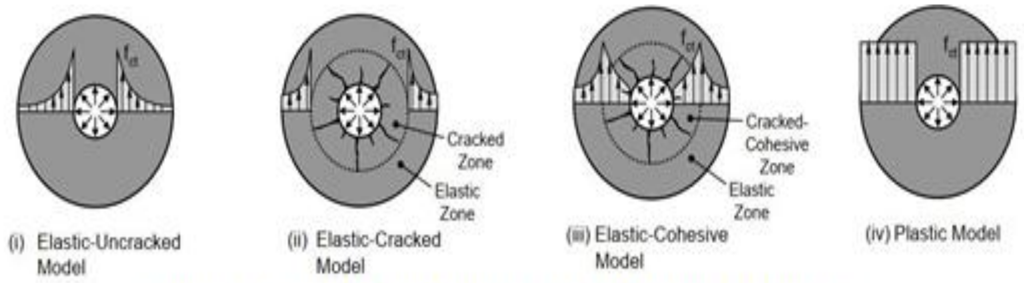
Beam-column joint

Crack-Failure of Shallow and Deep anchorage of headed bar (Ref. Sung chul chun et al)

a) Shallow anchorage performance of headed bar: (Ld<0.5L)

In shallow embedment of headed anchorage, the head bearing strength cannot fully developed due to formation of CCT node not fully developed and the joint strut is not confined by head. The capacity of strut linearly decrease as tensile load increase and failure of concrete is in the form of breakout cone and pulls out portion of concrete from the element. The anchorage process of headed bars consists of two stages. In the first stage, anchorage was carried almost entirely by bond stress, which peaks as the first stage ends. In the second stage, the bond began to deteriorate allowing bar stress to be transferred to the head. Throughout the second stage, bond declined and head bearing increased. The second stage ended with yield of the bar or bearing failure of the concrete at the head. As a result of this behaviour, peak bond and peak head bearing did not occur simultaneously. The capacity of the bar at failure was determined by the peak bearing capacity plus some contribution from reduced bond along the bar between the head and the point of peak bar stress.

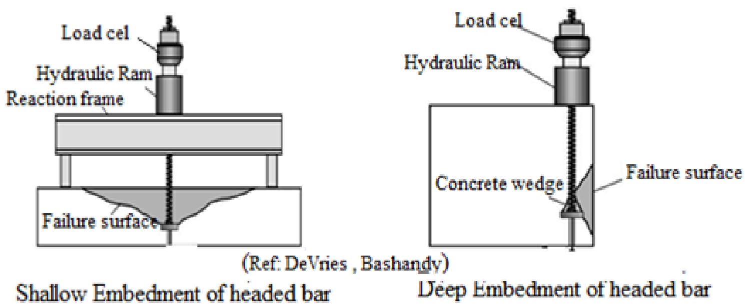
The bearing capacity of the heads was similar to the side blow-out capacity of deeply embedded anchor bolts and the bearing capacity of rigid plates on concrete. As per ACI code , the bearing capacity of AASHTO code useful to calculate the contribution of head for tie bar anchorage. Accordingly the bearing capacity of head depends on three main variables. They are (i) Net head area (A_{nh}), (ii) Compressive strength of concrete (fck), (iii) Notational area projected (An) beneath the surface of loaded plate. The notational area depends on cover conditions and limited to four times of bearing area (as per ACI 318-14). Vertically oriented heads typically project larger notional area than other heads as their proportions fit the shape of CCT node specimen. CCT nodes failed by mechanisms related to anchorage.



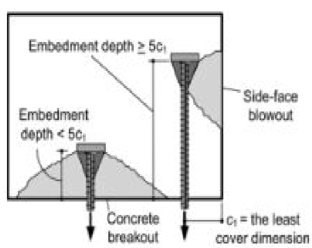
Anchorage behaviour of Single Headed bar under tension

Non-headed bars failed by pullout from the node. Headed bars failed when the bearing stress of head exceeded the bearing capacity of concrete. Failure of a CCT node anchored by a headed bar was explosive, resulting in rupture of the node and struts. Rupture was characterized by crushing just above the head and lateral splitting of the diagonal strut. The extent to which these two characteristics occur depends on head size and orientation.

Non-headed bars failed by pullout from the node. Headed bars failed when bearing stress at the head exceeded the bearing capacity of the concrete. Failure of a CCT node anchored by a headed bar was explosive, resulting in rupture of the node and struts. Rupture was characterized by crushing just above the head and lateral splitting of the diagonal strut. The extent to which these two characteristics occur depends on head size and orientation. The critical development point of the tie bar in a CCT node can be estimated as the intersection of the tie bar and the edge of the diagonal compression strut that is anchored by that tie bar. The development of the truss mechanism is a staged process. The strut-and-tie mechanism has a preference to transfer force along the most direct path between loads or reactions. In a Discrete (D)-region with stirrups or other reinforcement capable of acting as tension ties, force is initially transferred along a straight path from the point of load application to the CCT node. The formation of secondary strut paths may not occur until after the peak capacity of the member has been reached. The state of stress conditions at CCT node reversed on either side of the critical crack. Beneath the CCT node, compression stresses from the lower bearing plate necked inward to equilibrate spatially with the bearing face of the headed bar. This created a region of vertical and transverse compression. This region began at the bearing face of the head and extended to the surface of the critical diagonal crack where development of the bar began. On the other side of the crack, radial splitting stresses created by bond of the reinforcing bar caused a state of tension within the concrete. The anchorage length in the CCT node zone can be increased by confinement. Changes in the strut-and-tie mechanism (provided by adding vertical stirrups) allowed the critical development point of the headed bar to move away from the primary CCT node.



Failure pattern of Headed anchorage in shallow and deep embedment



Shallow versus deep embedment of headed bars

b) Deep anchorage performance of headed bar (Ld>0.5L)

The mechanism involved in deep headed anchorage system expressed such that CCT nodes are completely formed in anchored head. The crack damage occurred by failure compressive strut from bearing head to compressive zone of beam as per STM, The are of column reinforcement in joint region is insignificant except delay the crack formation at higher loads. In deep anchorage, the stresses induced by head bearing is greater than 0.85fck (fck: strength of concrete) and headed bearing fully developed when the embedment is greater than 0.70 anchorage length (Ld). The anchorage performance of bar in beam column joint much reflects the performance of anchored bolts. Deeply embedded anchor fails by side spall of concrete cover near the anchor head which referred as side blow-out failure. Greater bearing strength will be provided by greater embedment of headed anchorage due to confinement effect provided by the formation of diagonal compressive strut in the joint[14] .When the embedment depth of bar reached to 0.7 times column depth, then bearing strength of headed bar meets the full strength of concrete in beam column joint.

(v) Parametric influence of headed anchorage system

Following parameters are significantly influenced the performance of headed anchorage system.
(a) Confinement of Joint (b) Concrete strength (c) Influence of strut angle (d) Influence of column axial load e) Influence of Prying and Wedging force f) Influence of concrete cover.

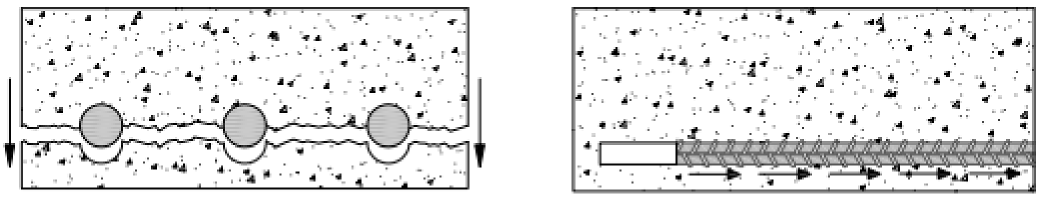
a) Confinement of joint

The influence of confinement in headed anchorage system emphasized under (i) Unconfined headed anchorage system, (ii) Confined headed anchorage system.

The confined anchorage system of headed bar is provided by transverse reinforcement in the form of Hairpins, Tie-downs or Stirrups (hooked or clamped). Strut-tie models demonstrate the effectiveness of transverse reinforcement to provide a clamping force on headed bar, dissipate the applied load, and the degree to which the capacity of a head influence the joint. Further column axial loads shows partial influence on joint confinement. When transverse reinforcement used to confine the test bar, the effects of additional cover were subdued. The unconfined conditions of headed bar anchorage will significantly influence the bond strength of straight bar and bearing strength of anchored head. This is due to effect of concrete strength in tension (which control the initial crack formation) and fracture energy which controls the crack propagation (Ref: Darwin et al. (2001) ,Zuo and Darwin et al, (2000). The previous experimental studies established that the increase of spacing (s) between multiple layered heads (spacing :s >8db) may increase the anchorage strength than closely spaced heads without transverse confinement. The anchorage strength of headed bar without confinement in large spaced bars (s>8db) is given in ACI318-14 under the expression,
Tc = 781 fcm0.24leh1.03db0.35. Research studies by Sperry et al. (2015) proposed modified expression for anchorage strength of closely space headed bar under the expression
Tc =781 fcm0.24leh1.03db0.35 (0.0836 s/db +0.3444). [where (0.0836s/db +0.3444) ≤ 1.0]

b) Concrete strength

The variation of bond and anchorage strength of headed bar in beam column joints are depends on material strength, geometry and state of stress conditions in joint connection. The mechanical property of concrete is an important factor for good bond performance of deformed bar. The splitting failure of bond depends on tensile strength of concrete. In STM the strength of concrete is resembled by strength of strut. But the strength of concrete shows less significance in presence of headed bar than hooked anchorage due to local crushing failure of concrete in anchored bent of hooked bars. The performance may emphasized under (i) Medium strength concrete and (ii) High strength concrete conditions. In medium strength conditions, crushing failure of concrete occurred around the headed bars prior to yielding of bars under tension. During high strength concrete conditions failure is attributed to allowance of limiting principle tensile stresses produced in joint [21]. Further the depth of embedment of headed anchorage system may have considerable importance in beam column joints. In shallow anchorage system, concrete strength influenced by anchorage performance of headed bar and the mode of failure is in the form of cone of fracture. Compared with shallow anchorage system, Deep anchorage system is less significant on failure as CCT node conditions are fully developed than shallow concrete.



Splitting failure   Pull out failure

Headed bar anchorage system

c) Influence of strut angle

The variations in strut angle not influence the bearing capacity of head or bond stress developed in the anchored bar. However, strut angle did affect the anchorage length of the bar. Shallow strut angles allowed a longer length of bar to be included within the bounds of the diagonal strut, and moving the critical development point away from the head and increasing anchorage length. The increase in the anchorage length of the tie bar results higher anchorage capacity of tie. However, decreases in strut angle also made the tie much less efficient for resisting the loads. Researcher Chun, et al (2014) observed that the joint aspect ratio is inversely proportional to the joint shear strength. Based on strut-and-tie mechanism, Hwang and Lee (1999) [18] indicated that the angle of inclination of diagonal compression strut (tan θ=hb/hc) is important for developing an efficient strut mechanism. On similar approach, researchers (Park, Mosalam 2012 [23]; Pauletta et al. 2015 [3]; Kassem 2015 [4]) considered the joint aspect ratio (hb/hc) for predicting the joint shear strength. They stated that for larger aspect ratio the diagonal strut becomes steep and leads to non-uniform flow of shear force. Previous researchers suggested that the maximum strut angle in strut-tie model is limited to 35° for efficient anchorage.

d) Influence of Column axial load

Column axial load significantly influence the confinement effect and shear capacity of beam column joint. The studies made by Masi et al., (2014) [5], Pantelides et al. (2002) [14], Barnes and Jogoral (2008) [10] , expressed that increase of column axial load improves shear capacity of joint. However the limit of axial strength ratio (ρ) = axial strength of concrete/ column axial load considered very low [between 0.15-0.30].The results are expressed that both joint deformation and ductility are significantly influenced by magnitude of column axial load and the level of maximum axial load identified in terms of shear strength as Pu = 0.42 f_c'A_g. Tran et al., (2016) analyzed the published experimental data of beam column joint and concluded that the effect of column axial load on joint shear strength was higher for the exterior joint than interior joints. Experimental results of Mohammed Ali Al-Osta et al.,(2018) [27], stated that at initial stage of loading, shear capacity of joint increased with increase of axial load and reducing its ductility. When (ρ) is greater than 0.60-0.70, the shear strength of joint starts decrease rapidly along with degradation of joint stiffness. Increase in column axial load above a level of 0.70 fc′Ag was found a decreased shear strength of joint and leading to failure by the column axial load.

Bakir and Boduroglu et al., (2002) [16] proposed an empirical model to evaluate shear strength of joint. But the expression considering the influence of anchorage details, longitudinal reinforcement of beam and aspect ratio of joint, except influence of column axial load .Also the proposed equation considered hooked anchorage system and not headed anchorage of joint system included.

$$V_c = 0.17\beta\gamma\left(\frac{100A_{sb}}{b_b d}\right)^{0.4289}\left(\frac{b_c+b_b}{2}\right)\left(\frac{h_b}{h_c}\right)^{-0.61}\times h_c\sqrt{f_c}$$

[Where Vc: shear strength of joint (Newtons), β = 0.85 for joints with U shaped anchorage of beam reinforcement, β =1 for standard 90-degree hook. γ can be taken as 1.37 for inclined bars in the joint and 1 for other cases, b_b : width of beam, bc: width of column, h_b :depth of beam, hc: depth of column, Asb: area of beam longitudinal reinforcement and fc :compressive strength of concrete]. ACI-ASCE recommended the following joint nominal shear strength equation for beam column joint.

$$V_n = 0.083\gamma\sqrt{f_c'}\, b_j\, h_c \text{ (Newtons)}$$

But the equation does not consider the influence of column axial load on joint and anchorage system of beam reinforcement .The design guidelines assumes that tension steel yields and do not take into account key parameters like aspect ratio, beam reinforcement ratio and column axial load for estimate the shear strength of a joint. [Vn: shear strength of joint, γ : value depends on connections classification and seismic magnitude, bj : efective joint width, hc :depth of the column in the direction of joint shear]

An average reduction of shear strength in beam column joint during reverse cyclic loading was found to be around 14% as compared to its monotonic loading. Ductility of joint was reduced with increase in axial load on column. This effect was more pronounced in column with axial loads greater than 0.60 fc′Ag. (Ref: Mohammed Ali Al-Osta et al.,2018)[1]

e) Influence of prying and wedging forces

Design guidelines for headed bars in beam-column joints were incorporated in ACI 352R-02.It recommends development length of headed bars and location of heads and the amount of head-restraining reinforcement required to prevent prying action of headed bars near the concrete surface. ACI 352R-02 defines two different development lengths of headed bars for Type 1 and Type 2 beam-column connections. Type2 joint is defined to have sustained strength under deformation reversals into the inelastic range, where as a Type1 joint is defined as a joint designed with no consideration of significant inelastic deformation.

f) **Influence of concrete cover**

ACI 318 puts limitations on clear cover (C) to headed reinforcement C $\geq 2\ d_b$,(d_b: bar diameter). But the experimental studies of Chun S.C et al [6] expressed that there is no significant effect on bar stress if C$\leq 2\ d_b$. The current design provisions of high strength lap splice, using headed bar in unconfined conditions are not well established as per ACI 318-11. Also the contribution of bond and bearing stresses of headed bar are inappropriate as per the code.

VI. CODE PROVISIONS FOR DETAILING ASPECTS OF HEADED ANCHORAGE SYSTEM

The design and detailing aspects of headed anchorage system is not well established by codes of R/C beam column joints. Researchers, Wright et al [15] , DeVries [6] et al., proposed some detailing aspects of headed anchorage system in beam column joints. Experimental results indicated that headed bar provides significant development of anchorage strength when it fulfil adequate confinement with respect to cover and transverse reinforcement .Hencethe detailing aspects are more important . In ACI 318-08 the concrete capacity design (CCD) methodology is used to determine the anchorage capacity of headed anchorage installed in mass concrete. In the CCD method, no bond stress is assumed along the length of a bar, and the concrete is treated to be unconfined.

ACI 318-14 code specified that the development length (L_{dt}) of headed bar in tension anchorage system is given by, $L_{dt} = (0.19\ \psi e\ fy\ d_b) / \sqrt{f'ck}$. (continuous geometric conditions) where , [L_{dt} should > $8d_b$ or 150 mm whichever is more ; fy :The specified strength of headed bars , fck: The design strength of concrete < 40MPa [d_b: bar diameter, ψe : 1.2 for epoxy-coated steel , ψe : 1.0 for other cases].

As per ACI 352R-02 code, the development length (L_{dt}) of anchorage in tension under discrete geometric conditions . In type-I joints $L_{dt} = (0.179\ fy\ d_b) / \sqrt{fck}$. (Non seismic conditions) and for type-II joints, $L_{dt} = (0.152\ fy\ d_b) / \sqrt{fck}$. (For moderate or high seismic conditions) .This is due to high concrete breakout capacity exists in headed bars anchored in diagonal strut under good confinement conditions. Design guidelines for headed bars in beam-column joints were incorporated in ACI 352-R10 for development length for headed bars and location of heads , amount of head-restraining reinforcement required to prevent prying action of headed bars placed near concrete-free surface.

Canadian code CSA .A23.3 -94, allows usage of headed bar as shear reinforcement under the following conditions. The headed anchorage shall be capable to develop full yield strength of the bar. The head area of the bar shall be at least 10 times the area of the bar unless experimental evidence justifies a smaller size. The factored total shear stress resistance (in SI units) shall be 1.33 times greater than the total allowed for members with conventional shear reinforcement.

The increases in concrete shear capacity result from the enhanced confinement effects headed bars should presumably provide. The design codes of ACI / NZS/ EURO/CSA , unable to explain the provisions of post installed headed anchorage system in R/C beam column joint. Also the codes restrict the strength of headed reinforcement (fy<415MPa) and concrete (fc'< 60MPa) due to lack of experimental test data. Hence the current design provisions needs modify to meet effective usage of headed bars for high strength conditions (Ref: Chun S.C et al-2013) [6]

VII. CONCLUSIONS

Headed anchorage system provides viable solution in high strength conditions of joints than hooked anchorage in R/C beam column joint. Headed system follows strut and tie mechanism and more effective in discrete joint conditions. This paper comprehensively discussed about force transfer mechanism, anchorage system, failure modes and parametric studies that influence satisfactory performance of headed bar anchorage in beam column joint. A brief review on past experimental research on anchorage system of beam column joint and usage of headed bars concluded that headed anchorage provides reliable performance than hooked bar under monotonic and cyclic load conditions. From the studies, it has been observed that the design codes of ACI/NZS/EURO not well establish the contribution of influential parameters on behaviour of headed bars. Expressions mentioned in design codes are not represented the influential parameters of headed anchorage system. In this context, Indian code is much deficient to establish design guidelines of headed bars. Use of headed bars in post installed anchorage system of un-bond and bonded conditions has much significance in precast constructions. But the relevant design provisions are not addressed in the codes. Specific conclusions of this study made as follows.

- Headed anchorage system shows good efficiency and performance than hooked system during monotonic and cyclic load conditions.
- Headed anchorage provides viable solution during high strength concrete conditions in beam column joints in terms of strength, confinement, ductility and constructability.
- Design codes are still lagging to establish expressions and detailing aspects of headed anchorage.
- Indian codes are insufficient and not well established design expressions of headed anchorage during high strength concrete and steel reinforcement.
- Design expressions mentioned in codes are related to hooked anchorage and not established with headed anchorage.

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