Influential parameters for Headed Bars in RC Beam-Column Joint: A Review

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Abstract

RC beam-column joint, a critical region of framed system often do not achieve adequate strength due to poor detailing and workmanship. Conventional anchors, straight and hooked bar anchor the flexural longitudinal bar terminating at the joint, have many design and construction drawbacks like steel congestion leading to honey combing in concrete, difficulties in implementation. This evolved development of headed bars and is highly advocated by the researchers, owing an alternative solution to conventional anchors. Various parameter like head geometry, embedment depth, grade of concrete etc., influence the behaviour of headed bar in the joints. This paper presents a review on headed bar for development of proper guidelines.

Keywords: Beam-Column Joints, Hooked Bar, Headed Bars, Anchorage Capacity, Pull-Out Capacity

Notation

A_{brg}	Bearing area of head
A_b	Area of bar
f_y	Specified strength of headed bar
db	Diameter of the reinforced bar
f_c'	Specified compressive strength of concrete
¢	Strength reduction factor
α	Stress multiplier for longitudinal reinforcement at joint/member interface
L_{dh}	Development length of hooked bars
Ψ_e	Factor for coating over reinforcement
L_{dt}	Development length of headed bar in mm

1. Introduction

The most important aspect of structural design is anchorage strength of development length reinforcing bars in beam-column joint which depends on the type of anchorage mechanism. Conventional method used to anchor the longitudinal flexural reinforcing bar terminating at the joint is either straight bar or hooked bar, which leads to steel congestion resulting in fabrication, compaction of concrete, honey combing, joint strength and other construction difficulties. Headed bar is a potential solution to this problems without affecting the structural performance due to its easy installation, time saving fabrication, minimization of steel congestion in joints and better concrete placement. Headed bars were primarily used in Europe for the construction of offshore oil platform and then expanded to North America where large number of headed bars were used on Hibernia platform located in Newfoundland, Canada. Today’s, demand of headed bar as longitudinal reinforcement and transverse reinforcement for relatively large reinforced concrete structure exposed to high seismic loads is increasing. Headed bar is a mechanical anchorage system with heads attached at the ends of the reinforcing bar. Different types of head attaching techniques are available like friction welding, forged welding and threading technique, among these threading technique is opted most due to proper interlocking property between bar and head. The ultimate load carrying capacity of headed bar influence with the factors like type of head attaching technique, yield strength of headed bars, diameter of reinforcing bar, concrete compressive strength, head geometry, embedment depth, side cover, and clear spacing between the bars, to some degree as shown in Figure1. ACI 408 (Development and splicing of Deformed bars) and ACI committee 439 (steel reinforcement) jointly prepared a report on headed bar using few tests data of prior researches and is refers to ACI352R-02 whose specification meets the specification of ASTM A970 for the use of headed bar terminating at the junction, a feasible option in disturbed regions of a concrete specimens with nonlinear strain distribution. The anchorage capacity of headed bar installed in the plain concrete is determined using Concrete Capacity Design (CCD) method[1]. CCD method basically used for the design of headed stud and anchors in which no bond stress was assumed along the length of the bar and the concrete was assumed as unconfined. No special details of headed bar is recommended for seismic and non-seismic design[1].

This paper reviews the past two decades research on beam-column joint subassemblies with headed bar, tested under different loading conditions such as monotonic loading or reversed cyclic loading. Most of the studies are on concentric beam-column joint and very few on eccentric beam-column joint used often in practice at the ends and corners of a building. Observed that eccentric connection had lower shear strength to some extent due to the existence of slab and transverse beams frame with low confinement which are more vulnerable to deterioration (side blow out failure); to overcome this difficulties the possible use of headed bar in eccentric beam-column joint has to be investigated. Large diameter of reinforcing (43 to 57mm)bars are widely used in construction of high rise buildings, bridge girder, deep beam and other large member, to eliminate the congestion and fabrication difficulties[2]. Almost all the studies so performed yet are on 36mm diameter reinforcing bars. In seismic design, the location of plastic hinge formation in beam is generally at the face of the column are vulnerable to yielding of reinforcement results in bond deterioration which require proper detailing of longitudinal bars to prevent the penetration of yielding thereby weakening the truss mechanism to transfer the shear across the joint core. The plastic hinge formation in beam-column joint can be eliminated either by shifting the plastic region slightly away from the face of the column or by increasing the beam depth and longitudinal bar which is not practical. A practical solution to this has been studied by using headed bar for relocating the plastic hinge in the beam[3]. Modern mechanical anchorage device, Headed bar, have wider advantages over conventional anchorage device, hooked bar. However, little literature on headed bar arise the requirement for deep investigation on headed bar for the development of proper guidelines for its provision in construction practices. This paper discusses on anchorage devices and stress transmission mechanism, parameters influencing performance of headed bar – grade of concrete and reinforcing bars, headed geometry, bearing ratio, clear spacing ,side cover, embedment depth, development length, confinement and behaviour of headed bars.

2. Anchorage Devices and Stress Transmission Mechanism

2.1. Conventional Anchorage Device vs Modern Anchorage Device- Headed Bars

Hooked bar anchorages are conventionally used for longitudinal beam flexural reinforcing bar terminating within the beam-column joint. The bends and tails of hooked bar promote the development of diagonal compression strut mechanism within the joint which is main joint resisting mechanism while the head plate in headed bar develop the diagonal compression mechanism[4]. Formation of bend take off the corrosion resisting layer from the surface of the bar accelerates corrosion of the bar at the bend[5]. The fabrication of hooked bar is time consuming as well as demands skilled labour. However, the hooked bar leads to steel congestion in a region where main bars of beam and column passes through or terminate which hinders the placement and compaction of concrete, results in honeycombing[5]. These all issues decreases anchorage strength of the hooked bar causes early failure of joint in the frames subjected to seismic load. Whereas the advantages of headed bar over hooked bar are reduces steel congestion, placed exactly at the desired location, save construction costs, better concrete consolidation and provide full anchorage without cover offers better bond strength and speed in construction process and hence, is an efficient form of mechanical anchorage device for beam-column joint[5].

2.2. Stress Transmission Mechanism

The adhesion between the reinforcing bar and surrounding concrete is referred as bond. Bond between steel and concrete ensures the strain compatibility and act as a composite section. The factors responsible for the bond strength between the deformed reinforcing bars and concrete are chemical adhesion, friction and deformation over the surface of reinforcement[6]. The deformed bar provides more efficient bond strength as compared to smooth reinforcing bar, as the bond of smooth bar is negligible whereas deformation enhance the bond strength[1].The bond force transfer occur in two forms 1) bearing and friction force on the bars and 2) adhesion and friction forces along the surface of the bar[5] (figure 2). Codes specified to use hook to anchor the longitudinal bar in beam with minimum embedment length. In-order to develop diagonal compression strut mechanism within the beam-column joint, bending of bar for a development length is recommended.

Whereas headed bar consists of head- bearing component and bond component, which are equally responsible for the transmission of stress from bar to head and head to concrete. As the stress is applied, the bond component predominantly carries the force, reaches peak bond capacity and subsequently the bar slip increases (1.5% to 2.5%) with the bond deterioration subsequently stress transfer to the head bearing component leads to failure (2.5% to 6% drift) at the peak anchorage capacity which implies that the anchorage capacity of headed bar is combination of bond contribution and head bearing contribution[6]. However, the bearing of head provide greater resistance as compared to bond component. Further the occurrence of crack formation at the interface of beam-column joint and in joint core results in the bond deterioration[7].

3. Influencing Parameters on Performance of Headed Bar

3.1 Grade of Concrete and Reinforcing Bars

The specified yield strength of headed bar and compressive strength of concrete are limited to 420MPa and 41MPa[1] whereas the specified strength of headed bar and concrete strength were also recommended up to 540MPa and 100MPa[7], which results into satisfactorily performance for both low seismic risk and moderate and high seismic risk joint with headed bars. Test has been performed on headed bar using high strength steel (815MPa) which exhibited low strength in beam column joint due to lack of development length. As large diameter of bar will not be feasible for the joint design criteria (very large dimension) of beam or column. High strength bar of diameter 43mm and 57 mm were permitted for the design of bridge and nuclear plants[8]. Member subjected to flexural hinging followed by modest joint deterioration are allowed to use maximum permissible size of the deformed bar is 36mm and normal weight concrete[7]. All these recommendations are not applicable to light weight concrete due to lack of experimental data, became the topic of research. To promote favourable anchorage behaviour in the beam-column joint, high strength reinforcement (690MPa) should be combined with high strength concrete (100MPa) [9]. Researchers observed that increase in grade of concrete for constant embedment depth increases the bond capacity of headed bar[10] (Table1).

3.2 Head Geometry and Bearing Ratio

Previous research on headed bar in Europe, Canada and The United States have revealed that the head area should be 3 times the nominal bar area[7, 11]. The geometry of head is responsible for the transfer of full rebar force into multi-axial stresses in concrete beneath the head without crushing or bending the head. Among various head plate shapes like circular, elliptical, rectangle and square as shown in the figure3 (a), the most efficient shape is found to be Circular shape head plate[12]. The pull-out resistance of different head geometry and bearing ratio ranging between 6 to 8 varies a lot, resulting in effective pull-out capacity of Circular > Square > Rectangle head with bearing ratio 6, which is greater than as specified in ACI381-08[13]. Large head plate of headed bar means large angle of anchor inclination near the concrete surface along with large surface area failure[12]. At failure the bond stress decreases with increase in the relative head area because large relative head area takes long time to transfer the bond stress to head and decline, and slip of head reduces with relative head area before the head attained its maximum capacity and increases steadily till failure[4]. No minimum criteria specified for net bearing ratio[14]. It is well understood that after bond deterioration the anchorage relies on area of head bearing because it is not necessary that large head size warrants a shorter development length to ensure adequate bond behaviour at low to moderate drift levels[14]. Headed bar having net bearing ratio greater than 4 is considered as large head which exhibit higher anchoragestrength but is impracticable as compared to small head with net bearing ratio less than 4 (A_{brg}/A_b=2.6) which relieves the congestion problems and minimize the column bar obstruction while inserting beam bar into column cage. The head thickness of 1db ensures effective head bearing strength with small deformation in steel[5]. A test on eccentric beam-column joint with double headed bar attached on each beam bar within the joint figure 3 (b & c) oriented in staggered pattern showed higher anchorage capacity prevent the push out on the back of the core. This also reduces the yield penetration and bond deterioration along the beam bar in the joint thereby delaying degradation of shear capacity beyond limiting drift ratio of 4%[15]. Further, on the basis of some research specified conditions for the design of headed bar with net bearing ratio greater than 4 which was found to be appropriate to ensure anchorage strength both in elastic and inelastic deformation. This introduces a provision for obstruction or interruption of bar deformation which should not extend more than 2db (diameter of bar) from the bearing face of the head[1] (figure 4). The net head bearing area is the difference between head area and bar area, also obtain by subtracting obstruction area from head area, is often absent in many cases.

The effect of detailing of single headed bars with large diameter of deformed bars have disadvantage in contrast to detailing of single headed bars with small diameter of deformed bars. Single headed large diameter bar causes splitting of cover along the bar with the generation of high compressive stress at the vicinity of the heads and leads to diagonal cracking[2].

Inadequate transverse reinforcement due to congestion at the joint proved to have brittle shear failure. Concrete mix is incorporated with 2% of steel fibre at beam-column joint using headed bar shown in figure 3(d) exhibit 45% higher ductility, stiffness and anchorage16.

3.3 Headed Bar Clear Spacing, Side Clear Cover and Edge Distance

ACI352R-02 recommends cover of 50mm headed bar from back of joint core where concrete bearing capacity is higher in diagonal compression strut. The restraining reinforcement is provided at beam-column joint to prevent the prying action of headed bar placed near concrete cover. The ultimate load carrying capacity of Headed Bar is also depends on its location i.e. edge bar, centre bar and corner bar, among which centre bars exhibit higher strength due to large area of failure surface and least for the cover bar[17]. In case of multiple headed bar the spacing between the headed bar and edge distance are provided to prevent the interaction between the bars during load application[12].

Side clear cover minimum 2db is required primarily to protect the reinforcement against extreme weather and fire while 35mm is specified for the head[14].

Clear spacing of the bar is an important aspect in the design and detailing of the beam, based on which the size and dimension of beam can be determined. ACI318-08 recommends the clear spacing between the headed bar shall be more than 4db, determined using lower bound values obtained from various lap splice tests which is significantly larger than the value (1db or 1.5db) required conventionally in beams and column. This conservative limitation are adopted to prevent the overlap of concrete cone failure surface area around the headed bar under tension. A study on clear spacing of 1.5db, 2db, 2.25db, and 4.25db showed that at 4.25db clear spacing, the degree of flexural yielding was small at the bar ends and higher at the critical section whereas in other cases concrete deformation exceeded the yield strain at the end of the bars[18]. The clear spacing between the bars greater than 4db is impractical, commonly it ranges between 1db to 3db in practice. Clear cover 3.6db and clear bar spacing 4.2db shows no effect on the seismic performance of headed bar in beam-column joint by reducing the amount of head restraining reinforcement[14].

For multi-layer reinforcing bar, where the spacing between the bars determines the failure surface, showed no influence on the lateral resistance of beam-column joint[14].ACI 318-14 recommends strictly minimum clear spacing as 3db which is adopted mostly in design and detailing of flexural member.

3.4 Embedment Depth

Embedment depth is the overall depth of the bar through which the force is transferred to or from the surrounding concrete, while effective embedment depth is distance from the bearing surface of the head[14]. The ratio of embedment depth to the clear cover less than 5 is termed as shallow embedment depth whereas greater than 5 is termed as deep embedment depth (figure 5). The ultimate load carrying capacity of headed bar enhance with the embedment depth which determines the size of pull-out concrete cone failure surface area[18]. Closely spaced multiple headed bar deeply embedded in the reinfored concrete column (10db,13db,15db) with minimum column ties spacing (3db,4.5db,6db and 9db) for different diameter of deformed bar(16, 22, 25 & 29mm) showed that the pull-out strength of individual headed bar increases over 125 % of yield strength of the bar[19]. Test had performed on a beam-column joint designed for joint shear requirement with an embedment depth 1.5 to 2 times of development length for headed bar resulting in less head bearing demand[14]. Beam-column joint consist of headed bar with small head along with development length of 15db capable to transfer moments and forces in the member without drift loss up to 3.5% .Larger the embedment depth(8.4db,12db &16db) resulted in higher bond strength, with smaller bearing ratio[13]. The embedment depth decides the failure behaviour of the headed bar, larger embedment depth leads to yielding of bar whereas smaller embedment depth leads to splitting of the concrete. Large embedment depth with large diameter of bar and side cover promotes the anchorage behaviour and side blowout capacity of headed bar.

3.5. Development Length

The minimum length of reinforcing bar require to develop bond strength to resist external tensile load is referred as development length, which is composed of bonded length and bearing length. When there is insufficient space for provision of bonded length of bar, the bar is terminated in the form of hook or head which add bearing force to bond force.

For the design of hooked bar, the development length for flexure longitudinal bar in tension is categorised on the basis of critical section, subjected to low seismic risk (type1) and moderate to high seismic risk (type 2) beam-column connection[7] as defined:

$$ldh = \frac{f_y\, db}{4.2\sqrt{f_c}'\emptyset} \qquad (type\ 1)$$

$$ldh = \frac{af_y db}{6.2\sqrt{f_c}'\emptyset} \qquad (type\ 2)$$

Where,

fy= specified strength of headed bar, db= diameter of the reinforced bar, fc'=specified compressive strength of concrete,¢= strength reduction factor, α= stress multiplier for longitudinal reinforcement at joint/member interface, ldh = development length of hooked bars in mm.

The development length of headed bar is 0.67 times the corresponding length for hooked bar indicates no significant loss of anchorage due to deterioration of joint under cyclic loading[7]. The development length of headed bar in tension is given by[1];

$$ldt = \frac{0.19\Psi \mathrm{e} f_y d\mathrm{b}}{\sqrt{f_c'}} \geq the\ larger\ of\ 8db\ and\ 152mm$$

Where,

f_y= specified strength of headed bar, db= diameter of the reinforced bar,

f_c'=specified compressive strength of concrete, $\Psi_e = 1.2$ for epoxy coated reinforcement and 1 for other. *ldt* = development length of headed bars in mm

Generally, the load distribution along the development length was assumed constant[7]. This assumption found to be no longer constant because of the load distribution depends on the bonded length of the headed bar. For more bonded length, the majority of the load is resisted by bonded length followed by slip of bar occur and the remaining load is borne by bearing length[20].

3.6. Anchor reinforcement and confinement in Beam-Column joint

The anchor reinforcement transfers the force from anchors into the structural member; the best example is Hairpins[1].It is revealed from various research that column main reinforcement and column ties influence the strength and ductile behaviour of headed bar. Column ties close to headed bars develop large strain but contribute to Pull-out capacity whereas column ties away from the headed bar develop small strain but have no contribution on Pull-out capacity.

The seismic performance of headed bar with moderate joint confinement does not influence adversely the anchorage capacity of the inter-story joints. This is due to external truss above the joint provide different bearing stress transfer path results in reduction in the transverse reinforcement when placing headed bar as beam longitudinal reinforcement[5]. Test on beam-column subassemblies with T-headed bar in combination with X-cross bar and hairpins as transverse reinforcement (shown in figure 7) was performed. This results showed enhancement in the ultimate strength by 10%, ductility by 12%, stiffness by 15%, showed much better crack control capacity and assist in alleviating congestion of steel, eases the pouring of concrete and helps in faster construction in site[22].

Confinement of longitudinal headed bar and lap splices in beam-column joint influenced the flexural behaviour of the member to a large extent. In general, lap splices fails a priory to longitudinal bar. The lap splices ranges from 15db to 25db were placed with various confinement pattern (unconfined, locally confined and standard confined) to eliminate the prying action and to increase the end bearing capacity. Standard confined lap splices contributed 73% increase in the end bearing capacity[23]. Use of U-shaped reinforcing bar and stick type bar for proper confinement of headed bar in exterior beam-column joint shown in the figure 8 provide proper confinement to the main headed bar which reduces the stress in concrete cover, enhances the bond strength and eliminate the diagonal cracking due to storey shear[24]. Closely spaced high strength headed bar in special moment frame subjected to cyclic loading were tested with different confinement criteria and found that ties provided at the column main bar in the joint at a spacing of 75mm promote better anchorage performance and delay in joint deterioration than 125mm spacing ties in the joint[9]. Transverse reinforcement as hairpin bars enhance the anchorage capacity of headed bars limiting the splitting crack failure arising from the bond stresses and confined the head bearing[23] as shown in figure9.

4. BEHAVIOUR OF HEADED BARS

Beam-column joint subassemblies fail in different pattern under reversed cyclic loading which are categorised on the basis of performance indexes as: Category I: beam-column flexural failure followed by modest joint deterioration; Category II: beam-column flexural failure followed by joint failure and Category III: joint failure prior headed bar yielding. Premature joint failure generally occur earlier than flexural failure when the ratio of peak moment to negative moment is less than 1 or no flexural yielding observed before the last cycle of the test[25].The strength of head anchor under tension depends on the material properties and dimension of the head. Deformation developed in the part of headed bar close to the applied load are generally larger than the part of headed bar close the head plate. These difference in deformation indicate that the bond between headed bar and concrete is not broken at the peak load and anchorage relies on the head bearing along with the bonded bar. The failure in the headed bar induced as a result of the tension forces. Mainly, the failure modes of headed bars associated with the anchorage of the head are (figure 10):

(a) Yielding of bar generally takes place in case of large deep embedment depth, the yielding mechanisms begins when the applied load on the headed bar exceeds the yield strength of the bar with occurrence of small slip causing breaking of top concrete conical surface (figure 10a).

(b) Pull-out failure or bond failure occurs due to insufficient bond between bonded length and surrounding concrete. Small embedment depth do not contribute proper bond between the bar and concrete resulting into failure of bond (figure 10b).

(c) Side blow out failure: occurs when the cover to headed bar is inadequate (figure 10c).

(d) Concrete splitting failure: which is diagonal cracking in beam-column joint occur due to lack of confinement of headed bar and insufficient concrete surface area to distribute the bond stress between the headed bar. In single headed bar, the bond stress on concrete from bearing plate exceeds the concrete bearing capacity resulting in concrete splitting failure[23] (figure 10d).

(e) Concrete breakout failure occurs for heads due to no reinforcement provision to redirect the stress path back to the concrete mass[28]. The head is a steel bearing plate which not only transfer the bond stress along the bar but also subjected to large bearing pressure on its face. When this bearing pressure exceeds the concrete bearing capacity, the concrete cone shaped failure occurs[18] (figure 10e).

5. CONCLUSION

Headed bar is proven to be more efficient mechanism as compare to the conventional anchorage system i.e. straight or hooked bar. Owing to its various advantages over conventional anchors such as reduced steel congestion in the joint, improved strength, providing speed to construction and economy. Hence, following conclusions are made through the knowledge gathered from the prior research for the design of beam-column joint using headed bar:

i. High strength reinforcing bar and high strength concrete enhance the anchorage behaviour of the headed bars.

ii. Head geometry determines the ultimate capacity of the headed bar with circular shape proved to be the most effective in contrast to rectangular, square and elliptical shaped headed bar.

iii. The load distribution ratio of development length bar varies with bonded length and increase in bonded length reduces slip of bar.

iv. Single headed bar with deformed bar diameter varying from 16mm to 29mm and embedment depth in the range of 8db to 12db enhanced the pull-out resistance by 95% of the bar yield load.

v. Increase in development length, head size and thickness, and decrease in joint shear demand results in a better performance of the joint.

vi. Closely spaced headed bar (1.5db to 2.25db) were found to be effective with no severe failure. Hence, clear spacing less than 2db can be acceptable for headed longitudinal bars.

vii. Multiple headed bar with large embedment depth and smaller tie spacing in the reinforced concrete column increases the pull-out resistance by 17.7% on average.

viii. Large embedment depth, edge distance, and head spacing with small tie spacing in the column, contribute to increase in Pull-out capacity.

Quantification of these various parameters for design and detailing are not dealt properly in any previous study. Application of headed bar in precast beam column joint as well as in light weight concrete may become future scope in construction practices.

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Table1: Influence of Grade of concrete on bond capacity of Headed Bar[10]

Sr. No.	Grade of Concrete	Embedment Depth(mm)	Bond Capacity(kN)
1.	M20	200	55
2.	M30		120
3.	M40		140
4.	M20	240	160
5.	M30		190
6.	M40		220
7.	M20	280	200
8.	M30		220
9.	M40		230

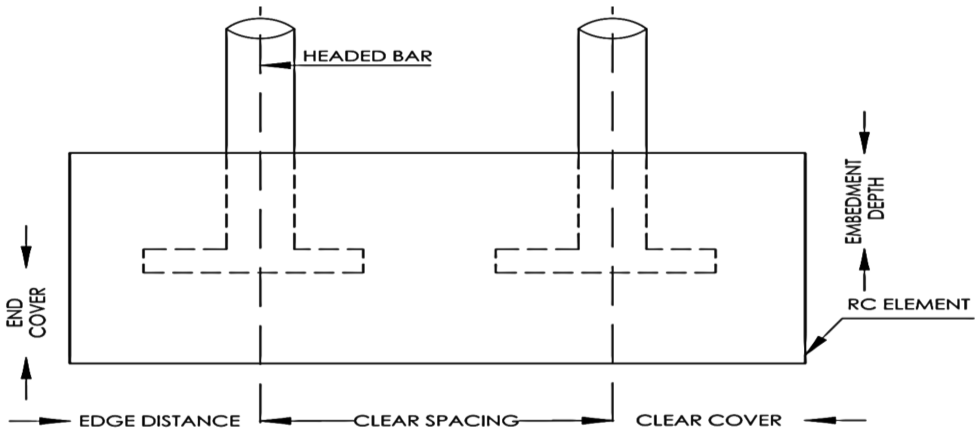


Figure 1: Detail of headed bar embedded into the concrete

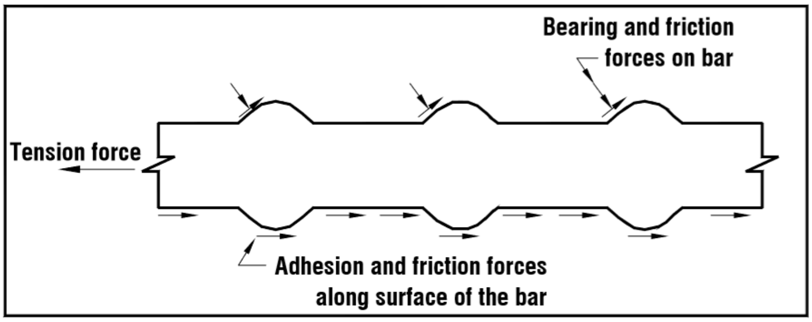
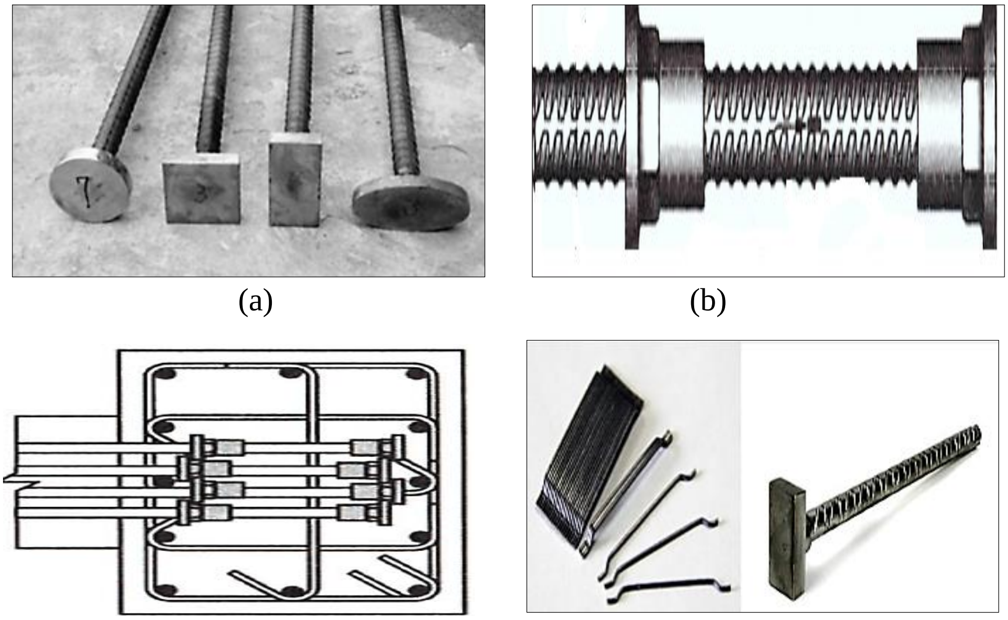


Figure 2. Stress transfer mechanism between rebar and concrete



(a) (b)

(c) (d)

Figure 3: (a) Different head geometry[12], (b) Double headed bar[16], (c) Arrangement of double headed bar in staggered pattern[16], (d) Steel fibre and headed bar[17]

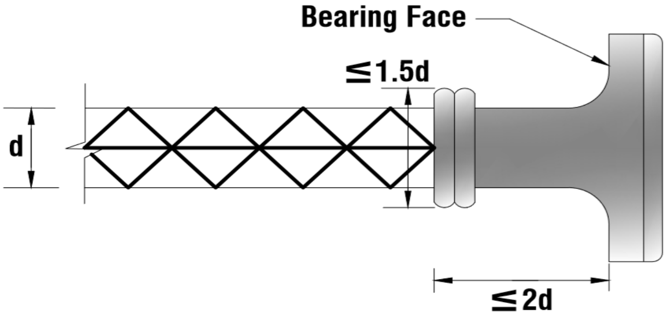


Figure 4: Obstruction and interruption for headed bars

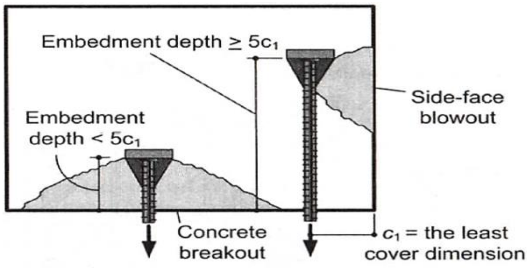


Figure 5: Shallow embedment depth Vs deep embedment depth[15]

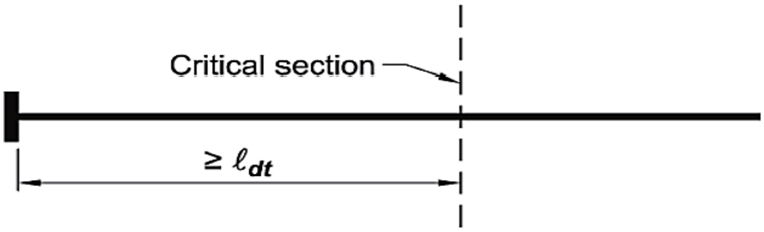


Figure 6: Development length of headed bar[21]

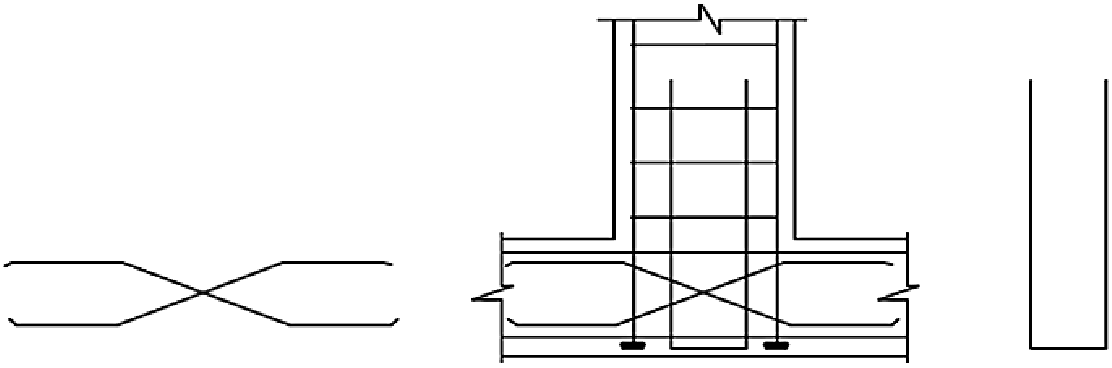


Figure 7: Detailing of beam-column joint using headed bar with X-cross bars and hairpins

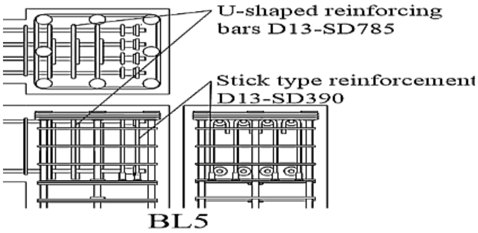


Figure 8: Arrangement of U-shaped reinforcing bar and Stick type reinforcement in beam-column joint[24]

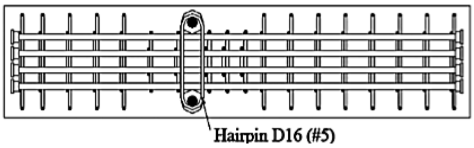


Figure 9: Arrangement of hairpins transverse reinforcement in beam –column joint[23]

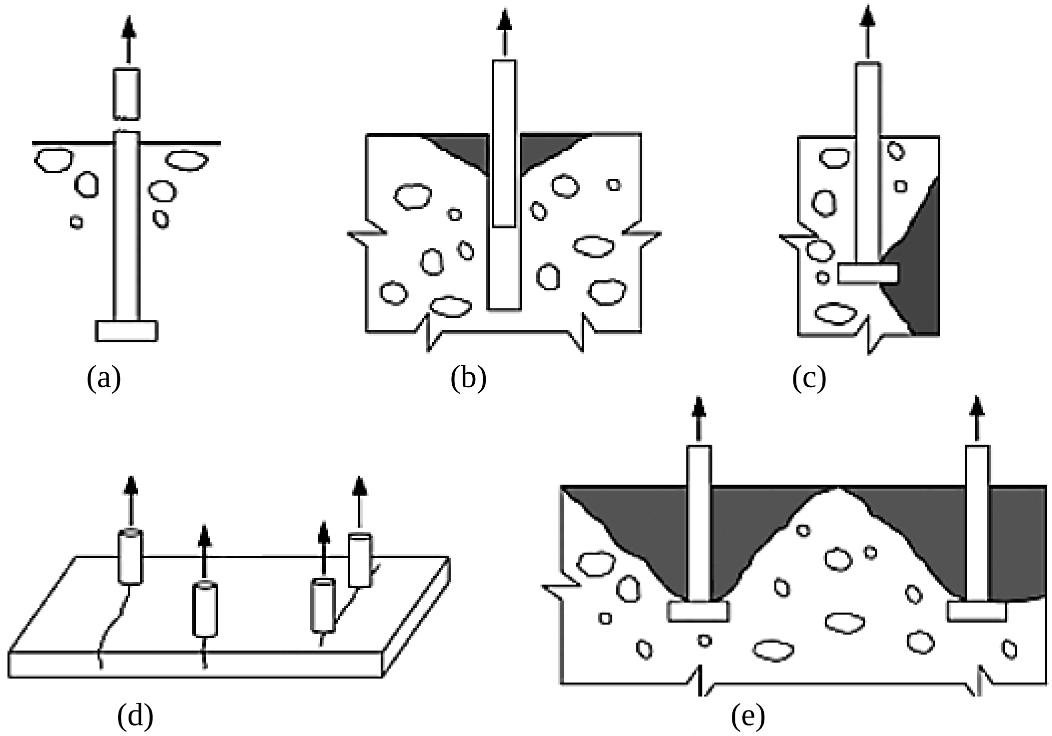


Figure 10: Different types of failure modes of Headed bar[1]: (a) Bar yielding failure, (b) Pull-out failure, (c) Side blow out failure, (d) Concrete splitting (e) Concrete breakout failure