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Original Research Article

Analytical Studies on Retrofitted Anchorage System in Concrete using Strut and Tie Method

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Abstract

Analytical studies were conducted on force transfer mechanism of retrofitted anchorage system in structural concrete by Strut-and-Tie modeling (STM). Post Installation of Headed anchorage (PIHA) as supplementary system introduced for implicit strengthening of anchorage system. The boundaries of STM are considered under direct tension pull-out test. Five different configurations of conventional reinforcement anchorage in concrete with straight bar, 90-degree bend, 180-degree hook, single head and double head bars are retrofitted by using PIHA technique. The mechanics of force transfer in anchorage system was analyzed by STM and validated the results by experimental program. The study parameters considered are (i) location of nodal zone, (ii) strut angle, (iii) size of strut (concrete) contributed during failure. The study variables are (i) configuration of anchorage system (ii) characteristic node formation and (iii) presence of supplementary reinforcement. The result shows good agreement with experimental findings against failure mode, stress pattern, and location of critical zone in conventional and retrofitted anchorage system. Use of this study may further extended to assess theoretical evaluation of failure mode, formation of critical section and stressed regions of discrete RC elements such as corbel projection, bracket connections and beam-column joints.

Keywords: Anchorage, configuration, strut and tie, supplementary anchorage, failure mode.

1. INTRODUCTION

Detailing aspects of reinforcement in discrete elements of structural concrete is key parameter during the performance evaluation of anchorage system. Brittle failures of anchorage system often found in discrete elements of structural members such as corbel projection, beam-column joint, and bracket system etc. when it subjected to intensified static or dynamic loads. In this context researchers suggested on performance based Concrete Capacity Design (CCD), where the detailing aspects of reinforcement shows significant influence on failure mechanism. But most of the ductile detailing as per design codes are unable to establish due to constructability issues such as rebar fabrication, anchoring and fixing in constrained geometry. Due to poor vicinity of rebar detailing and anchorage system brittle failures often occurred in joints when subjected to seismic and impact loads. And the failures mainly intended due to anchorage failure by loss of bond, shear deformation of joint and splitting tensile stresses of joint concrete apart from yielding of reinforcement.

Appreciable research work was established in the past by external retrofitting of beam-column joint such as fiber wrapping technique, section enhancement, plate bond technique and use of composite sections etc. These techniques are good at improving ultimate strength of joint but not for improved ductility. Hence the scientific community focused on Implicit strengthening measures of anchorage system with both active and passive confinement techniques to improve joint performance at post failure conditions. The suggested techniques are use of different fibers in green concrete, external pre-stressing, and use of shear studs in joint concrete. The techniques shows good prominence of ductility and strength, but applicable to green concrete only. Hence a novel technique called “Post Retrofitting of Anchorage System” (PRAS) by using supplementary bars was introduced by the author and conducted experimental tests on five different configurations of rebar anchorage system. The obtained results were validated by ANSYS modeling.

As per the notes given in the design code of ACI 318-19 provision of reinforcement detailing in discrete concrete elements shall be followed by Strut-and-Tie modeling (STM). This paper focused on to conduct analytical study on strut-and- tie formation in five different types of conventional and retrofitted anchorage system .Two types of bond stresses are generally exist in anchorage system that was (1) Local bond stress, (2) Anchorage bond stress. Despite uneven distribution of bond strength, the local bond strength do not influence the ultimate strength of reinforcement, whereas anchorage bond strength of rebar under tension or compression shows significant influence on strength of integrated connection system by bond or development length. This point was focused in STM studies and accordingly theoretical evaluations are made for different configurations of anchorage system. Formation of compression struts and tension ties and corresponding nodal zones crucially influence the strength of anchorage system in STM. Design code ACI318-19 suggested that the formation of compression strut at angle 2:1 shows more effective. Based on recommendations, the subsequent developments are addressed by other nations of NZS 3101-08, CEB-FIP, EC-2, CSA following STM approach. But Indian codes (IS456, IS2502, SP16) do not mentioned STM analysis but provides guidelines on strengthening of joint against local bond strength development length and confinement of joint core.

Tension pull-out tests are widely accepted means to evaluate the bond strength of anchorage system. The test conditions resemble STM boundaries and shows good prominence to evaluate anchorage strength against different failures. Two types of pull-out tests are generally in embedded rebar anchorage system in concrete. They are (i) Classical pull-out test (meant for shear resistance of anchorage) and (ii) Direct tension pull-out test (meant for tensile resistance of concrete). The formation of nodal zones (CCT,CTT,TTT) and critical plane may directly represent the failure pattern and anchorage strength. Based on boundary conditions, direct tension pull-out test gives lower bound of anchorage strength with the formation of nodes. Theoretical studies based on STM analysis were conducted on different configurations of conventional and retrofitted anchorage system. Post Installation of Supplementary Anchorage (PISA) is a new technique addressed in this paper, where the implicit strengthening mechanism of rebar anchorage could attain by post retrofitting of headed bar in the existing anchorage system of hardened concrete. Further this study was focused on to describe the strength of different anchorage systems and the pattern of its failure based on formation of nodal zones, strut angle, and volume of strut in both conventional and retrofitted anchorage system. The rebar anchorage represents unconfined boundary conditions of tested specimens.

2. LITERATURE REVIEW

Most of the retrofitting techniques are based on external measures as it develops ultimate strength of concrete rather than ductility. From the literature it was found that the retrofitting methods on implicit strengthening measures of concrete may develop good ultimate strength and ductility. The headed bars as supplementary anchorage provides system typical formation of strut-tie force transfer mechanism, and the studies related to post damage and retrofitted anchorage system provides most essential data for rehabilitation process of critical elements Studies of Jung-Wong Park *et al*., (2007) expressed that STM analysis useful for calculating the strength of RC deep beams. The proposed method employs constitutive laws of cracked concrete, by considering strain compatibility. STM method accounts to detect failure modes by crushing of concrete at nodal compression zone. Sung-Gul Hong, *et al*., (2007) used STM analysis for development of headed bars in an exterior beam-column joint and proposed to investigate realistic force transfer of headed bars in joint core. The results concluded that the tensile resistance in headed bar may be developed by head bearing and bond of bar with partial embedment length. Mohamed E. El-Metwally *et al*., (2012) discussed on current developments of strut-and-tie model for the application to continuous deep beams. Based on the results, concrete strength (normal or high) and the shear spanto-depth ratio, the effectiveness factors of concrete struts are modified. The effectiveness factors for nodal zones are chosen based on the force boundary conditions. Shyh-Jiann Hwang, *et al*., (2002) expressed that the discontinuities caused by abrupt changes in cross-sectional dimensions or by concentrated loads result in discontinuity regions due to disturbance in the flow of internal forces. A simplified method, based on the softened strut-and-tie model, for determining the shear strength of discontinuity regions failing in diagonal compressions is proposed. Yasuteru Okahashia *et al*., (2017) used softened strut-and-tie model (STM) is developed for interior reinforced concrete (RC) beam-column joints without any steel hoops in the joint or intermediate longitudinal column steel reinforcement, and discontinuous bottom beam flexural steel reinforcement. The STM model is extended to identical joints retrofitted with Carbon Fiber-Reinforced Polymer (CFRP) composites.

3.RESEARCH SIGNIFICANCE

Strengthening of structural anchorage system in discrete concrete components such as integrated joints system received greater attention during rehabilitation of integrated connection of RC framed systems. Research work in this area was scarcely available at present scenario. This paper focused on to present theoretical evaluation of post retrofitted anchorage system by using STM analysis. In this sequence five different configurations of anchorage systems retrofitted by PIHA technique and validated with experimental results. This study may useful to evaluate the failure mechanics of discrete structural elements such as beam-column joint, corbel projection and deep beams.

4.STUDY OBJECTIVES

This studies focused on Strut-and-Tie formation in different configurations of rebar anchorage system in conventional and post retrofitted anchorage system by using PIHA technique. Following sequence of activities are carried out in this regard.

- Identify the mechanics of node formation in five different types of conventional and retrofitted anchorage system (straight, 90 degree bend, 180 degree hook, single headed bar, double headed bar)
- Evaluate the influence of supplementary steel for retrofitting of conventional anchorage system using PISA technique (straight, 90 degree bend, 180 degree hook, single headed bar, double headed bar)
- Identify the location of critical plane based on principal stresses developed in anchorage system
- Find out the possible failure mode of anchorage system with respect to configuration of anchorage
- Validate the obtained results with Experimental findings (conventional and retrofitted)

5. NORMAL STRESS IN ANCHORAGE SYSTEM

As per analysis, the normal stress in anchorage system is proportion to shear stress force in the embedment depth of bar. Due to this most of anchorage failures are associated with slip of bar by shear conditions along the embedment depth and crushing of concrete by bearing stress at tail end of bar. Formation of strut and tie mechanism is critical factor during force transfer mechanism in conventional anchorage system. Most of the anchorage failures are occurred by absence of STM analogy and results splitting or shear failure in concrete. Based on configuration distribution of normal stress, and formation of critical sections are differed in the anchorage system. In this scenario, anchored bars subjected to single shear conditions by its unconfined state. Post-installation of supplementary steel results double shear and confined zone conditions of anchorage system. Hence more uniform distribution of normal stress may happened in retrofitted anchorage. Also the implicit strengthening measure promotes shear failure of concrete rather than bearing or tensile failure. As a result considerable shift of crack formation towards more intensified normal stresses. Also the presence of supplementary bars improves lateral confinement of main anchorage and develops normal cracks in the presence of intensity of tensile stress conditions. The distribution of normal stress and location of critical section (x-x) of five different conventional and retrofitted anchorage systems are explained by Fig 1-to- Fig5. The location of critical section was evaluated by ANSYS modeling that was published by the Padmanabham. K *et al.* (2022).

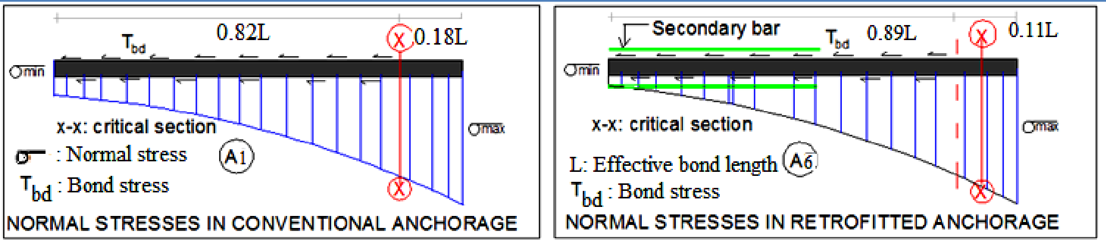

Fig 1: Distribution of normal stress in Conventional straight &Retrofitted anchorage

Failure of conventional straight anchorage (A1) was happened by loss bond and reduction of development length in embedded reinforcement. The initial failure is in the form of tensile crack at critical section x-x (Figure1) that was located at 0.82L form tail end of reinforcement. At ultimate load, pullout force develops more circumferential stresses along the reduced effective length of bar and leads to bond failure by intensified shear conditions. The corresponding observations are presented in Table-1A.

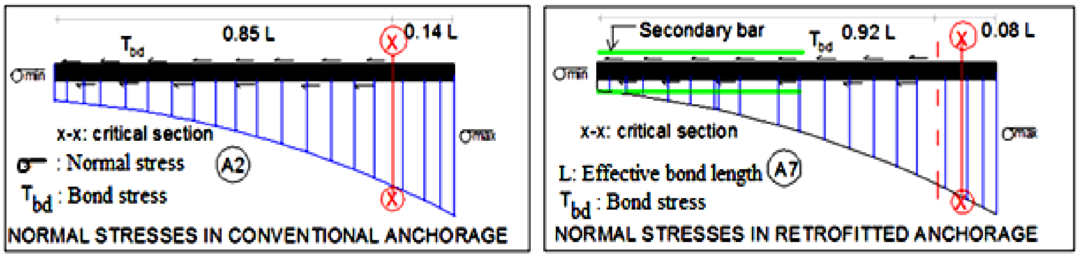

Fig 2: Distribution of Normal stress in Conventional 90^0 bend & Retrofitted anchorage

Figure 2 represents the intensified normal stresses and decrease the effective length (0.85L) by anticipated stress conditions of embedded reinforcement in anchored .The bearing stress at 90 degree bend may increase at initial phase of anchorage till crushing of concrete happened at tail end of bend due to induced compressive stresses in concrete. The pull-out force develops more circumferential stresses along the reduced embedment length of bar (0.85L) and results bond failure by induced high shear conditions. The retrofitting of anchored bar (A7) was done by post installation of secondary reinforcement (Fig-2b). This technique provides implicit strengthening anchored bar against its transverse confinement. The fracture mechanics of retrofitted anchorage system (A7) initiated by tensile failure of concrete at critical section 0.92L from tail end. The reduced effective length of embedment further intensify the stress concentration along the length of bar and leads to bond failure by high shear conditions. The presence of secondary reinforcement provides good lateral confinement to main reinforcement and uniform normal stresses along the bar. A considerable shift of initial crack towards face end was observed in retrofitted anchorage (A8). The reduction of effective length of rebar anchorage leads to bond failure at high shear conditions.

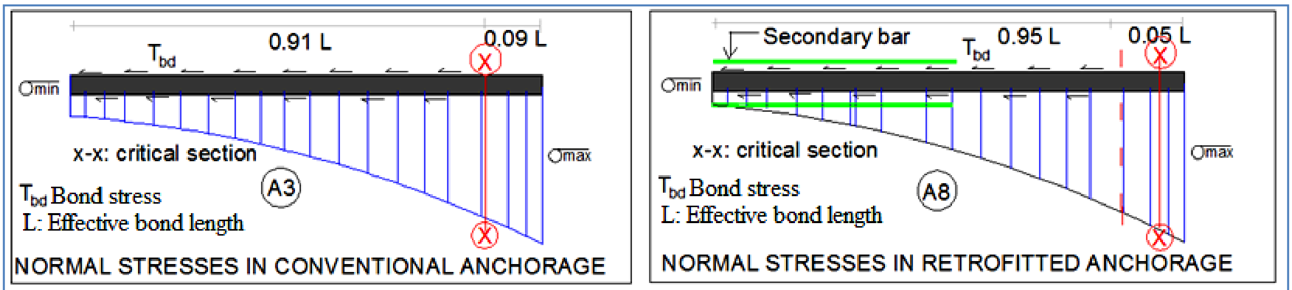

Fig: 3 Distribution ofNormal stress in Conventional 180^{0}Hook and Retrofitted anchorage

Figure.3 Shows normal stress distribution at critical failure of 180 degree hooked anchorage system (A3). The failure is intended to loss of bond strength along the embedment of bar followed by crushing of concrete by excess bearing stresses. The conventional hooked portion develops initial stress at tail end of bar and significantly improves uniform stress distribution along the length of bar. The initial failure was happened when tensile crack formed at critical section x-x (Fig-3a) which located at 0.91L from tail end of reinforcement. As per theory the normal stresses are proportional to bond strength of anchorage system. The normal stress intensified by decreasing the effective length (0.91L) along the length of bar. The bearing stress of bent portion increase initial stresses in anchorage till bearing failure happened by crushing of concrete. The result of bearing failure in hooked portion and loss of development length leads to "Rack out failure" of anchorage system as it forms 0.42L from tail end. The Retrofitting of hooked anchorage system (A8) was provided by Post installation of supplementary reinforcement by bonded fastening using epoxy grout. Hooked anchorage system develops minimum strength capacity against normal stresses the presence of supplementary bars improves formation of strut and tie mechanism against force transfer. The fracture mechanism initiated by development of principal tensile stresses in concrete. There was a shift of critical section (x-x) to high normal stresses in the presence of supplementary reinforcement and effective bond length increased to 0.95L from tail end. This result "Rack out failure" by tensile stress developed in concrete.

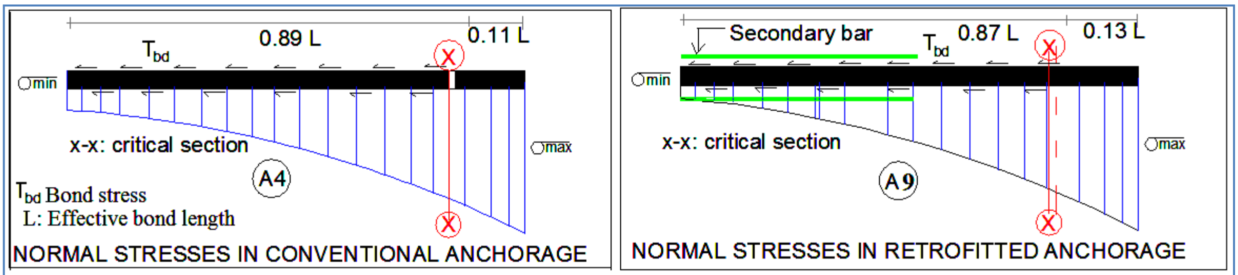

Fig 4: Distribution of Normal stress in Single headed bar & Retrofitted anchorage

Figure.4 shows normal stress distribution in single head mechanical anchorage (A4).The failure of anchorage governed by excess bearing stress at head and bond failure along the length of bar. Since the pull out force develops initial bearing stress at tail end of head and results splitting tensile stress developed in concrete. The headed mechanical anchorage gives more uniform stress along the length bar and there by subsequent increment of minimum stress at tail end. Since the single head anchorage allows efficient force transfer mechanism by strut and tie method, the failure of anchorage by cone of fracture by splitting tensile stresses of concrete. The critical section (x-x) of anchorage formed at 0.87L from tail end due to loss of bearing stresses at head and bond stress over the length of bar. Retrofitting of headed anchorage system (A9) was provided by Post installation of supplementary reinforcement used by epoxy fastening device. The presence of supplementary bars aimed to provide tensile resistance of cracks formed against cone of fracture. More uniform stress distribution observed by the presence of supplementary bars and good formation of strut and tie force transfer mechanism. But there is no shift of critical section (x-x) in retrofitted anchorage system (A9) except uniformity of normal stresses formed at critical section 0.87L.

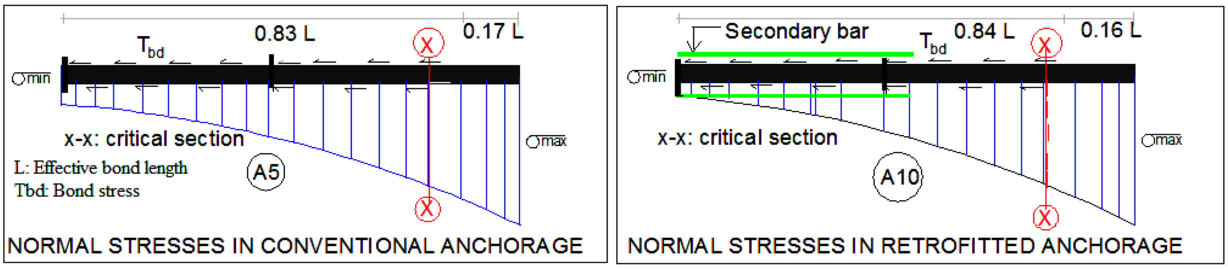

Fig 5: Distribution of Normal stress in Double headed bar & Retrofitting of anchorage

Figure5 shows the normal stresses at ultimate failure of double head anchorage system (A5). It was comprised by loss bearing failure at both head and subsequent bond failure of along the bar. The pullout force initiates bearing stress at head and there by splitting tensile stresses developed in concrete. The double headed mechanical anchorage initiates more uniform stress distribution along the length of bar and subsequent increment of minimum stress at tail end. The failure of anchorage system intends by double cone of fracture due to splitting tensile stresses developed in concrete .The critical section (x-x) observed at 0.83L from tail end. Retrofitting of double headed anchorage system (A10) by Post installation of supplementary reinforcement aimed to provide resistance against developed tensile cracks. The mechanical anchorage develops good formation of strut and tie mechanism where uniformity of stress observed by supplementary bars. The location of critical section x-x was unchanged except more uniform stress distribution till effective length of 0.84L. The failure is in the form of double cone of fracture by splitting tensile stresses.

6. MECHANICS OF STRUT-AND-TIE ANALYSIS

Detailing of reinforcement anchorage in discrete regions of concrete can be established by STM approach. Based on this approach the resistance force of anchorage system is governed by shape and size of selected truss model and subsequent arrangement of reinforcement in load path. The key parameters influencing the failure of anchorage system are bearing strength, bond strength, shear strength and tensile strength of concrete. The corresponding failure modes of STM approach are crushing of concrete at nodal zones, crushing or splitting of diagonal strut and yielding of reinforcement at tie. Fuchs *et al.*, proposed CCD method to predict cone resistance of headed anchorage system. As per the formulation, the cone of fracture depends on nominal tensile strength of concrete (σ_{ct}) and projected area of failure cone (A_e). As per STM analysis geometric configuration of anchorage system plays key role against force transfer mechanism. Accordingly the failures of straight anchorage system associated with slip of bar by loss of bond strength. Similarly five types of anchorage systems configured by straight bar, 90 degree bend, 180 degree hook, single head and double headed anchorage systems were analyzed under STM subjected to direct tension pull-out tests. Based on STM analysis in different configuration of anchorage system, considerable shift of node formations are happens during force transfer mechanism.

The failure of anchorage systems in cast-in-place concrete was associated with bearing strength, bond strength and shear strength of concrete. Except improved shear conditions, researchers are integrated structural system of reinforced concrete (RC) members. Bond stress of anchorage system is dealt with shear resistance or mechanical interlocking of embedded reinforcement in concrete. The designers are versatile on theoretical evaluation of bond strength of different anchorage systems due to sufficient guide lines are available from design codes. In this context, a considerable volume of experiments has been carried out to investigate ultimate strength of cast-in-place and chemically bonded anchors under static pullout test load conditions Most of the failures are concentric on applied tensile force of anchorage system. If proper embedment depth and geometry of headed bar is used during post retrofitting process of damaged anchorage system [kp], then the failures are attributed to cone of fracture.

The force transfer mechanism of discrete anchorage system is analyzed by strut and tie method where the formation of compression struts in concrete and tensile ties in reinforcement are meet at nodal point to ascertain equilibrium condition. The strength of node defines the capacity of anchorage system. Strut and tie modeling is crucially influence the detailing aspects of reinforcement. The formation of strut - tie mechanism and its nodal zones are significantly influenced by type of anchorage system and boundary conditions. Based on location and boundary conditions, nodes are formed (CCT, CTT,TTT, CCC) and the limiting stress of concrete was calculated at bearing face of strut and node interface. To minimize the crack width, supplementary reinforcement 0.3% of effective sectional area of strut is proposed to accommodate the tensile strains developed in concrete strut. The mechanics of STM analogy for different anchorage systems are discussed in detail. Subsequently the influence of supplementary reinforcement on main anchorage system (by Post installation method) was discussed by STM analysis It was found that the location, size and number of node formation are significantly influence the strength and failure mode of anchorage system. The anchorage failure was intended by loss of bond by shear, crushing of concrete by bearing and splitting failure of concrete by tension. In this process, the tensile strains produced are less than 0.003 and appeared as thin hair line crack in concrete. This crack formation was not influenced the design strength but transform the failure against shear. The cracks are formed by induced stresses along the embedded length of reinforcement and reduce the effective length of anchorage system.

7. STM Analogy and Crack pattern

7.1. Analysis of Straight anchorage

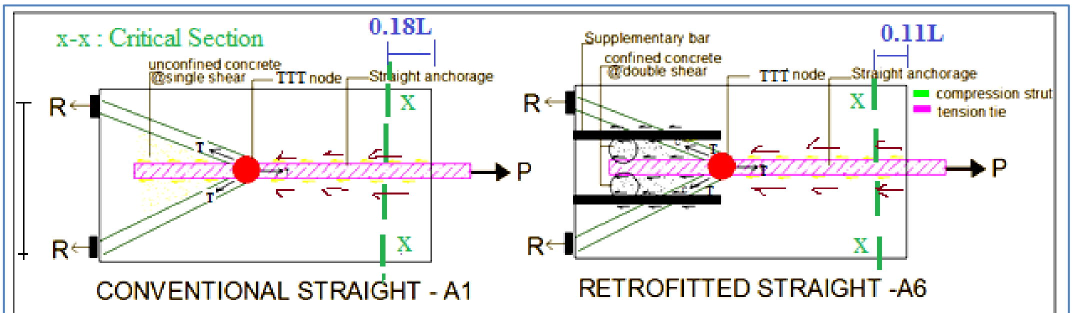

FIG.6A STM ANALOGY OF STRAIGHT ANCHORAGE SYSTEM

FIG.6B EXPERIMENTAL OBSERVATION OF STRAIGHT ANCHORAGE

Figure:6A & 6B shows STM analogy of straight anchorage system by direct tension pull-out test. The conventional straight anchorage system (A1) forms Tension-Tension-Tension (TTT) internal node formation and concrete in truss model and subjected to single shear condition. The node in direct anchorage system was un-confined and leads to double crack formation (figure.6B). This type of anchorage is vulnerable to shear failure. The presence of supplementary bar by post retrofitting measures of anchorage system (A6) provides implicit strengthening of direct anchorage system. As shown in figure (6A), the retrofitted straight anchorage system forms TTT internal node with good confinement that leads to single crack formation. The confined concrete at node was subjected to double shear conditions and shows relatively higher shear strength than conventional anchorage system. The presence of supplementary bars also provides tensile strength against concrete failure. Hence the retrofitted anchorage shows more anchorage strength than conventional anchorage and its failure was attributed slip of bar due to loss of bond stress. The critical section formed between TTT node and face at a distance of 0.18L and 0.11L in both conventional and retrofitted anchorage and results shear failure by loss of bond.

7. 2 Analysis of 90 degree bend

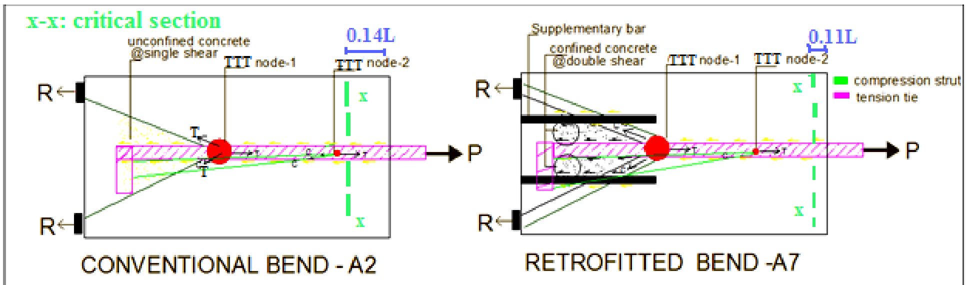

FIG.7A STM ANALOGY OF 90 DEGREE BEND ANCHORAGE

FIG.7B EXPERIMENTAL OBSERVATION OF 90 DEGREE BEND

Figure 7A & 7B shows STM analogy of 90^0 bends under direct tension pull-out tests and corresponding experimental observations. The conventional bend (A2) forms internal (TTT) Tension-Tension-Tension node1 (figure.7A) and concrete was subjected to crushing of concrete at bed followed by shear failure due to loss of bond and anchorage length. The rebar anchorage subjected to single shear condition. The secondary internal node (Node2) formed near to critical section that was very unstable and subjected to tension. The strength of this node is small compared with node1. At ultimate failure the concrete inside bent portion of rebar was subjected to crushing by bearing stresses. The critical section extended between Node-1 and Node-2 and the failure is attributed to crushing of concrete at bend followed by shear failure by loss of bond. This was observed in figure.7b when the cracks are widely spread at bottom due to crushing of concrete and thin crack by shear failure at face of anchorage. Presence of supplementary anchorage by post installation method (A7) provides implicit strengthening of existing anchorage system by passive confinement. The retrofitted bend forms TTT internal node and the concrete between tail end and Node-1 is under double shear conditions with good confinement by presence of supplementary bars. This ultimately leads to uniform stress distribution and higher shear strength than conventional anchorage system and the presence of supplementary bars provide confinement against concrete failure. Hence the retrofitted bend anchorage shows more anchorage strength with two nodes (Node1, Node2) and its failure leads to slip of bar due to loss of bond stress. The strength of Node2 is very small compared with Node1. The critical section considered between Node1 and Node2 and the failure is attributed to shear by slip of anchorage and loss of bond.

7.3. Analysis of 180 degree hook

Figure 8A & 8B shows STM analogy of 180^0 hook by direct tension pull-out test. The conventional bend (A3) forms strong internal Node.1 (TTT) and concrete near the tail end subjected to single shear and inside the hook was subjected to crushing by excess bearing stress induced at hooked portion. The second TTT node forms struts from hooked portion and anchored bar under tension. The strength of Node-2 is less compared to Node-1. And the critical section forms between Node1 and Node 2, and the failure plane forms at Node2.(figure.8A). The failure is attributed to rack-out of concrete followed by shear failure of anchorage as shown in figure.8B.

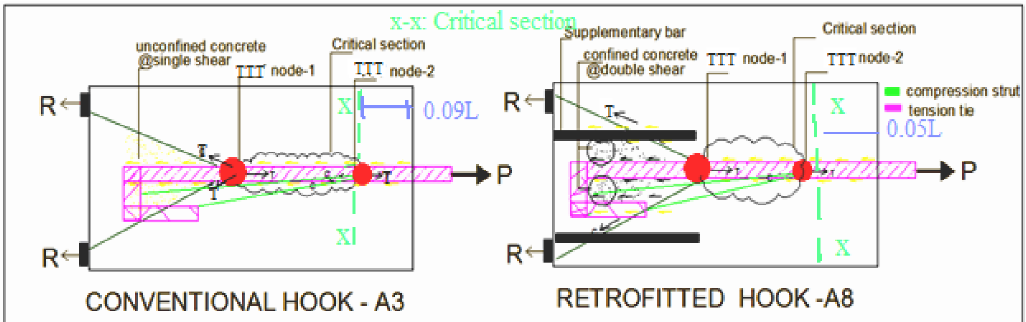

FIG.8A STM ANALOGY OF 180 DEGREE HOOK ANCHORAGE

FIG.8B EXPERIMENTAL OBSERVATION OF 180 DEGREE HOOK

The presence of supplementary bars in anchorage system (A8) provides implicit strengthening measures of direct anchorage system. The retrofitted hook anchorage forms TTT node and the concrete between tail Node-1 and Node-2 receive good confinement by post installed supplementary bars. This ultimately results higher shear strength than conventional anchorage system and the presence of supplementary bars provide tensile strength against concrete failure. As a result the retrofitted bend anchorage shows more pull-out strength than conventional anchorage and its failure was attributed shear failure by loss of bond along the bar.

7.4. Analysis of Single headed bar

Figure: 9A & 9B shows STM analogy of headed bar by direct tension pull-out test. The conventional headed bar (A4) forms strong external Node1 (TTT) by reaction force and internal Node.2 at tail end. Since both the nodes are in strong conditions, without confinement and the critical plane forms outside of nodal zone. Critical section forms at near to face of anchorage at 0.11L, and failure is attributed to bearing failure at head followed by bond failure of stem. As a result the failure mode is in the form of cone of fracture.

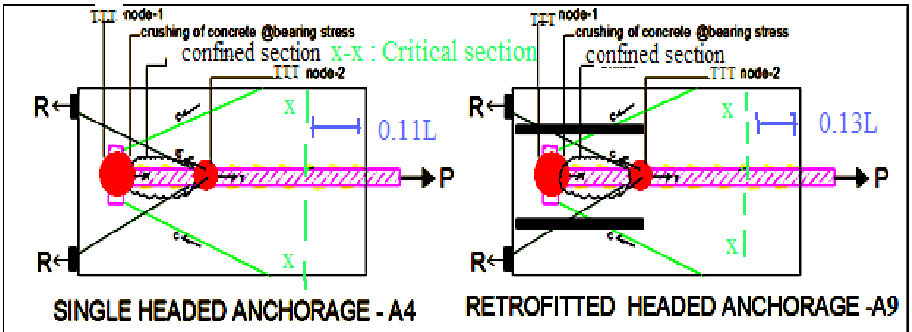

FIG.9A STM ANALOGY OF SINGLE HEADED ANCHORAGE

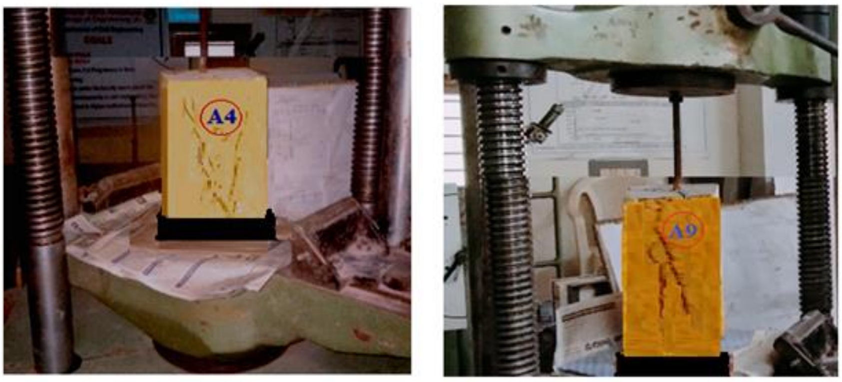

FIG.9B EXPERIMENTAL OBSERVATTION OF SINGLE HEADED ANCHORAGE

The presence of supplementary bars of main anchorage system (A9) provides implicit strengthening to direct anchorage system. The retrofitted single head forms TTT nodes and the concrete between tail Node-1 and Node-2 receive good confinement with supplementary bars. The results shows retrofitted headed anchorage with more anchorage length at failure than conventional anchorage system and its failure was attributed crushing of concrete at bearing head followed by loss of bond along the bar and finally results cone of fracture.

7.4. Analysis of Double headed bar

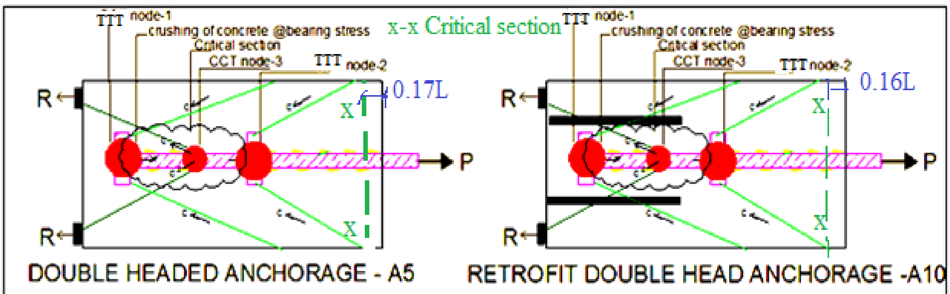

FIG.10A STM ANALOGY OF DOUBLE HEADED ANCHORAGE

FIG.10B EXPERIMENTAL OBSERVATION OF DOUBLE HEADED ANCHORAGE

Figure: 10A & 10B shows STM analogy of double headed bar by direct tension pull-out test. The conventional bend (A5) forms internal (TTT) node-1 which shows good strength and the concrete near the tail end subjected to single shear and inside the hook was subjected to crushing by excess bearing stress induced. The second TTT node formed compression struts from headed bar and anchored bar under tension. The strength of Node-2 is similar to Node-1, and the critical section was formed between Node-1 and Node-2 and the failure is attributed to shear by loss of bond stress. Presence of supplementary anchorage system (A10) provides implicit strengthening measures by passive confinement.

Figure 10B shows the retrofitted double head anchorage system as it forms strong nodes (Node 1, Node 2, and Node 3) and the concrete between tail Node-1, Node-3 shows good confinement with post installed supplementary bars. This results shows higher shear strength at tail end than conventional anchorage system and the provision of supplementary bars provide tensile strength by concrete failure. As a result, the retrofitted system with double headed anchorage shows more uniform stress flow and retrofitted anchorage failure by rack-out of concrete. Hence the presence of supplementary anchorage transforms double head anchorage transformed from cone of fracture to shear failure of anchorage (figure.10B).

The post damage state of concrete may significantly be influenced by splitting tensile strength of concrete. To meet this requirements, post installation of headed bars introduced by using supplementary reinforcement in the existing anchorage system. The discussion on theoretical observations on various anchorage systems are as follows.

8. RESULTS AND DISCUSSION

Table-1: Failure Mode of Anchorage system

Anchorage type	**Node formation**		**Failure Mode**		**Application of supplementary bar**
	Conventional	Retrofitted	Conventional	Retrofitted	
Straight bar (A1 & A6)	Single node	Single node	Shear failure	Shear failure	Provide confinement
90 degree bend (A2&A7)	Two node	Two node	Crushing at tail end & shear failure	Shear failure	Provide confinement
180 degree hook (A3 & A8)	Two strong nodes	Two strong nodes	Rack-out failure at tail end & shear failure of stem	Shear failure	Provide tensile resistance to concrete and confinement
Single head anchorage (A4 & A9)	Two strong nodes	Two strong nodes	Bearing failure at head & bond failure f stem (Cone-of fracture)	Shear failure	Provide splitting tensile resistance against cone of failure
Double head anchorage (A5& A10)	Three strong nodes	Three strong nodes	Bearing failure of head & splitting tensile failure of concrete (Double. Cone-of fracture)	Rack-out failure	Provide tensile resistance to concrete against splitting failure

- Failure of straight anchorage system in conventional and retrofitted form was attributed to slip of anchorage by loss of bond. Except confinement, supplementary bar was not contributed against improvement of shear strength. And it will reduce the formation of shear crack due to uniform stress distribution as it can see in figure 6A. At ultimate failure 0.82L and 0.89L bond length of anchorage system (L= development length) will be participated to contribute to develop resistance of straight conventional and retrofitted anchorage.
- Failure of 90 degree bend anchorage system is attributed to shear by crushing of concrete at bend due to excess bearing stress followed by reduction in anchorage length. Presence of supplementary anchorage may delay the crack formation at bend by its passive confinement process, but it wills small improvement of ultimate load at failure. The critical section forms after supplementary anchorage. It was observed in figure 7A. At ultimate failure 0.82L and 0.89L bond length of anchorage system (L= development length) will be participated to contribute to develop resistance of 90 degree bend conventional and retrofitted anchorage.
- Failure of 180 degree conventional hook anchorage system is due to shear deformation by crushing of concrete at hook followed by rack out failure of concrete by splitting tensile stress in concrete. Presence of supplementary anchorage transforms the tensile failure to shear failure by its passive confinement technique. The critical section observed close to the face of anchorage that shows supplementary anchorage shows crucial role against delay the failure and increase the ultimate load. Figure 8A. Represents the experimental crack pattern of retrofitted anchorage of hooked bar .It was observed in figure 8A. At ultimate failure 0.91L and 0.95L bond length of anchorage system (L= development length) will be participated to contribute to develop resistance of hooked conventional and retrofitted anchorage.
- Failure of single head anchorage system is followed by cone of fracture due to splitting tensile stress exist in concrete. The cone will be formed at 1: 2.5 angles. The resistance of anchorage system followed by bearing strength of head and bond strength of stem, Presence of supplementary anchorage produce tensile resistance against splitting of concrete at ultimate load. The critical section forms after supplementary anchorage. It was observed in figure 9A. At ultimate failure 0.89L and 0.87L bond length of anchorage system (L= development length) will be participated to contribute to develop resistance of single head conventional and retrofitted anchorage.
- Failure of double head anchorage system is followed by double cone of fracture in opposite direction due to splitting tensile stress exist in concrete. The cone will be formed at 1: 2.5 angle. The resistance of anchorage system followed by bearing strength of head and bond strength of stem, Presence of supplementary anchorage produce

tensile resistance against splitting of concrete at ultimate load. The critical section forms after supplementary anchorage. It was observed in figure 10A. At ultimate failure 0.83L and 0.84L bond length of anchorage system (L= development length) will be participated to contribute to develop resistance of double head conventional and retrofitted anchorage.

9. CONCLUSIONS

The versatility STM technique this study focused on to apply the same for conventional and retrofitted anchorage system when it subjected to direct tension pull-out conditions. Following principle observations are made in this context.

1. A good agreement between results of STM and Experimental observations was addressed for conventional and retrofitted anchorage system.
2. Location of confined zone and critical sections of five different types of anchorage systems such as straight, 90 degree bend, 180 degree hook, single head and double head anchorage systems can be are addressed for both conventional and retrofitted anchorage system
3. Crack pattern can be identified at most possible extent by using STM analysis. Also the crack pattern can be analyzed by STM analysis to most possible extent
4. STM analysis gives clarification of various failure modes in conventional and retrofitted anchorage system. More probable results could be predict in STM with help of stress contours of ANSYS modeling
5. Based on STM analysis, strut angle represents the possible formation of cracks in the system, for which STM will gives precise solutions.

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