

Static Pullout Tests on Retrofitted Anchorage System in Concrete Using Supplementary Reinforcement

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DOI: [10.36348/sjce.2022.v06i04.004](https://doi.org/10.36348/sjce.2022.v06i04.004)

| Received: 06.03.2022 | Accepted: 09.04.2022 | Published: 15.04.2022

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Abstract

This paper presents experimental results of retrofitted anchorage system of structural concrete by using Post-Installation of Supplementary Anchorage (PISA) as a implicit strengthening measure and to improve the nonlinear performance of conventional anchorage system in hardened concrete. A total sixty specimens of M25 grade concrete (150x150x300mm) with two different size of rebar anchorage of 12mm, 16mm and five different configuration of conventional anchorage system was retrofitted by PISA technique is verified under direct tension pullout quasi static loads. The configuration of anchorage comprised by straight bar (A1), 90degree bend (A2), 180degree hook (A3), single head bar (A4) and double head bar (A5). The test parameters considered are bond strength, ductility, stiffness and bar-slip and test variables are configuration of anchorage, size of rebar and presence of supplementary steel. The obtained results validated by ANSYS modeling. This study concludes that a considerable improvement of nonlinear parameters such as ultimate load (3-8%), stiffness (4%-17%), ductility (16%-52%) and concrete contribution (6%-23%) by using PISA technique.

Keywords: Post installation, pullout test, configuration of anchorage, supplementary anchorage.

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1. INTRODUCTION

Brittle failure of structural anchorage system often found in discrete regions of RC framed structures. The failures are mainly attributed to poor performance of anchorage system and vulnerable against dynamic loads such as impact, seismic, and blast loads etc. Lack of detailing aspects, constructability issues, high shear and deficient bond conditions are the key parameters involved for anchorage failure. The current use of high strength concrete and steel was further anticipated this issue. Extensive research happened in the past few decades (Looney *et al.*, 2012; Wang *et al.*, 2016) to improve strength and ductility of anchorage system of structural concrete. In this context, the design codes of various nations (ACI-318, ACI-352, NZS-3101, IS-13920) established guide lines on configuration and detailing aspects of conventional anchorage that includes straight bar, 90 degree bend, 180 degree hook, single head and double head bar (ACI-355,1991). Critical issues of rebar anchorage often found in construction phase such as fabrication of anchored bar, installation, and pouring of concrete found more complex and unable to implement as per detailing. As a result brittle failure of anchorage often found during

high shear and loss of bond conditions. In this context research works on explicit strengthening measures such as local confinement, section enhancement and fiber wrapping technique of anchorage widely established. But the explicit technique intends to improve elastic performance of anchorage. Hence this study focused on implicit strengthening measures so as to meet its inelastic performance such as bond strength, ductility and slip of rebar anchorage. Tension pull-out tests conducted by Thomas H and Sang K *et al.*, [25] expressed that small headed bars shows better performance than conventional hooked anchorage system and apply to RC exterior beam-column joints. Eligehausen R *et al.*, [21] stated that geometric parameters of rebar anchorage shall be influence load carrying capacity. Akshat, Chourasia *et al.*, [7] addressed that headed bar exhibit high bond strength, minimum slip and may treated as potential substitution to hooked anchorage. Experimental results of Kah Mun Lam *et al.*, [23] expressed that closely spaced headed bars are capable to develop full yield strength without severe brittle failure of concrete provided the spacing is between 2.5-4.0 times diameter of bar. During the seismic action discrete beam-column joints of RC

framed structures often exposed to brittle failure by high shear and bond loss of anchored bar. In this context a comprehensive test program was conducted on five different types of anchorage system that was retrofitted by post installation of supplementary reinforcement. The results were verified by non-linear finite element based ANSYS modeling. The test program was conducted under direct tension pull-out load under quasi-static test conditions by Universal Testing Machine (UTM). The tests observations were made on bond strength, normal stress, bar slip, stiffness and ductility of retrofitted anchorage system. The variable parameters considered in the test are configuration of anchorage system, size of anchored bar and presence of supplementary reinforcement. Specific observations are made about tensile strength of concrete and crack pattern of anchorage during its unconfined state of failure. This study may enable to evaluate the non-linear parameters of bond strength, stiffness and ductility with the use of PISA system as a retrofitting measure.

2. STUDY OBJECTIVES

The Objective of this study is to focus on to evaluate the inelastic performance of deep embedded conventional anchorage systems that was retrofitted by PISA technique and subjected to quasi-static test loads. Since PISA technique provides implicit strengthening measures to the anchorage system, this experimental program focused on to evaluate the improvement of passive confinement and tensile strength of hardened concrete in the presence of post supplementary anchorage system. Different configuration of conventional anchorage systems are verified under the following norms.

- Identify the location of critical section of and distribution normal stresses in conventional and retrofitted anchorage systems under quasi-static test load.
- Generate ANSYS based non-linear finite element modeling of normal stress and its distribution of both conventional and retrofitted anchorage systems.
- Identify the crack pattern and failure mode of conventional and retrofitted anchorage systems.
- Evaluate the parameters that contributed to improve non-linear performance of anchorage with PISA technique.
- Evaluate the size effect of rebar anchorage against non-linear performance of retrofitted anchorage system

3. RESEARCH SIGNIFICANCE

Brittle failure of structural anchorage system often results disintegration of global system in framed concrete structures. But limited research work was done to improve the strength of anchorage system in concrete such as addition of fibers and use of mechanical

anchorage in concrete etc. Also external strengthening measures of anchorage was rarely addressed in the past, such as fiber wrapping and post tensioning of rebar anchorage. In this context the current study focused on provision of implicit strengthening measures by Post Installation of supplementary anchorage (PISA) and verified its influence against confinement and tensile strength of concrete against the applied normal loads. PISA is a novel technique that can be useful to mitigate constructability issues of anchorage provisions and improvement of strength and performance aspects of anchorage system. It provides feasible construction practice by post retrofitting measures in discrete elements such as exterior beam-column joints, corbel elements, and bracket connections in RC framed structures.

4. STUDY SCOPE AND LIMITATIONS

This study intends to find the lower limiting conditions of anchored concrete that was retrofitted by anchorage. The boundary conditions of test reveals strut and tie mechanism under quasi-static loads. The configured rebar system considered as deep embedment in absence of lateral confinement. Failure of the anchorage system intends to concrete only such as tension, bond loss. The intent of this study is to evaluate the effect of rebar configuration and its size effect during pullout of anchorage system. Both conventional and retrofitted phase of anchorage system is verified in the experiment. The specimens of concrete (M25) are intended to medium strength with Fe415 grade steel as most of the structural anchorage in RC framed structures needs rehabilitation measures in the current scenario.

5. ANALYSIS OF NORMAL STRESS

As per the analysis, normal stress in anchorage system may proportion to shear stress of the embedded bar. Due to this most of anchorage failures are associated by slip of bar due to high 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 strut-tie 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 Figs 1-10.

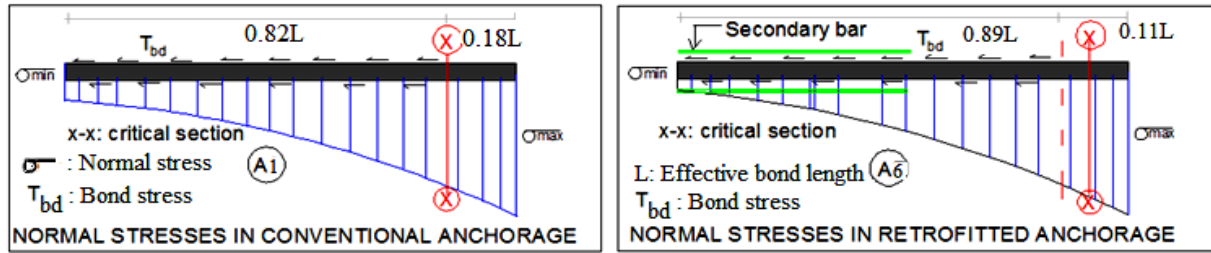


Fig 1: Distribution of normal stress in Conventional straight & Retrofitted anchorage

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 from tail

end of reinforcement. At ultimate load, pullout forces develop more circumferential stresses along the reduced effective length of bar [18] and leads to bond failure by high shear conditions. The corresponding observations are presented in Table-1A.

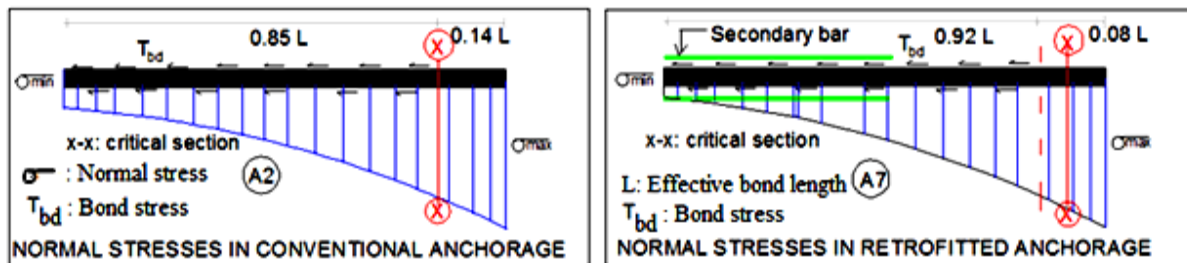


Fig 2: Distribution of Normal stress in Conventional 90° bend & Retrofitted anchorage

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.

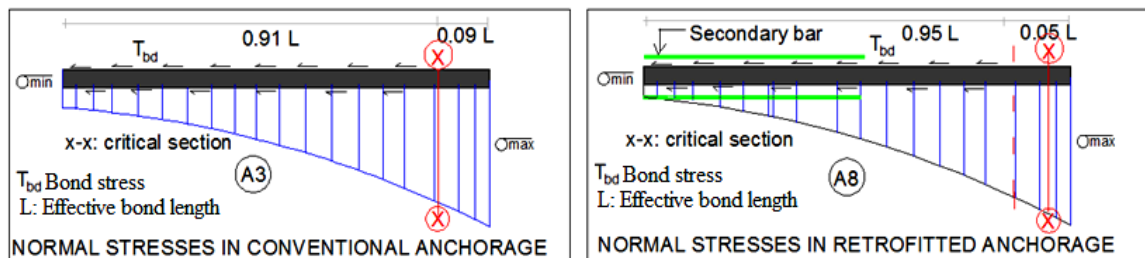


Fig: 3 Distribution of Normal stress in Conventional 180° Hook and Retrofitted anchorage

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 theoretical evaluation normal stresses are proportional to bond strength of anchorage. The normal stress intensified with reduction of effective length ($0.91L$). The bearing stress of bent portion increases the initial stresses in anchorage until the failure happens 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 results "Rack out failure" by tensile stress in concrete.

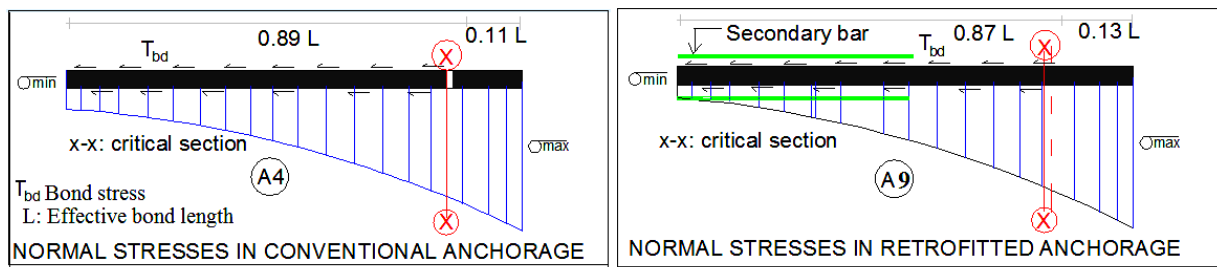


Fig 4: Distribution of Normal stress in Single headed bar & Retrofitted anchorage

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. The pull out force develops initial bearing stress at tail end of head that 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 $0.87L$.

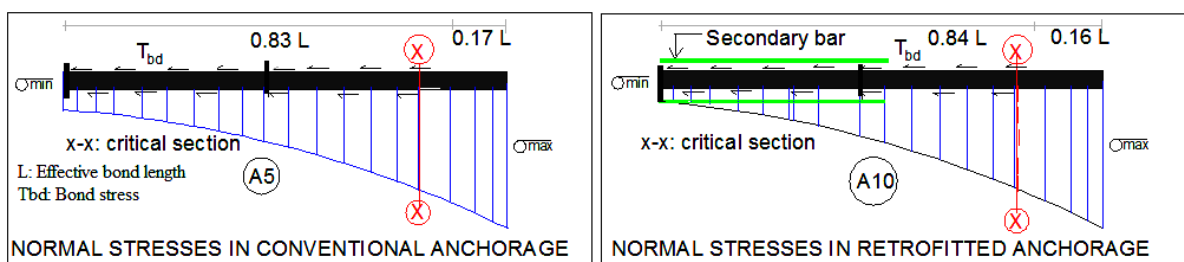


Fig 5: Distribution of Normal stress in Double headed bar & Retrofitting of anchorage

Figure 5 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 anchorage initiates uniform stress distribution along the length of bar and subsequent increment of minimum stress at tail end. The failure of anchorage intends by double cone of fracture due to

splitting tensile stresses developed in concrete. The critical section (x-x) formed 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

development of splitting tensile stresses.

6. MODELING OF ANCHORAGE STRESS

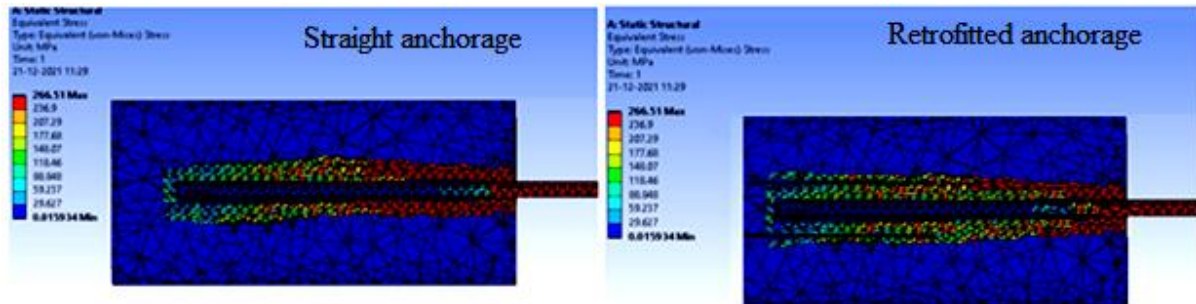


Fig.6 ANSYS modelling of Normal stresses in Straight & Retrofitted anchorage

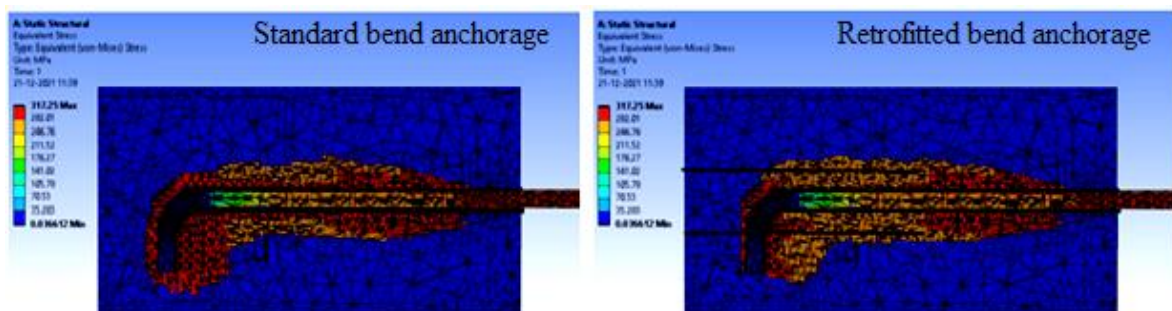


Fig.7 ANSYS modelling of Normal stress in standard 90° bend & Retrofitted anchorage

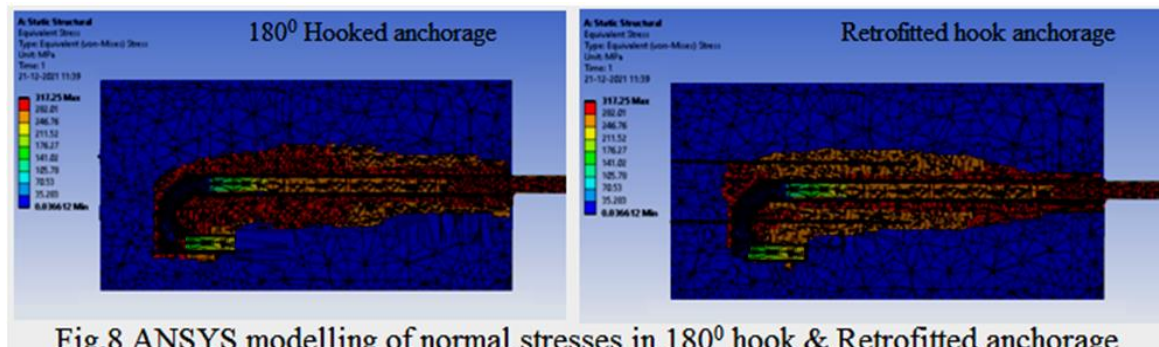


Fig.8 ANSYS modelling of normal stresses in 180° hook & Retrofitted anchorage

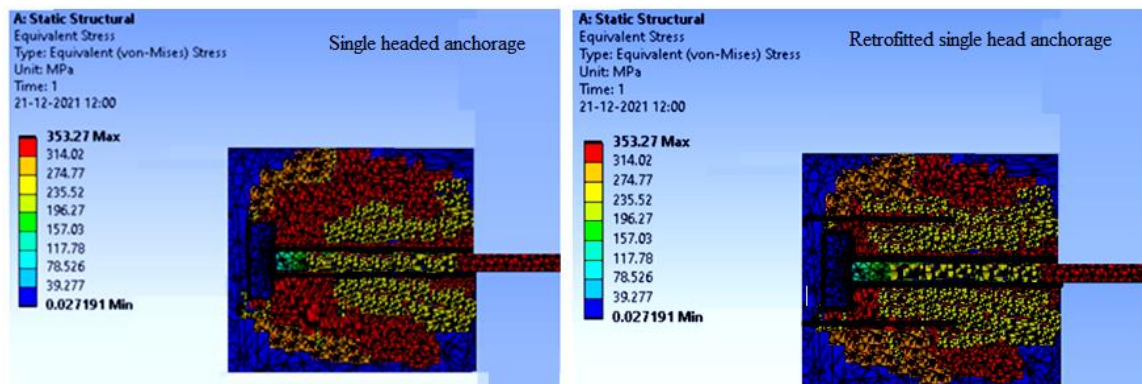


Fig.9 ANSYS modelling of normal stresses in Single headed & Retrofitted anchorage

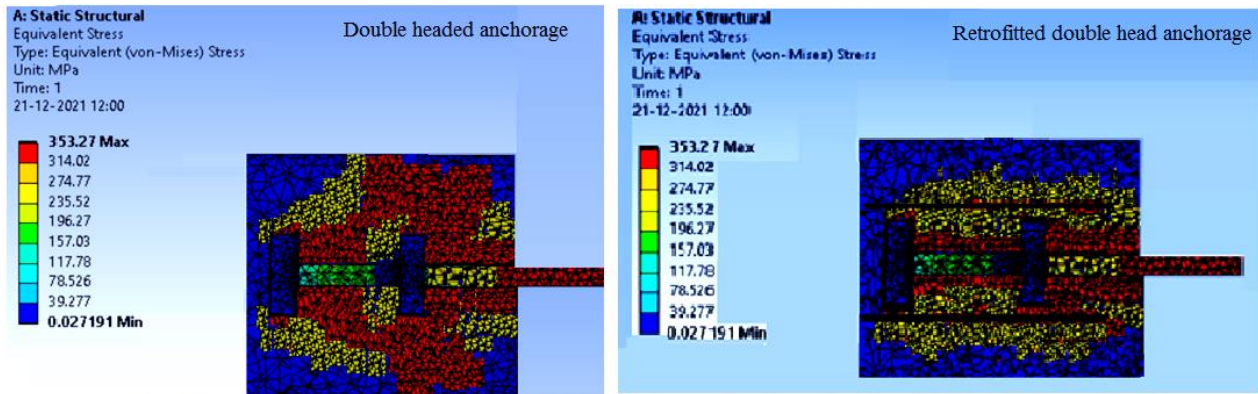


Fig.10 ANSYS modeling of normal stress in Double headed & Retrofitted anchorage

7. EXPERIMENTAL PROGRAM

Full scale experimental program was conducted on different rebar anchorage embedded in structural concrete. The embedded length of anchorage systems were considered at L_d , $0.87L_d$, $0.81L_d$, $0.76L_d$ and $0.68L_d$ corresponding to A1, A2, A3, A4 and A5 anchorage respectively. The experiment was conducted at material testing laboratory, Gayatri Engineering College (Autonomous), Visakhapatnam, India. A total 60 test specimens in two series (Group-A Group-B) are verified under quasi-static loads by using 400kN capacity Universal Testing Machine of ASTM C234 test conditions. The specimens are $150 \times 150 \times 300$ mm dimension casted by M25 grade concrete (f_{ck} :25MPa) with two different size of rebar anchorage (12mm, 16mm diameter HYSD bar). Five different types of conventional anchorage system casted in Group-A series (control specimens) comprised by straight (L_{A1}), standard 90° degree bend (L_{A2}), standard 180° degree hook (L_{A3}), single head (L_{A4}) and double head (L_{A5}) bars with 260mm embedment depth of concrete. Each configuration of anchorage was tested by 3 specimen samples such that a total 15 specimens were tested against 12mm rebar anchorage in Group-A and was notation by L_{A1-12} , L_{A2-12} , L_{A3-12} , L_{A4-12} , L_{A5-12} and rebar of 16mm size anchorage notation by L_{A1-16} , L_{A2-16} , L_{A3-16} , L_{A4-16} , L_{A5-16} of 3 tested samples of each configuration and a total of 15 specimens are tested. Hence a total of 30 control specimens were casted in Group-A series. Similarly 30 test specimens of retrofitted anchorage system configured by post installation of supplementary reinforcement to the main anchorage of control specimens with 12mm rebar noted by L_{B1-12} , L_{B2-12} , L_{B3-12} , L_{B4-12} , L_{B5-12} (15 samples) and rebar anchorage with 16mm diameter of L_{B1-16} , L_{B2-16} , L_{B3-16} , L_{B4-16} , L_{B5-16} (15 samples) are considered in Group-B series. The configuration of conventional and retrofitted anchorage systems are shown in Fig16. No confinement reinforcement was provided to the test specimens of Group A & Group B and test conditions are follows by design provisions of ACI 318-19. Direct tension pull-out load are applied under quasi static test loading conditions applied at 1kN/minute on free end of anchored bar. The tail end of concrete specimen was fixed by mechanical fasteners assembled in Universal

Testing Machine (UTM). The rebar anchorage was confirmed to use of high yield strength deformed bars (Fe415) to avoid yielding of steel at ultimate load. The initial load of anchorage system was taken from ANSYS modeling and test are ceased when concrete attains maximum crack width 0.3mm confirming to limiting strain in concrete $\epsilon_c = 0.003$ of ACI 318-19 design provisions. The loads are applied at 20kN/min and boundary conditions of test specimens are followed by strut and tie analogy.

7.1 Specimen properties

Size of tested concrete specimen = $150 \times 150 \times 300$ mm (depth), Grade of concrete = M25, Theoretical bond strength of concrete (T_{bd}) = 2.24MPa, Characteristic compressive strength (f_{ck}) = 26.84MPa, Tensile strength of concrete (σ_{ct}) = $0.30 (f_{ck})^{2/3} = 2.56$ MPa, Elastic modulus (E_c) = $5000 (f_{ck})^{1/2} = 0.26 \times 10^5$ MPa, Static modulus of elasticity (E_{RCC}): Range: 0.94×10^5 - 0.14×10^5 (MPa), Poisons ratio: $\mu = 0.21$, Allowable limiting strains in concrete $\epsilon_{cs} = 0.003$, Grade of steel reinforcement, Fe415, Size of main anchored bars = 12mm & 16mm, Yield strength (f_y) = 432.60MPa, Ultimate strength (f_u) = 512.40, Elastic modulus (E_s) = 2.10×10^5 MPa.

7.2 Test Observations

Figure 11a represents the failures of conventional straight anchorage system (L_{A1}) due to high shear conditions and slip of anchored reinforcement. In this process high intensity of splitting tensile stresses are developed between anchored bar and surrounding concrete that results shear failure along the development length of anchored bar. It was further noticed that the contribution of concrete was low and that results brittle failure of system and sudden loss of bond strength. Formation of multiple cracks observed at initial stage at face end and progressed towards tail end of anchorage during ultimate load.

Figure 11b represents the failure of retrofitted straight anchorage system L_{A6} due to double shear conditions and slip of anchored reinforcement. The development of splitting tensile stresses between anchored bar and surrounding concrete is controlled by

provision of four supplementary rebar to main anchorage system that induce confinement and tensile resistance to concrete and avoid formation of multiple cracks. The presence of supplementary bars produce double shear conditions to main anchorage. It was

further noted that the contribution of concrete was moderately improved and loss of bond strength due to high shear. A single crack observed at face of sample and progressed towards tail end of anchorage with increase of load.

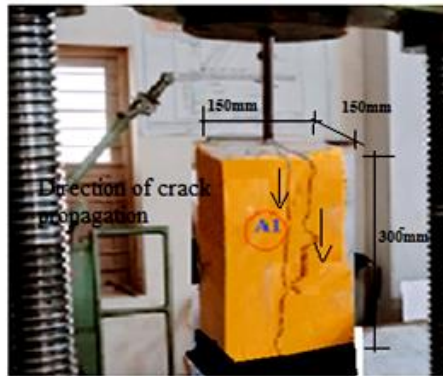


Fig. 11a

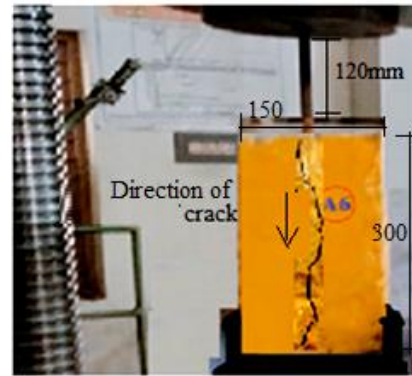


Fig. 11b

CONVENTIONAL STRAIGHT ANCHORAGE-A1 RETROFITTED STRAIGHT ANCHORAGE-A6

Figure 12a represents the failure of conventional 90° bend anchorage L_{A2} by high shear and slip of bar by crushing of concrete at tail end of anchored bend. The observations further addressed that the contribution of concrete was low and anchored bend will increase the pull out capacity before failure but results brittle failure of the system at ultimate load. Formation of multiple cracks observed at initial stage at face end and progressed towards tail end of anchorage during ultimate load. From the figure, 1 indicates direction of crack propagation, 2 indicates crushing of concrete by excess bearing stress and 3 indicates shear failure of anchorage due to loss of bond. Figure 12b represents the failure of retrofitted anchored bend L_{A7} by high shear conditions. The splitting tensile stresses

developed between anchored bar and surrounding concrete was controlled by provision of four supplementary rebar to main anchorage system as it induce confinement effect restrict crushing of concrete by excess bearing stress developed at tail end. Further presence of supplementary bars produce double shear conditions to main anchorage. It was further noticed that the contribution of concrete was improved. A multiple crack observed at face end of specimen and progressed towards tail end of anchorage as shown in Fig 12b. The location 1 shown in Fig 12b indicates the direction of crack propagation, 2 indicates crack due to shear failure and 3 indicates multiple crack by presence of normal stress at face.



Fig 12a

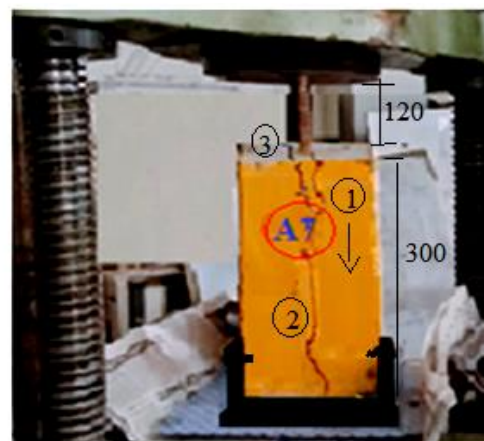


Fig 12b

CONVENTIONAL ANCHORED BEND-A2 RETROFITTED ANCHORED BEND-A7



Fig.13a



Fig.13b

CONVENTIONAL HOOKED ANCHOR-A3 RETROFITTED HOOKED ANCHOR-A8

Figure 13a represents the failure of conventional 180° hooked anchorage L_{A3} by tensile failure followed by shear due to loss of bond. At tail end of hooked portion, high bearing stresses developed that ultimately leads splitting failure of concrete as shown in location1 followed by slip of bar due to high shear conditions along the development length of bar as shown location 2. Further observations made against contribution and identified considerable volume of concrete participated till initial crack formation and later cracks are propagated due to loss of bond by high shear. Figure.13b represents the failure of retrofitted 180° hooked anchorage L_{A8} by double shear conditions. During ultimate loads splitting tensile stresses

developed between anchored bar and surrounding concrete which was controlled by provision of four supplementary bars arranged on face of main anchorage system to induce confinement effect. Further it restricts splitting of concrete by excess tensile stress developed between hook and face end. The presence of supplementary bars produce double shear conditions to main anchorage. It was further noted that the contribution of concrete is good enough against ductile failure. Cracks are propagated from face end of specimen and progressed towards tail end of anchorage (Fig 13b). The location.1 indicates direction of crack propagation, 2 indicates development of crack by shear.

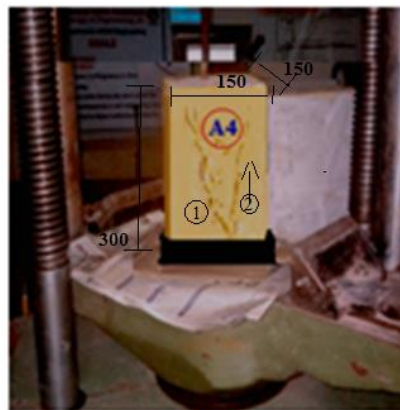


Fig.14a



Fig.14b

MECHANICAL HEADED ANCHORAGE-A4 RETROFITTED HEADED ANCHORAGE-A9

Figure 14a shows the failure of mechanical single head anchorage L_{A4} by cone of fracture due to splitting tensile stresses in concrete. The tail end of headed anchorage develops high bearing stresses and leads cone of failure due to splitting tensile stresses developed in concrete as shown in location1. The direction of failure starts from tail end and progressed towards face. The contribution of concrete is more as it develops cone of fracture. Figure.14b represents the failure of retrofitted headed anchorage L_{A9} by bearing failure due to splitting tensile stresses developed in

concrete. The presence of supplementary bars gives, good confinement at tail end of headed bar followed by considerable resistance against splitting failure of concrete against its cone of fracture. Hence parallel splitting cracks observed at ultimate failure. A good contribution of concrete observed during failure that leads to ductile failure of anchorage. The direction of crack propagation is from tail end of head and progressed towards face end of specimen. Fig-14b, shows crack propagation (1) by splitting tensile stress and direction of crack (2) propagation.

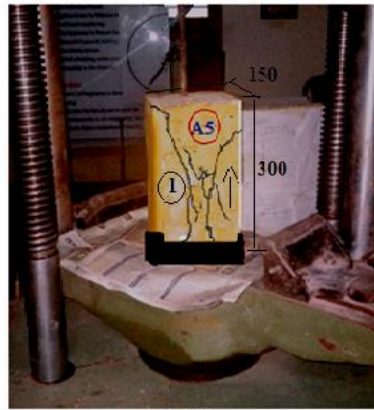


Fig.15a
DOUBLE HEADED ANCHORAGE-A5



Fig.15b
RETROFITTED DOUBLE HEADED ANCHORAGE-A10

Figure 15a Shows the failure of double headed anchorage L_{A5} due to splitting tensile stresses of concrete. The tail end of headed anchorage develops high bearing stresses and develops double cone of fracture by presence of multiple heads. The direction of failure starts from tail end and progressed towards face end of specimen. The contribution of concrete was considerably more than rest of all anchorage systems. This results ductile failure of double headed anchorage.

Figure.15b represents the failure of retrofitted double headed anchorage L_{A10} by induced tensile stresses in concrete. The presence of supplementary bars significantly contributes for tensile resistance and confinement of anchorage. Also a good contribution of concrete was observed against ductile failure of anchorage. The splitting tensile cracks observed between successive heads and progressed towards face end of specimen.

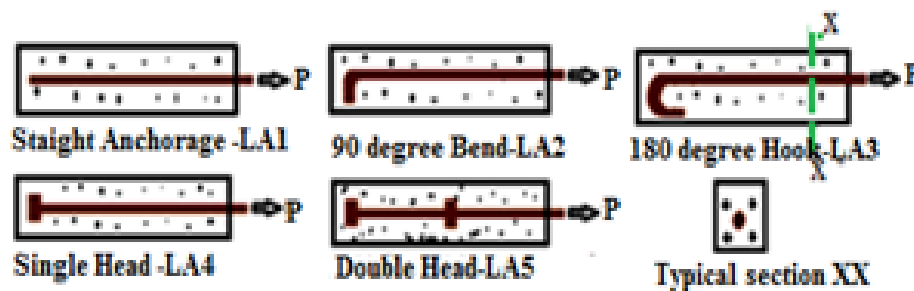


Fig.15C. Conventional Anchorage

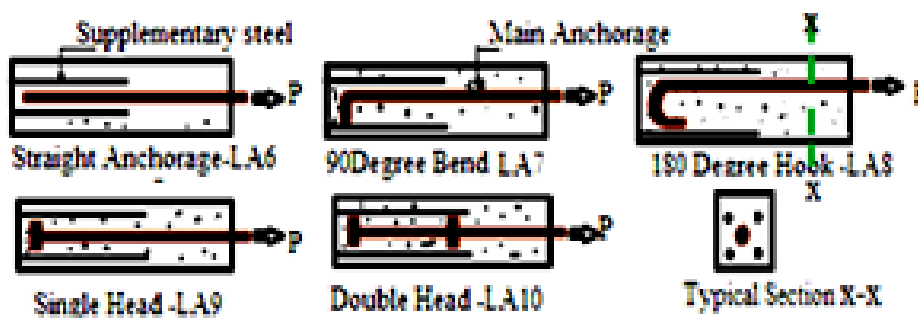


Fig.15d. Retrofitted Anchorage

8. RESULTS AND DISCUSSION

Static pull-out tests were conducted on five different types of conventional anchorage system that was retrofitted by post installation of supplementary reinforcement. To find the size effect of rebar anchorage the test program conducted by 12mm and 16mm diameter high yield strength deformed bars confirmed to Fe415. The observations were made

against maximum pull, normal stresses in concrete, bond strength and induced tensile stresses in concrete at ultimate load. The test results are verified by finite element based ANSYS modeling. The inelastic performance of conventional and retrofitted anchorage system was evaluated by concrete contribution (Table-2A), crack width and ductility (Table-3A), stiffness (Table-4A) and slip of bar against different

configuration of anchorage and its retrofitted model (Table-4A). A relative comparison made between five types of conventional and retrofitted anchorage systems. The observations are made by bond strength and tensile strength (Fig-16), contribution of concrete (Fig-17), and slip of anchorage (Fig-18a, Fig-18b).

8.1 Analysis of stresses

- Table-1A Shows analysis of stresses at ultimate failure of conventional and retrofitted anchorage. Salient features of observations are as follows.
- Both conventional and retrofitted straight bars (LA1 & LA6) shows minimum normal and tensile strength at failure. Subsequently high normal stress, bond stress and tensile stress exists at critical failure of headed anchorage (LA4, LA9).
- A good correlation observed between the results of experiment and ANSYS modeling (Correlation factor C.C=0.92 for normal stress, 0.96 for bond stress, 0.91 for tensile stress)
- Bearing failure of hooked bar (LA3) transformed to shear failure in the presence of supplementary bars.

TABLE-1A
STRESSES AT ULTIMATE FAILURE OF CONVENTIONAL & RETROFITTED ANCHORAGE SYSTEM
(ANCHORAGE BAR DIAMETER: 12 mm HYSD, CONCRETE GRADE: M25)

Configuration of Anchorage	*Theoretical Value (ACI 318 & ACI 352)				Modeling analysis				Experimental Value				Type of Failure
	P_u (kN)	σ_n (MPa)	τ_{bd} (MPa)	σ_{tc} (MPa)	P_n (kN)	σ_n (MPa)	τ_{bd} (MPa)	σ_{tc} (MPa)	P_n (kN)	σ_n (MPa)	τ_{bd} (MPa)	σ_{tc} (MPa)	
Plain bar LA1-12	25.40	225.30	2.46	2.30	27.00	266.51	2.79	1.64	26.10	261.00	2.76	1.10	Bond
Standard Bend LA2-12	27.48	243.10	2.46	2.30	29.00	317.26	2.91	1.75	29.40	294.00	2.87	1.30	Bond
Standard Hook LA3-12	36.32	321.86	2.46	2.30	36.00	361.92	2.38	1.97	36.20	362.00	2.43	1.56	Bearing
Single Head LA4-12	35.08	310.20	2.46	2.30	37.00	352.53	2.43	1.91	37.50	386.40	2.48	1.54	Tension
Double Head LA5-12	32.86	286.02	2.46	2.30	37.00	347.56	2.39	1.85	37.10	379.35	2.47	1.47	Tension
Plain bar LA6-12	25.40	-	-	-	27.00	262.36	2.89	1.62	26.80	267.42	2.84	1.11	Bond
Standard Bend LA7-12	27.48	-	-	-	33.00	355.47	2.91	1.68	33.20	368.65	2.97	1.37	Bond
Standard Hook LA8-12	36.32	-	-	-	38.00	378.92	2.68	1.89	37.60	374.32	2.53	1.56	Shear
Single Head LA9-12	35.08	-	-	-	37.00	350.47	2.56	1.86	37.40	389.58	2.59	1.55	Tension
Double Head LA10-12	32.86	-	-	-	37.00	346.72	2.24	1.84	37.10	353.46	2.46	1.49	Tension

TABLE-2A
CONCRETE CONTRIBUTION OF CONVENTIONAL & RETROFITTED ANCHORAGE
(ANCHORAGE BAR DIAMETER: 12 mm HYSD, CONCRETE GRADE: M25)

S No	Type of anchorage	Specimen	P_u Exp.	τ_{bd} Exp	V_c Exp	V_s Exp	$\eta_c = \frac{V_c}{V_s} \times 100$	$\rho_s = \% \text{ of steel}$
		notation	kN	MPa	mm ³	mm ³	%	%
1	Conventional Plain bar.	LA1-12	26.10	2.76	759.10	28274.16	2.68	0.50
2	Conventional Standard Bend	LA2-12	29.40	2.87	1125.06	33476.20	3.36	0.50
3	Conventional Standard Hook	LA3-12	36.20	2.43	19329.84	44334.51	43.62	0.50
4	Conventional Single Head	LA4-12	37.50	2.48	29785.20	44274.30	67.27	0.50
5	Conventional Double Head	LA5-12	37.10	2.47	31356.14	53407.24	58.71	0.50
6	Retrofitted Plain bar	LA6-12	26.80	2.84	950.26	45216.36	2.10	1.39
7	Retrofitted Standard Bend	LA7-12	33.20	2.97	1654.30	50440.60	3.28	1.39
8	Retrofitted Standard Hook	LA8-12	37.60	2.53	17125.20	61298.30	27.90	1.39
9	Retrofitted Single Head	LA9-12	37.40	2.59	17209.24	61238.93	28.10	1.39
10	Retrofitted Double Head	LA10-12	37.10	2.46	27676.20	77238.90	35.20	1.39

8.2 Contribution of concrete

- Table-2A Shows the contribution of concrete at critical failure of anchorage system. This property may significantly influence ductility of anchorage.
- Less contribution of concrete indicates brittle failure of anchorage system This failure may intended due to loss of strength by the presence of high stresses
- Maximum contribution of concrete (67.27%) observed in conventional single head anchorage (LA4) at ultimate pull-out load of 37.50kN .This indicates a good ductile performance shown by conventional single headed bar.
- The retrofiting of standard 90° bend exhibit maximum bond strength (2.97MPa) at ultimate load (33.20kN). Maximum enhancement of pull-out load was observed (12.90%) in standard bends where as its effect was nominal in other anchorage system.
- Conventional hooked anchorage and retrofit double headed bar exhibit minimum bond strength of 2.43MPa and 2.46MPa respectively at ultimate load.

8.3 Crack width & Ductility

- Table-3A Shows following observations on crack width and ductility at ultimate load of anchorage
- Conventional double headed bar shows maximum elastic strength (27.10kN) and minimum crack width (0.18mm) than rest of anchorage systems. Hence use of double headed bar anchorage system is more effective at serviceable conditions.
- Maximum normal stress in concrete was observed at ultimate load of conventional and retrofitted states of hook (A3 & A8) and single headed (A4) anchorage system.
- Key observations are made against ductility of material (ρ_m) and system (ρ_s). Improvement in post cracking behavior of anchorage was accomplished if material ductility greater than system ductility. In this context conventional anchorage of A3, A4, A5 may shows good ductile performance. But the retrofiting of all anchorage systems shows considerable improvement in material ductility than system ductility. This indicates significant inelastic performance by post installation of supplementary bars in all anchorage systems.

TABLE-3A
CRACK WIDTH & DUCTILITY OF CONVENTIONAL & RETROFITTED ANCHORAGE
(ANCHORAGE BAR DIAMETER: 12 mm HYSD, CONCRETE GRADE: M25)

No	Anchorage	Specimen	Pi	Pf	Wci	Wcf	σ_y	σ_u	(ρ_s) stress	(ρ_m) materl
	Configuration of anchorage	Notation	Pullout @ initial crack	Pullout @ final crack	Initial crack width	Final crack width	Stress@ initial crack	Stress@ final crack	Ductility factor $(\frac{\sigma_u - \sigma_y}{\sigma_y})$	Ductility factor $(\frac{W_{cf} - W_{ci}}{W_{ci}})$
S.No	Description		kN	kN	mm	mm	MPa	MPa		
1	Conventional Plain bar.	LA1-12	21.70	26.10	0.24	0.30	0.74	1.10	0.48	0.25
2	Conventional Standard Bend	LA2-12	23.20	29.40	0.21	0.30	0.89	1.30	0.46	0.43
3	Conventional Standard Hook	LA3-12	24.50	36.20	0.20	0.30	1.13	1.56	0.38	0.50
4	Conventional Single Head	LA4-12	26.30	37.50	0.20	0.30	1.14	1.54	0.35	0.50
5	Conventional Double Head	LA5-12	27.10	37.10	0.18	0.30	1.22	1.47	0.20	0.67
6	Retrofitted Plain bar	LA6-12	21.90	26.80	0.21	0.30	0.82	1.11	0.35	0.43
7	Retrofitted Standard Bend	LA7-12	23.60	33.20	0.20	0.30	0.96	1.28	0.33	0.50
8	Retrofitted Standard Hook	LA8-12	24.80	37.60	0.18	0.30	1.18	1.56	0.32	0.67
9	Retrofitted Single Head	LA9-12	26.40	37.40	0.17	0.30	1.21	1.55	0.28	0.75
10	Retrofitted Double Head	LA10-12	26.90	37.10	0.18	0.30	1.23	1.49	0.21	0.67

8.4 Stiffness of Anchorage

- Table-4A gives the following observation on stiffness of rebar anchorage system under static loads.
- Both single and double headed bar exhibit maximum elastic stiffness (155.29 kN/mm, 149.44 kN/mm) and inelastic stiffness (125kN/mm & 123.60kN/mm) at

ultimate loads of 155.29kN and 149.44kN respectively

- Conventional straight anchorage possess minimum inelastic stiffness (87kN/mm) at failure load.
- The rate of stiffness degradation is maximum in double head anchorage (17.90%) and minimum in conventional hooked anchorage (1.49%).

TABLE-4A
STIFFNESS (K) PROPERTY OF CONVENTIONAL & RETROFITTED ANCHORAGE
(ANCHORAGE BAR DIAMETER: 12 mm HYSD, CONCRETE GRADE: M25)

	Anchorage	Specimen	Pi	Pu	We	Wu	Ke	Ku	$KA=100 \times (K_e - K_u) / K_e$
	Type of anchorage	Notation	Load @initial crack	Load @final crack	Elastic crack width	Final crack width	Elastic stiffness	Ultimate stiffness	% Rate of stiffness degradation
S.No	Description		kN	kN	mm	mm	kN/mm	kN/mm	%
1	Conventional Plain bar	L _{A1-12}	21.70	26.10	0.24	0.30	90.42	87.00	3.78
2	Conventional Standard Bend	L _{A2-12}	23.20	29.40	0.22	0.30	105.45	98.00	7.06
3	Conventional Standard Hook	L _{A3-12}	24.50	36.20	0.20	0.30	122.50	120.67	1.49
4	Conventional Single Head	L _{A4-12}	26.30	37.50	0.20	0.30	131.50	125.00	4.94
5	Conventional Double Head	L _{A5-12}	27.10	37.10	0.18	0.30	150.56	123.60	17.90
6	Retrofitted Plain bar	L _{A6-12}	21.90	26.80	0.21	0.30	104.20	89.33	14.27
7	Retrofitted Standard Bend	L _{A7-12}	23.60	33.20	0.20	0.30	118.00	110.60	6.72
8	Retrofitted Standard Hook	L _{A8-12}	24.80	37.60	0.18	0.30	137.78	125.30	9.05
9	Retrofitted Single Head	L _{A9-12}	26.40	37.40	0.17	0.30	155.29	124.60	16.54
10	Retrofitted Double Head	L _{A10-12}	26.90	37.10	0.18	0.30	149.44	123.60	17.40

TABLE 5A
BAR SLIP- CONVENTIONAL & RETROFITTED ANCHORAGE
(ANCHORAGE BAR DIAMETER: 12mm & 16mm HYSD, CONCRETE GRADE: M25)

				12mm diameter				16mm diameter		
	Anchorage	Specimen	Ultimate Load	12mm Bar Slip	12mm diameter	Percentage bar Slip	Ultimate Load	16mm Bar Slip	16mm diameter	Percentage bar Slip
	Type of anchorage	Anchorage	Pu	ΔL_{12}	$P_u / \Delta L_{12}$	ϵ_{12}	Pu	ΔL_{16}	$P_u / \Delta L_{12}$	ϵ_{16}
S.No	Description	Notation	kN	mm	-	%	kN	mm		%
1a	Conventional straight bar	L _{A1-16}	26.10	13.78	1.89	—	34.70	20.69	1.68	—
1b	Retrofitted straight bar	L _{A6-16}	26.80	20.40	1.31	+48.04%	35.10	28.01	1.25	+35.37%
2a	Conventional 90° Bend	L _{A2-16}	29.40	19.44	1.51	—	35.30	19.56	1.80	—
2b	Retrofitted 90° Bend	L _{A7-16}	33.20	23.46	1.40	+20.67%	36.10	21.85	1.65	+11.71%
3a	Conventional 180° Hook	L _{A3-16}	36.20	33.12	1.09	—	49.70	36.48	1.36	—
3b	Retrofitted 180° Hook	L _{A8-16}	37.60	39.25	0.95	+18.51%	50.90	40.53	1.25	+11.10%
4a	Conventional Single Head	L _{A4-16}	37.50	37.11	1.01	—	50.20	32.42	1.54	—
4b	Retrofitted Single Head	L _{A9-16}	37.40	42.47	0.87	+14.40%	51.70	35.60	1.45	+9.80%
5a	Conventional Double Head	L _{A5-16}	37.10	41.34	0.90	—	49.70	32.61	1.52	—
5b	Retrofitted Double Head	L _{A10-16}	37.10	44.82	0.83	8.42%	51.20	35.01	1.46	+7.34%

Notations: Pu: Pull out load at ultimate failure (kN), ΔL_{12} : Bar slip (mm), ϵ : Percentage bar slip against conventional anchorage, % slip; +ve: Indicates increase, -ve: Indicates decrease

8.5 Size effect on slip of bar

- Table-5A shows the following observations on bar-slip of different anchorage systems and size effect of rebar. From the figure positive sign (+ ve) as relative decrease of bar-slip and negative sign (– ve) indicates relative increase of bar-slip.
- Small size of anchored bar (12mm diameter) shows more bar-slip than large bars (16mm).The retrofitting process shows more

effective for reduction of bar-slip in straight anchorage than other systems. Subsequently minimum bar-slip observed in double headed anchorage and it was not influenced by size of anchorage.

- Single and double headed anchorage (A5& A10) exhibit maximum elastic stiffness (155.29 kN/mm and 149.44 kN/mm) than other systems. The size of initial crack width considered as per ACI 318-19 (0.3mm) .

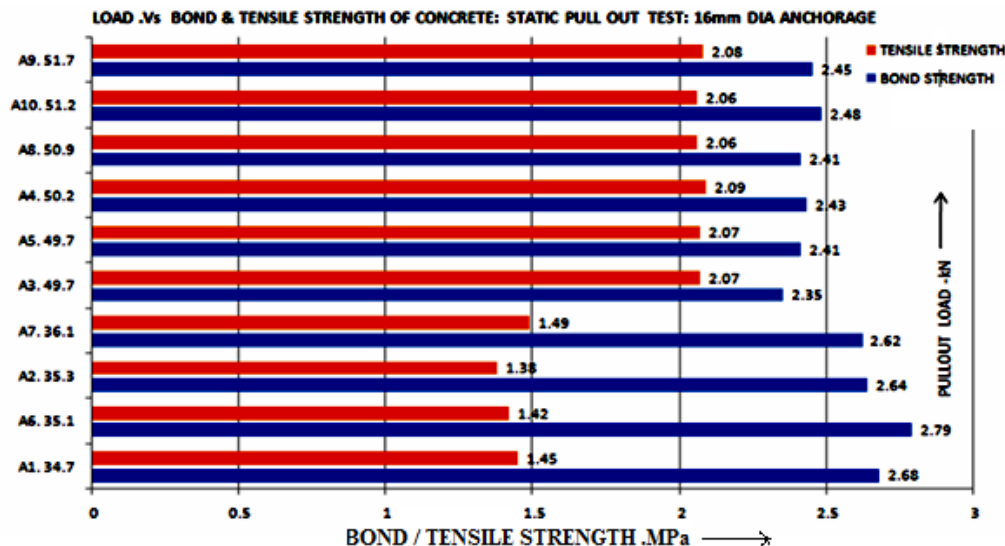


Fig 16: COMPARISON OF BOND/TENSILE STRENGTH AT ULTIMATE PULL

8.6 Bond and Tensile strength of Anchorage

Fig 16 shows about influence of bond and tensile strength of concrete at ultimate loads. The following observations are drawn.

- Retrofitting of conventional anchorage A3, A4, A5 shows appreciable improvement of bond and tensile strength at ultimate load. Headed anchorage systems of A4 and A5 possess maximum bond strength (2.7MPa) than conventional type anchorage systems. But minimum improvement found in bond and tensile strengths of conventional anchorage A1, A2 after retrofitting.
- Retrofitting technique shows more effective in hooked anchorage system (A3) than other type of anchorage systems. The retrofitted anchorage shows good improvement of

ultimate load (50.9kN), bond strength (2.41MPa) and tensile strength of concrete (2.06MPa) during its failure.

8.7 Bar size on contribution of concrete

Fig 17 shows contribution of concrete on size of rebar. The following observations were drawn

- The contribution of concrete decreased with increase in size of anchorage as noted in A4, A5 and A10. Similarly the contribution of concrete increased with increase in diameter of anchorage systems such as A1, A2, A3, A6, A7 and A8.
- Single head (A4) and double head (A5) anchorage shows good contribution of concrete (67.27% and 58.71%) and less size effect of anchored rebar.

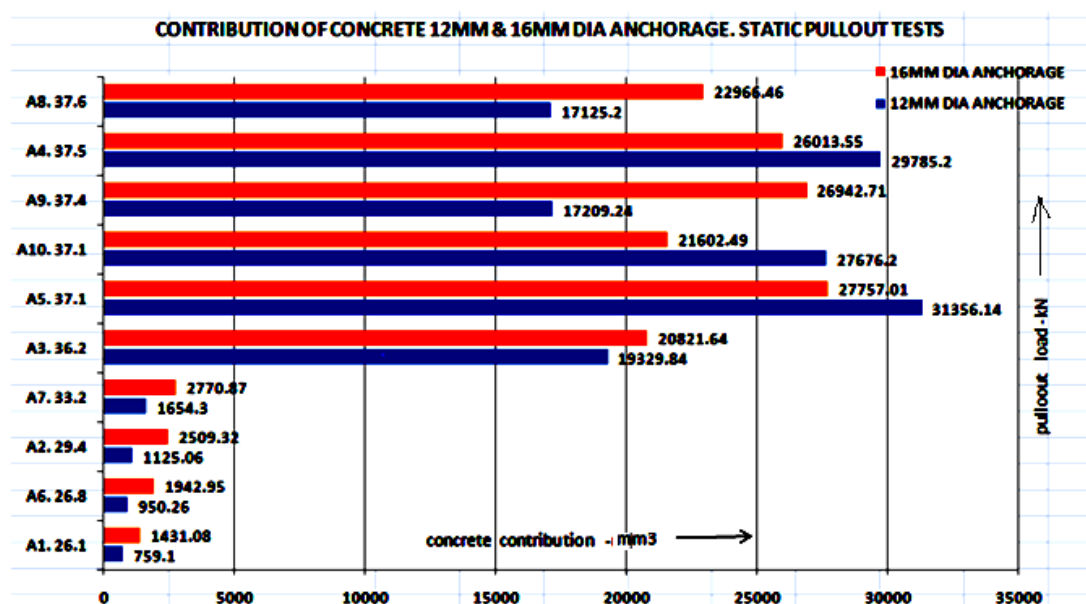


Fig 17: CONTRIBUTION OF CONCRETE ON SIZE OF ANCHORAGE SYSTEMS

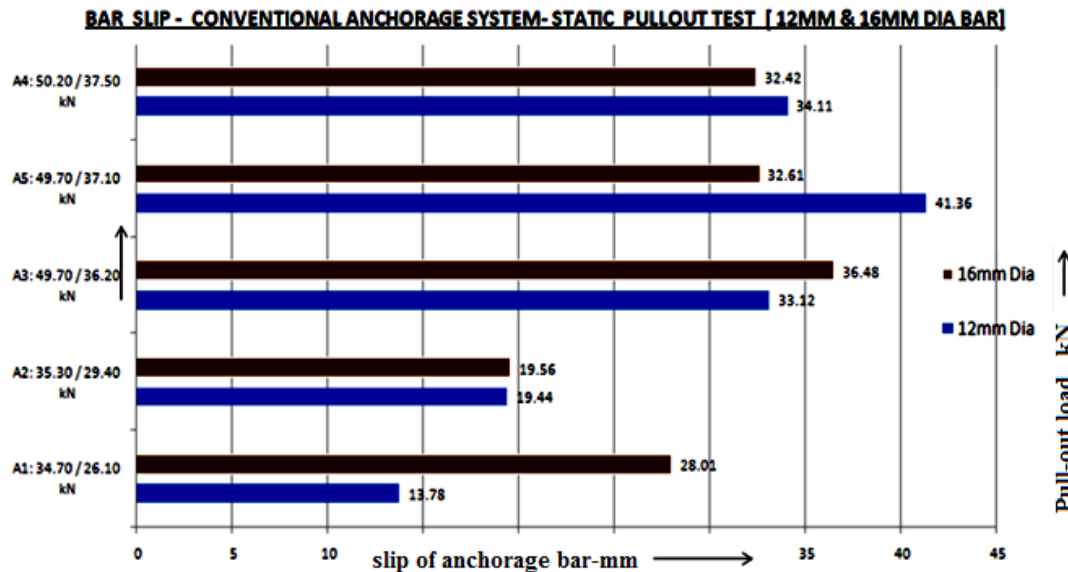


Fig 18a. BAR SLIP OF CONVENTIONAL ANCHORAGE SYSTEM

8.8 Size effect on Bar-slip of Anchorage

Fig 18a shows bar slip of anchorage system at 12mm and 16mm rebar anchorage. Following observations were drawn.

- Except straight (A1) and hooked (A3) anchorage system, all conventional anchorage systems shows decrease of bar slip with increase in size of bar. The bar slip of headed anchorage was not influenced by size effect of rebar.
- Straight anchorage system allows maximum bar slip and increased with size of bar
- Slip of bar in conventional 90° bend (A3) was not influenced by size of bar.

Fig 18b shows bar -slip of retrofitted anchorage system and the following observations are made.

- Size of anchor bar not influenced by slip of bar in the retrofitted straight and hooked bars.
- The retrofitted anchorage system of A7, A9 and A10 shows considerable reduction in bar slip with increase in diameter of rebar anchorage. This is due to confinement of main anchorage system by supplementary steel and mechanics of double shear conditions exist after retrofitting.

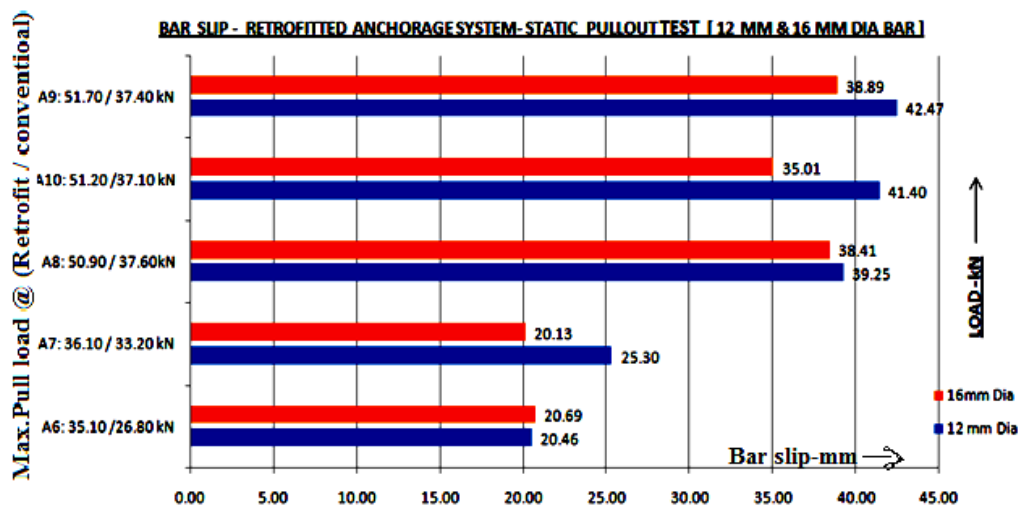


Fig 18b: BAR SLIP OF RETROFITTED ANCHORAGE SYSTEM

9. CONCLUSIONS

Results of this study expressed about implicit strengthening measures of structural anchorage system of hardened concrete more prominently used for

discrete structural elements such as corbel projection, beam-column joint, and pile cap etc. Five types of conventional anchorage systems that was practiced in reinforced concrete was retrofitted by supplementary anchorage by using headed bar and tested under quasi-

static loading conditions. The following observations were drawn in this study.

1. Post-Installation of Supplementary Anchorage (PISA) may consider as an effective technique to improve nonlinear performance of anchorage system. Significant improvement was observed against ductility, stiffness, crack width and stiffness of anchorage at ultimate loads. This technique may considered as effective measure to non-engineered conventional anchorage under static loading conditions.
2. A good improvement of ductility observed in retrofitted specimens. This improvement is maximum (72%) in retrofitted straight anchorage (A6) and minimum (6%) in retrofitted double headed bar (A10).
3. Maximum stiffness of retrofitted anchorage observed in A8 (137.80kN/m & 125.30kN/m), A9 (155.29kN/mm & 124.60kN/mm) and A10 (149.44kN/mm & 123.60kN/mm) in both elastic and inelastic loads under static test loads. Maximum degradation of stiffness observed in A9 (16.54%) and A10 (17.40%) during its failure.
4. Maximum contribution of concrete observed in single head A4 (67.20%) and double head A5 (58.71%) anchored bars and the contribution reduced in retrofitted state A9(28.10%) and A10(35.20%).
5. Maximum tensile strength in concrete observed during the failure of conventional anchorage (σ_c : 1.54MPa) and the retrofitted hooked anchorage (σ_c : 1.56MPa) and single head anchored bar (σ_c : 1.55MPa).
6. The presence of supplementary bar in all conventional anchorage transforms failure mode from brittle to ductile. Considerable improvement was observed about bond strength and reduction in slip of anchored bar by use of supplementary reinforcement.
7. Supplementary steel shows no influence on distribution of normal stress (σ) in retrofitted single head (A9) and double head (A10) anchorage systems
8. Rate of stiffness degradation increased with use of supplementary anchorage and is maximum in retrofitted mechanical anchorage system of A9 and A10.
9. Post-installation of supplementary anchorage provides passive confinement to the existing rebar anchorage in hardened concrete. It is a novel technique and can be used to retrofitting of discrete location of structural anchorage system such as corbel elements, beam-column joint and bracket connections in RC structures.

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