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Review Article

Experiment Program on Retrofitted Anchorage System under Impact Loads

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Abstract

This study aims to evaluate the strength and performance of retrofitted anchorage system in concrete under impact loads. A novel technique called "Post Installation of Supplementary Anchorage" (PISA) is introduced to retrofit five different configurations of rebar anchorage system used in concrete. The configurations of rebar are straight bar (A1), 90 degree bend (A2),180 degree hook (A3), single head (A4) and double head (A5) bars which was retrofitted by supplementary steel reinforcement. Direct tension pullout loads are applied on 60 anchorage specimens (each 30 of conventional and retrofitted) casted with M25 grade concrete. The boundaries of tested specimens were followed by strut-and-tie analogy. The rebar anchorage tested at 1.58, 1.52 impact factor using two different bars of 12mm and 16mm diameter respectively. The deterministic characteristics of test parameters are normal strength, bond strength, ductility, and slip of anchorage at ultimate load. The test variables are rebar configuration, size of anchored bar, and presence of supplementary steel. The results validated by nonlinear finite element based ANSYS modeling. A good agreement of results between experiment and model analysis was observed. Also a considerable improvement of nonlinear characteristics of retrofitted anchorage such as ultimate load (3%-6%), bond strength (1%-6%), ductility (3%-4%), concrete contribution (20%-32%), bar slip (8%-48%) and crack width (30%-42%) was obtained. This study promotes useful information to retrofit non-engineered anchorage system by PISA technique. Application of this technique may further extended to retrofit discrete regions of concrete elements such as bracket connection, corbel projection and beam-column joint subjected to impact loads.

Keywords: Pullout, impact load, retrofitted anchorage, supplementary steel, post-installation.

1. INTRODUCTION

Constructability issues of structural concrete anchorage system often impose brittle failure conditions by high shear and tensile stresses imposed by impact loads such as blast, vibration and seismic forces. Designers often face difficulty to establish detailing aspects of anchorage in the congested geometry of discrete systems. As a result brittle failures are more prominent in discrete concrete elements such as bridge bearing, corbel projection, and beam-column joint. Use of non-engineered detailing, minimum contribution of concrete, tensile stress, shear force, and loss of bond are the key parameters influencing brittle failure of anchorage. The established bond between anchorage and concrete contribution plays a vital role for distribution of normal loads in embedment depth of anchorage.

Understanding the mechanics of structural anchorage is a complex phenomenon when a member subjected to dynamic load. So far limited research work was done in this area. In this context Hong S *et al.*, [15] conducted an experimental study on bond-slip and constitutive relation of rebar anchorage under dynamic loads. The result shows that for a given load, maximum strain in concrete exists at surface of anchorage and it increases with compressive strength of concrete. Maziliguney *et al.*, [17] expressed that dynamic loads imparts bending moment on deep anchorage and is more significant when high shear exist on anchorage. This condition observed at interfacial elements of machine foundation, bridge bearing etc. In this context the designer's assumption of uniform bond stress of distribution (average bond stress) in rebar anchorage is true for short embedded depth only as elastic strains developed in short development length of bar (less than 5 times bar diameter). But the assumptions are differed in deep anchorage system as considerable inelastic strains developed by local bond stress [3]. Since the local bond shows significant influence on development of normal stress and slip of anchorage observed by strain penetration [14]. This issue was experimentally established by T. Kang *et al.*, [14], Huang Z *et al.*, [5] and Gothenberg *et al.*, [6] stated that the critical parameters that influence bond strength are compressive strength, splitting tensile strength and elastic modulus of concrete. In most of the situations, elastic and inelastic response of anchorage system was influenced by development length of anchorage as it results bond-slip and splitting tensile stress in concrete. Subsequently Bassam A *et al.*, [7] expressed that the failure of retrofitted anchorage was governed by its embedment length and contact area of reinforcement. And in deep embedment length of anchorage, if the contact area of reinforcement increases then anchorage tends to brittle failure by splitting tensile cracks. In this context limited guidelines were addressed in ACI318-19, ACI352-02R, NZS3101-08, IS13920-18, IS2502-13 design codes under static loading conditions, but no guide lines are mentioned to control inelastic performance since it is significant in deep anchorage system and presence of impact loads. Since impact loads exhibit sudden release of strain energy and more anticipated towards brittle failure of anchorage system. Fujikaki *et al.*, [25] conducted experimental studies on issues related to application of loading rate but not included impact conditions of anchorage system. Post installation of Supplementary Anchorage (PISA) is a novel technique proposed in this study for implicit strengthening of structural anchorage thereby enhancing its non-linear performance. This study focused on to evaluate the non-linear performance of retrofitted anchorage and the parameters considered to study are ultimate load, bond strength, tensile strength, concrete contribution, crack width and influence of size effect of rebar anchorage under impact loads.

2. OBJECTIVES

This test program was focused on to evaluate performance of retrofitted anchorage system under impact loading conditions. The objectives of the test program is broadly classified as follows.

- Conduct experimental study to evaluate nonlinear parameters of retrofitted anchorage system. The parameters include normal stress, bond stress, tensile strength, concrete contribution, and size effect, bar slip, failure mode of rebar anchorage.
- Evaluation of size effect on various rebar configurations used in retrofitted anchorage.
- Simulate stress contours of conventional and retrofitted anchorage with five different types of rebar configuration using ANSYS modeling.
- Addresses the effectiveness of PISA technique for five types of rebar configurations used in retrofitted anchorage system.

3. RESEARCH SIGNIFICANCE

Emerging issues of blast resistance, impact loads and seismic action on RC structures results brittle failure of structural anchorage system. Research works by Randl [14], Kim 2014 [19], Brencich [10] expressed that implicit strengthening measures of anchorage provides good improvement by passive confinement and bond improvement of anchored bar through which non-linear performance of the system can be improved. In this context a novel technique of Post-Installation of Supplementary Anchorage (PISA) introduced on hardened concrete and tested its effectiveness to retrofit five different conventional anchorage systems. One of the studied observations are retrofitting of RC structures in Gaza strip of Israel and Palestine countries where retrofitting by post installation techniques are adopted for rehabilitation of damaged structures. This study addressed about anchorage issues of discrete regions in concrete structures such as bracket connection, corbel projection and beam-column joint subjected to impact loads.

4. STUDY SCOPE & LIMITATION

This study evaluates non-linear performance of retrofitted deep anchorage system under impact loading conditions. A comprehensive test program was conducted on five different configurations of anchorage systems using 12mm and 16mm anchored bars. Direct tension pullout tests are used to reveal lower bound strength of anchorage. The test loads are applied at impact factor 1.52, 1.58 for 12mm, and 16mm anchored bars respectively. The test conditions are follows to satisfy strut-and-tie analogy. The failure mode of anchorage focused about tension, shear and bond-slip. No lateral confinement was provided during the testing. The rebar provided under deep anchorage and the failure mode was governed by concrete strength rather than steel failure. Adhesive bond installation technique used to fix supplementary bars post drilled hole of hardened concrete. A good bond between the interface of steel and concrete was established by non-shrink (CONBEXTRA) epoxy grout.

5. SIMULATION OF NORMAL STRESSES

The normal stress of both conventional and retrofitted anchorage system was modeled by non-linear finite element based ANSYS program. The continuum of finite element analysis was discritized by plane stress quadrilateral brick element and steel reinforcement as truss element. To simulate the concrete damages smear crack model was considered. The bond between steel and concrete was established by linear inter face element by considering the tangential response of bond stress. In this context constitutive bond-slip model proposed by Anaelle Casanova *et al.*, [14] was followed. The loads are applied at impact factor of 1.58 and 1.52 corresponding to 12mm, and 16mm anchored bars respectively.

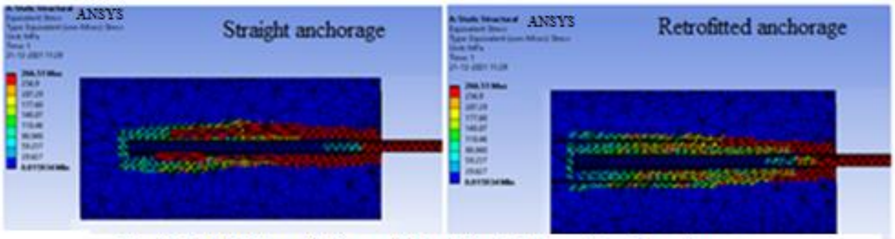


Fig.1 ANSYS modelling of Straight & Retrofitted anchorage

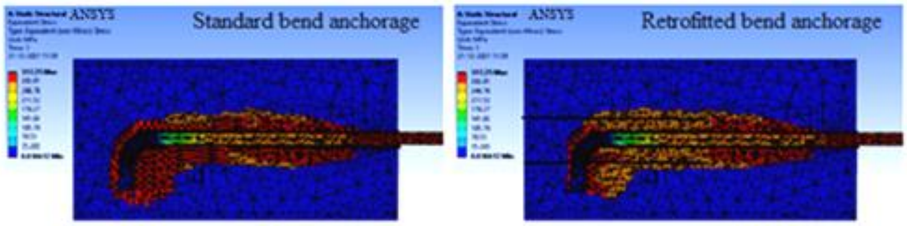


Fig.2 ANSYS modelling of normal stress in 90 degree Bend & Retrofitted anchorage

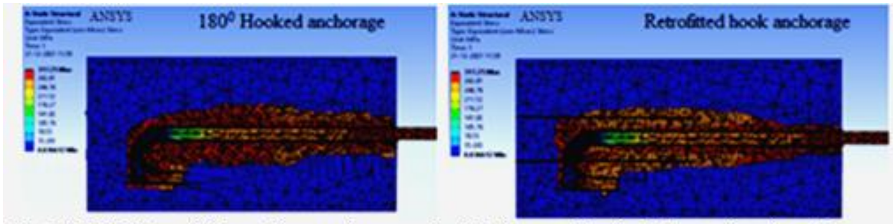


Fig.3 ANSYS modeling of normal stress in 180 degree Hook & Retrofitted anchorage

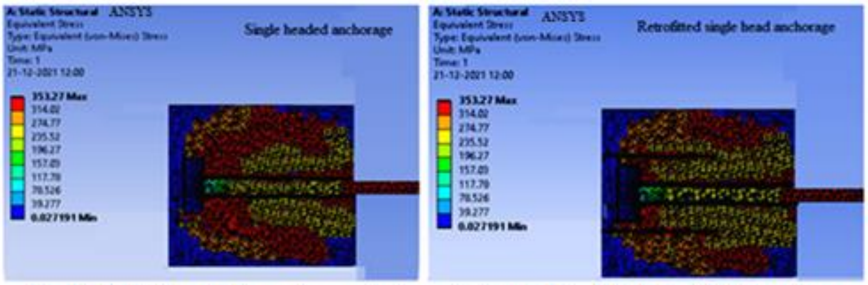


Fig.4 ANSYS modeling of normal stress in Single Head & Retrofitted anchorage

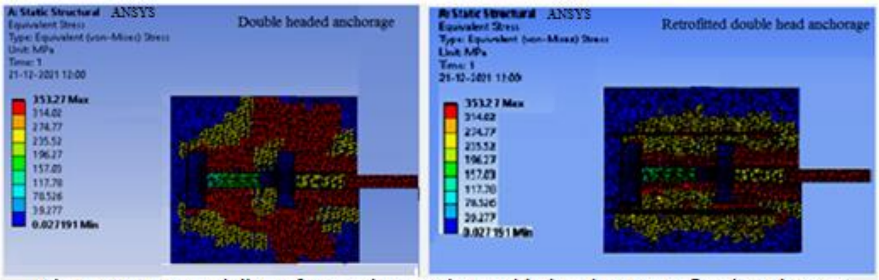


Fig.5 ANSYS modeling of normal stress in Double head & Retrofitted anchorage

6. EXPERIMENTAL PROGRAM

Full scale experimental program was conducted on rebar anchorage system under dynamic impact loads. A total 60 pullout specimens comprised by two groups (Group-A ,Group-B) were casted and testing by rapid pull-out loads under servo controlled Universal Testing Machine confirming to ASTM C234 test standards. This study program was instituted at material testing laboratory, Gayatri Vidya Parishad Engineering College (Autonomous), Visakhapatnam, India. The size of test specimens are 150x150x300mm and grade of concrete is M25 (fck: 25MPa) and size of anchored bars are12mm & 16mmconfirmed to Fe415 (fy:415MPa) grade deformed steel.

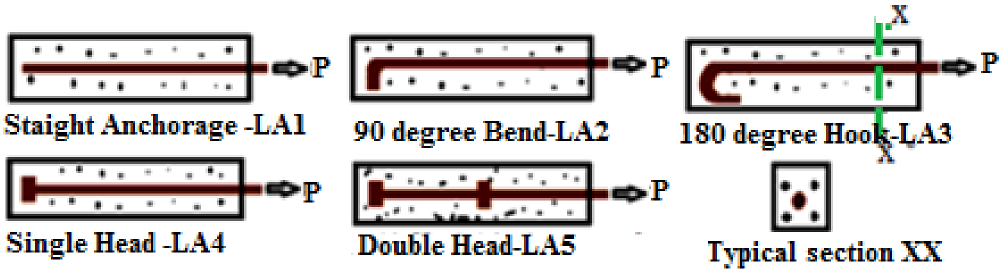


Fig6a. Conventional Anchorage system

Five types of conventional anchorage system considered in Group-A series with 30 control specimens of straight bar (L_{A1}), 90 degree bend (L_{A2}), 180 degree hook (L_{A3}), single head (L_{A4}) and double head (L_{A5}) bars casted by 260mm embedment depth of concrete. Each configuration of anchorage was cast and tested for 3 specimens such that a total 15 specimens were tested under 12mm rebar anchorage. The notation of test specimens are mentioned by $L_{A1-12,}$ $L_{A2-12,}$ L_{A3-12}, $L_{A4-12,}$ $_{LA5-12}$ .Similarly 16mm rebar anchorage of 15 numbers with notation $L_{A1-16,}L_{A2-16,}$ L_{A3-16}, $L_{A4-16,}$ L_{A5-16} were tested such that each configuration of sample tested for 3 specimens. The casted 30 specimens under Group-A series was shown in figure 6a.

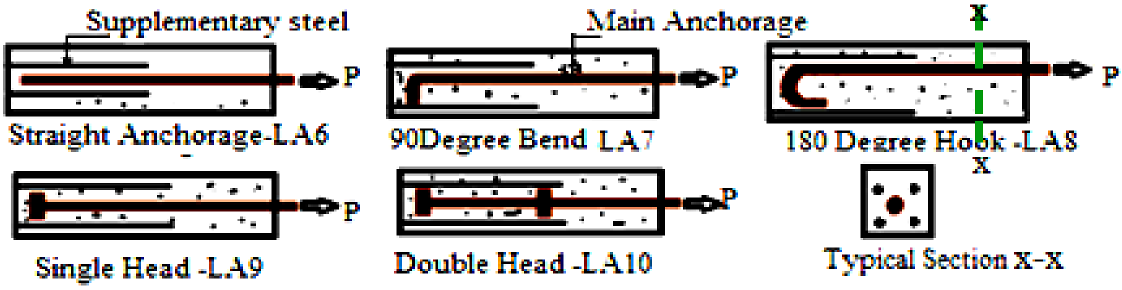


Fig.6b Retrofitted Anchorage system

Fig 6b represents the configuration of retrofitted specimens in Group-B series. A total 30 test specimens comprised by 12mm rebar anchorage of mentioned by $L_{B1-12,}$ $L_{B2-12,}$ L_{B3-12},$L_{B4-12,}$ L_{B5-12} (15 samples) and 16mm rebar anchorage of $L_{B1-16,}$ $L_{B2-16,}$ L_{B3-16}, $L_{B4-16,}$ $_{LB5-16}$ (15 samples) are considered. No confinement reinforcement is provided to the tested samples. The equivalent embedment depth of 12mm conventional anchorage was 1.0Ld, 0.84Ld, 0.63Ld,0.66Ld, and 0.64Ld corresponding to A1,A2,A3,A4 and A5 anchorage respectively Similarly the equivalent embedment depth of 16mm conventional anchorage was 1.0Ld, 0.79Ld, 0.66Ld,0.49Ld, and 0.48Ld corresponding to A1,A2,A3,A4and A5 anchorage respectively The tests conditions follows the design norms of ACI 318-19. The tail end of concrete specimen was fixed at bottom using mechanical fasteners that was assembled with Universal Testing Machine. The loads are applied at impact factor 1.52 and 1.58 against 12mm and 16mm rebar anchorage system.

6.1 Material Properties

Size of concrete specimen 150x150x300mm (depth), Grade of concrete M25, Theoretical bond strength (Tbd) 2.24MPa, Characteristic cube compressive strength (fck) 26.84MPa, Tensile strength of concrete [σ_{ct} = 0.30 $(fck)^{2/3}$] 2.56 MPa, Elastic modulus of concrete (Ec) 5000 $(fck)^{1/2}$ = 0.26 x10^5 MPa, Static modulus of elasticity (E_{RCC}): Range: 0.94 x10^5 ~ 0.14x10^5 (MPa), Poisons ratio (μ) 0.21, Allowable limiting strains in concrete (Ɛ.cs) 0.003, Size of anchored bars: 12mm & 16mm, Yield strength of steel (fy) 432.60MPa, Ultimate strength of steel (fu) 512.40 MPa, Elastic modulus of steel (Es) 2.10x10^5MPa .

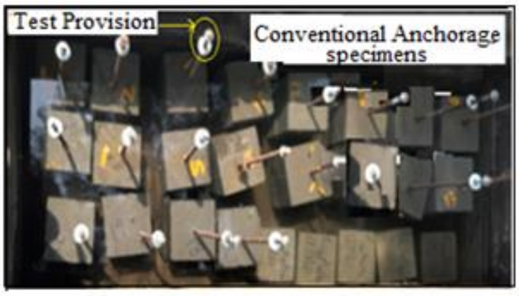
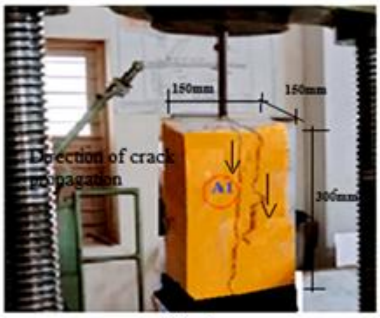


Fig.7a.Test specimens of Conventional Anchorage Fig.7b. Test specimens of Retrofitted Anchorage

6.2 Test observations

Impact force produce sudden release of strain energy at ultimate load of anchorage system, the failures of anchorage system was majorly followed by splitting tensile or shears failure of concrete rather than other modes of concrete failures [18]. The boundary conditions and test parameters follows strut and tie analysis of force transfer mechanism. The supplementary bars are installed by making drilled holes in hardened concrete and fastened 8mm diameter deformed bars by adhesive bond technique using CONBEXTRA epoxy grout. It will establish good bond between interface of steel and concrete. The failure mode of rebar anchorage was significantly influenced by its size effect. Typical failures of concrete observed in retrofitted anchorage due to slip of bar, splitting tensile stress in concrete and rebar pull-out.



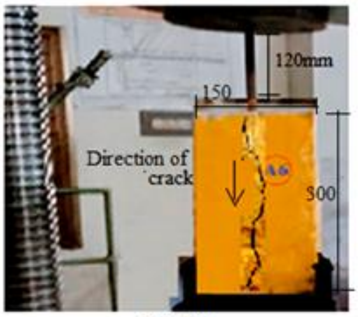


Fig.8a Fig.8b

Conventional Staright Anchorage.A1, Retrofitted Staright Anchorage A6

Experimental observations of straight rebar anchorage (A1) shows multiple cracks and pullout failure of rebar anchorage due to bond loss. The test observations were presented in table1.The failure at ultimate load was noted by 17.53kN, 20.64kN of 12mm, and 16mm bar respectively. The applied loads imparts intensified normal stresses between anchored bar and concrete that results bond loss of anchorage by formation of multiple cracks as shown in Figure 8a. As the size of anchored bar increases, the bond stress of corresponding decrease since more rebar area was in contact with concrete. As shown in Figure 8b, the retrofitted straight anchorage A6 shows slip of anchorage due to bond loss. The size effect of anchored bar shows significant influence on transformation of failure mode from bond to splitting of concrete. In this context failure loads of 18.28 kN and 21.94 kN was observed in 12mm and 16mm bars.

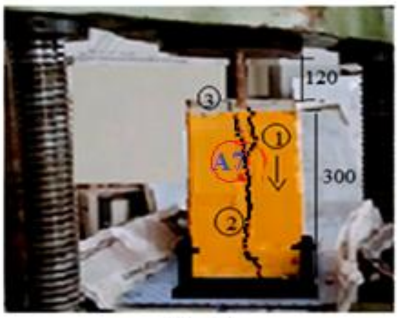


Fig.9a Fig.9b

Conventional 90 degree Bend.A2 Retrofitted 90 degree Bend.A7

Experimental observations of 90 degree bend anchorage (A2) shows multiple cracks at tail end and leads to splitting of concrete due to bearing generated at bend. The test observations are represented in Table 2. Failure of anchorage at ultimate load are noted at 22.10kN, 22.58kN of 12mm, and 16mm bar respectively. The applied loads imparts high intensity of bearing stresses at tail end of anchorage that results splitting failure of anchorage and formation of multiple cracks as shown in Figure 9a. The retrofitted 90 degree bend (A7) that shows shear failure of anchorage due to bond loss. The size effect of anchored bar shows significant influence on transformation of failure mode from bond to splitting of concrete. The corresponding failure loads of 22.75kN and 22.50kN was observed for 12mm and 16mm anchored bars. The size of anchored bar does not show significant improvement of ultimate load but transformed the failure mode of anchorage from bond loss to splitting tensile mode.

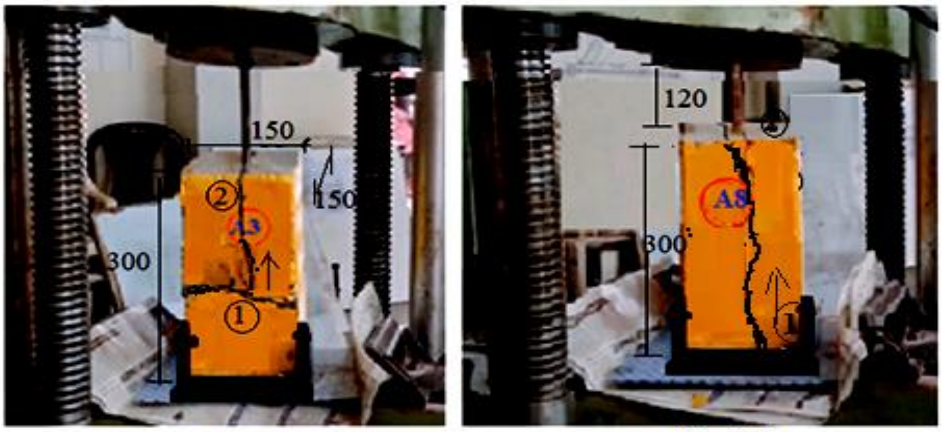


Fig.10a Conventional 180 degree Hook

Fig.10b Retrofitted 180 degree Hook

Test observations of 180 degree conventional hook anchorage (A3) shows large number of splitting cracks at bearing of hook due to crushing stress developed in concrete. The test result of normal stress, bond stress and tensile stress of concrete during failure was mentioned in Table3a.The failure loads are noted as 25.74kN, 31.36kN of 12mm, and 16mm rebar anchorage with successive impact factor of 1.58 and 1.52 respectively. The impact loads exerts high intensity of bearing stresses at tail end of anchorage and leads to crushing failure of anchorage as shown in figure 10a. This ultimately leads to loss of bond stress and splitting cracks appeared in concrete. Failure of retrofitted 180 degree hook (A8) constituted by shear failure due to loss of bond. The size effect of anchored bar shows significant influence on transformed the failure mode from shear failure to tension failure of the system. A substantial improvement of failure loads 26.80kN and 32.15kN are observed in 12mm and 16mm anchored bars respectively.

Fig.11a Conventional Single Head anchorage

Fig 11b Retrofitted Single Head anchorage

Figure 11a demonstrates the failure of single head anchorage (A4) by cone of fracture. The tail end of headed anchorage develops high bearing stresses before bond failure of rebar and leads to cone of failure by splitting tensile stresses developed in the concrete as shown in figure 11a. The test result of normal stress, bond stress and tensile stress of concrete at failure are presented in Table 4a. The direction of failure starts at tail end and progressed towards face. The presence of supplementary bars provides good confinement at tail end and considerable tensile resistance against splitting failure of concrete. Hence parallel splitting cracks may observe during failure. A good contribution of concrete observed during failure that leads to ductile failure of anchorage. The splitting cracks are formed at tail end of head and progressed towards face. There is considerable improvement of ultimate load during failure of headed anchorage and is increased with size of anchorage as mentioned in Table 4b.

Fig.12a Double headed anchorage

Fig.12b Retrofitted Double headed anchorage

Figure 12a represents failure of double head anchorage (A5) by splitting tensile stresses induced in the concrete. The tail end of headed bar develops high bearing stresses and leads to double cone of fracture between multiple heads. The direction of failure starts from tail end and progressed towards face end of specimen. The test result of normal stress, bond stress and tensile stress of concrete at failure are presented in Table 5a. Also contribution of concrete is more than rest of anchorage system and helps to ductile failure of anchorage. Figure 12b shows failure of retrofitted double head anchorage (A10) trough tensile stresses developed in concrete. The presence of supplementary bar influence the failure mode and it helps to improve both tensile and confinement resistance by passive confinement effect. A good contribution of concrete was observed during the failure which indicates contribution towards ductile failure of anchorage. Also shear cracks formed between successive heads and progressed at face end of the specimen. The failure of retrofitted anchorage accompanied by loss of bond and bearing stress that leads to ductile failure. The test result of normal stress, bond stress and tensile stress of concrete presented in Table 5b.

7. RESULT AND DISCUSSION

Impact tests are conducted on five different types of conventional and retrofitted anchorage system by using Post-Installation of Supplementary Anchorage. To elevate the size effect of embedded rebar of main anchorage, the tests are conducted with the use of 12mm and 16mm high yield strength deformed bars confirmed to Fe415. The test observations were made for ultimate load, normal stresses in concrete, bond stress and tensile stresses of concrete at ultimate load. The experimental results are validate by finite element based ANSYS modeling. The tested parameters are concrete contribution (Table 2), crack width (Table 3), and bar-slip (Table 4) of both conventional and retrofitted anchorage. A comparison was brought between bond and tensile strength contribution at ultimate loads as addressed in Figure.13a, 13b. The contribution of concrete for different diameter of rebar anchorage was presented in Figure.14

7.1 Parametric study

The observations related to parametric influence on strength and performance of anchorage system by PISA retrofitting technique was studied under concrete contribution, slip of anchorage, failure modes and analysis of stresses were discussed below.

7.1.1 Analysis of stresses

- The results of experimental, numerical and theoretical evaluation (Ref:ACI318-19 & ACI352-02R) are presented in Table-1. Maximum tensile stresses observed in conventional double head (A5) and retrofitted single head (A9) anchorage systems which indicate the anchorage systems are good in tension.
- Splitting failures are prominent in most of conventional anchorage systems and it was

transformed into bond failure in the retrofitted anchorage.

- Normal stress shows significant influence on double head retrofitted anchorage (A10) and minimum influence in straight anchorage system (A1).
- A good correlation of test results observed in retrofitted anchorage system. The correlation factor (CF) evaluated for ultimate load (CF: 0.86), tensile strength (CF: 0.92), and bond strength (CF: 0.94) which shows significant influence of post retrofitting technique on the evaluated parameters.

7.1.2 Concrete contribution

Table.2 shows contribution of concrete during critical failure of anchorage system .This parameter significantly influence the ductile property of anchorage such as less contribution indicates brittle failure and more contribution indicates ductile failure.

- Maximum contribution of concrete (52.92%) observed in conventional single head anchorage (A4) at ultimate failure load of 29.15kN. Also considerable ductility observed in A4,A5,A8,A9 and A10 which indicates good ductile performance of shown by conventional single headed bar.
- Retrofitting of standard 90^0 bend exhibit maximum bond strength (2.97MPa) at ultimate load (33.20kN). Maximum improvement of ultimate load observed (12.90%) in anchored bend and minimum effect was observed in conventional anchorage system.
- Conventional hook and retrofitted double head anchorage system exhibit minimum bond strength of 2.43MPa, 2.46MPa respectively.

TABLE-1
EXPERIMENTAL RESULTS OF IMPACT PULLOUT TEST (DEEP ANCHORAGE SYSTEM)
STRESSES AT ULTIMATE FAILURE OF CONVENTIONAL& RETROFITTED ANCHORAGE SYSTEM
(ANCHORAGE BAR DIAMETER: 12 mm HYSD, CONCRETE GRADE: M25, IMPACTFACTOR: 1.58)

Configuration of Anchorage	*Theoretical Value (ACI 318 & ACI 352)				Modeling analysis				Experimental Value				Type of Failure
	Pu (kN)	σn (MPa)	τ_{bd} (MPa)	σ_{tc} (MPa)	P_u (kN)	σ_n (MPa)	τ_{bd} (MPa)	σ_{tc} (MPa)	P_u (kN)	σ_n (MPa)	τ_{bd} (MPa)	σ_{tc} (MPa)	
Plain bar L_{A1-12}	15.88	-	2.46	2.30	19.52	313.62	2.56	1.08	17.53	384.25	2.47	0.92	Bond
Standard Bend L_{A2-12}	17.18	-	2.46	2.30	24.26	326.26	2.67	1.72	22.10	381.50	2.71	1.24	Bearing
Standard Hook L_{A3-12}	22.70	-	2.46	2.30	26.35	374.32	2.69	1.65	25.74	376.48	2.42	1.38	Splitting
Single Head L_{A4-12}	21.92	-	2.46	2.30	27.10	346.54	2.81	1.72	29.15	362.65	2.49	1.42	Splitting
Double Head L_{A5-12}	20.50	-	2.46	2.30	25.40	314.25	2.76	1.76	28.30	349.52	2.34	1.44	Splitting
Plain bar L_{A6-12}	15.88	-	-	-	21.34	271.48	2.69	1.62	18.28	378.65	2.32	1.06	Bond
Standard Bend L_{A7-12}	17.18	-	-	-	25.84	323.65	2.82	1.74	22.75	376.24	2.67	1.29	Bond
Standard Hook L_{A8-12}	22.70	-	-	-	27.26	368.54	2.87	1.72	26.80	372.85	2.39	1.43	Bond
Single Head L_{A9-12}	21.92	-	-	-	28.15	342.40	2.92	1.79	27.45	357.48	2.45	1.46	Bond
Double Head L_{A10-12}	20.53	-	-	-	28.90	336.15	2.96	1.82	27.16	328.63	2.41	1.40	Bond

Notations: * Theoretical values calculated as per design code ACI 318 &ACI 352-02R by using HYSD bar & Impact factor 1.58, P_u: Impact load at ultimate failure (kN), σ_n: Stress in concrete at ultimate load(MPa), τ_{bd}: Bond stress at failure (MPa), σ_{tc}: Tensile stresses of concrete

7.1.3 Slip of rebar anchorage

Table-4 Shows slip of rebar 12mm &16mm under impact loads. The impact factor of 1.52 & 1.58 considered for 12mm & 16mm bars and finding the influence of PISA technique on slip of bar. The bar- slip was calculated from principle of strain energy .Following observations are drawn.

- Bar-slip increased with size of anchored bar in the conventional anchorage system. In retrofitted anchorage bar-slip decreased with increase size of bar.
- Two different size of rebar anchorage (12mm & 16mm), and maximum bar-slip observed in straight anchorage and also minimum bar slip (13.78mm) observed in retrofitted double head (44.82mm) bar.
- Bar slip increased by use of supplementary anchorage of PISA technique. Maximum increment of bar-slip (48.04%) observed in 12mm straight rebar anchorage (A6) and minimum increment of bar-slip (8.42%) observed in 12mm double head retrofitted anchorage (A10).

TABLE-2
EXPERIMENTAL OBSERVATIONS - IMPACT PULLOUT TESTS OF DEEP ANCHORAGE
CONCRETE CONTRIBUTION OF CONVENTIONAL & RETROFITTED ANCHORAGE
(ANCHORAGE BAR DIAMETER: 12 mm HYSD, CONCRETE GRADE:M25, IMPACT FACTOR :1.52)

S No	Type of anchorage	Specimen	Pu Exp.	T_{bd} Exp	Vc Exp	Vs Exp	η_c= (Vc/Vs) x100	ρ_a = % of steel
		notation	kN	MPa	mm^3	mm^3	%	%
1	Conventional Plain bar.	L_{A1-12}	17.53	2.47	518.24	28274.16	1.83	0.50
2	Conventional Standard Bend	L_{A2-12}	22.10	2.71	684.32	33476.20	2.04	0.50
3	Conventional Standard Hook	L_{A3-12}	25.74	2.42	14526.58	44334.51	32.15	0.50
4	Conventional Single Head	L_{A4-12}	29.15	2.49	23462.16	44274.30	52.92	0.50
5	Conventional Double Head	L_{A5-12}	28.30	2.34	26348.42	53407.24	49.33	0.50
6	Retrofitted Plain bar	L_{A6-12}	18.28	2.32	624.32	45216.36	1.38	1.39
7	Retrofitted Standard Bend	L_{A7-12}	22.75	2.67	932.64	50440.60	1.84	1.39
8	Retrofitted Standard Hook	L_{A8-12}	26.80	2.39	14436.38	61298.30	23.52	1.39
9	Retrofitted Single Head	L_{A9-12}	27.45	2.45	12342.72	61238.93	20.15	1.39
10	Retrofitted Double Head	L_{A10-12}	27.16	2.41	24342.64	77238.90	31.51	1.39

Notations:

Pu: Load at ultimate failure (KN), Tbd : Bond stress of anchorage at ultimate failure (MPa) ,
Vc Volume of concrete contributed at failure (mm^3), Vs: Volume of steel contributed at failure (mm^3)
η_c: % of concrete contribution at ultimate failure , η_c = (Vc / Vs) x 100, ρ_a = % of steel used =(Ast/Ac) x100

TABLE-3
EXPERIMENTAL RESULTS-IMPACT PULLOUT TESTS OF DEEP ANCHORAGE SYSTEM
CRACK WIDTH OF CONVENTIONAL & RETROFITTED ANCHORAGE
(ANCHORAGE BAR DIAMETER: 12 mm HYSD, CONCRETE GRADE: M25)

No	Anchorage	Specimen	Pu	Wci	Wcf	Tbd	Failure
	Configuration of anchorage	Notation	Impact load @ final crack	Initial crack width	Final crack width	Bond Strength @ final crack	Type
S.No	Description		kN	mm	mm	MPa	
1	Conventional Plain bar.	L_{A1-12}	17.53	0.30	1.20	2.47	Bond
2	Conventional Standard Bend	L_{A2-12}	22.10	0.30	1.00	2.71	Bond
3	Conventional Standard Hook	L_{A3-12}	25.74	0.30	0.90	2.42	Bearing
4	Conventional Single Head	L_{A4-12}	29.15	0.30	0.60	2.49	Tension
5	Conventional Double Head	L_{A5-12}	28.30	0.30	0.40	2.34	Tension / Bond
6	Retrofitted Plain bar	L_{A6-12}	18.28	0.30	0.80	2.32	Bond
7	Retrofitted Standard Bend	L_{A7-12}	22.75	0.30	0.70	2.67	Bond
8	Retrofitted Standard Hook	L_{A8-12}	26.80	0.30	0.50	2.39	Bond
9	Retrofitted Single Head	L_{A9-12}	27.45	0.30	0.40	2.45	Bond
10	Retrofitted Double Head	L_{A10-12}	27.16	0.30	0.40	2.41	Tension

Notations: Pu: Impact pull out load at final crack (kN), Wci: Initial crack width as per ACI 318-19 : 0.30mm Wcf: Final crack width (mm) , Tbd: Bond strength at failure (MPa)

7.2. Effect of bar size on configuration of anchorage

The influence of anchored bar size (12mm & 16mm) on various configurations of anchorage system are discussed below. Specific observations are made for crack width, strength, concrete contribution and crack formation was discussed.

7.2.1 Effect of bar size on crack width

Table.3 shows crack width of conventional, retrofitted anchorage system and following conclusions were drawn.

- Except retrofitted double head (A10) all other anchorage systems are susceptible to bond failure by supplementary anchorage. A significant influence of shear conditions exists by PISA technique that reduce tensile failure of concrete in retrofitted anchorage.
- A Substantial reduction of crack width was observed in all types of retrofitted anchorage system except double head bar (A10). Minimum crack width observed in retrofitted single head (A9) and double headed bar (A10). Use of supplementary anchorage does not shown any

influence on crack width of double head anchorage (A5).

- The bearing stress at hook and head of anchored rebar shows significant effect on fracture mechanics of A3,A4,and A5 anchorage. Failure mode of these anchorage systems are influenced by developed splitting tensile stress of concrete which was effectively addressed by PISA technique.
- Failure modes of anchorage systems are shown in from Fig 7a,7b -to-Fig12a,12b.One of the key observation found in failure mechanics of anchorage systems are with the use of retrofitted technique, failure modes of conventional anchorage was transformed to bond failure.

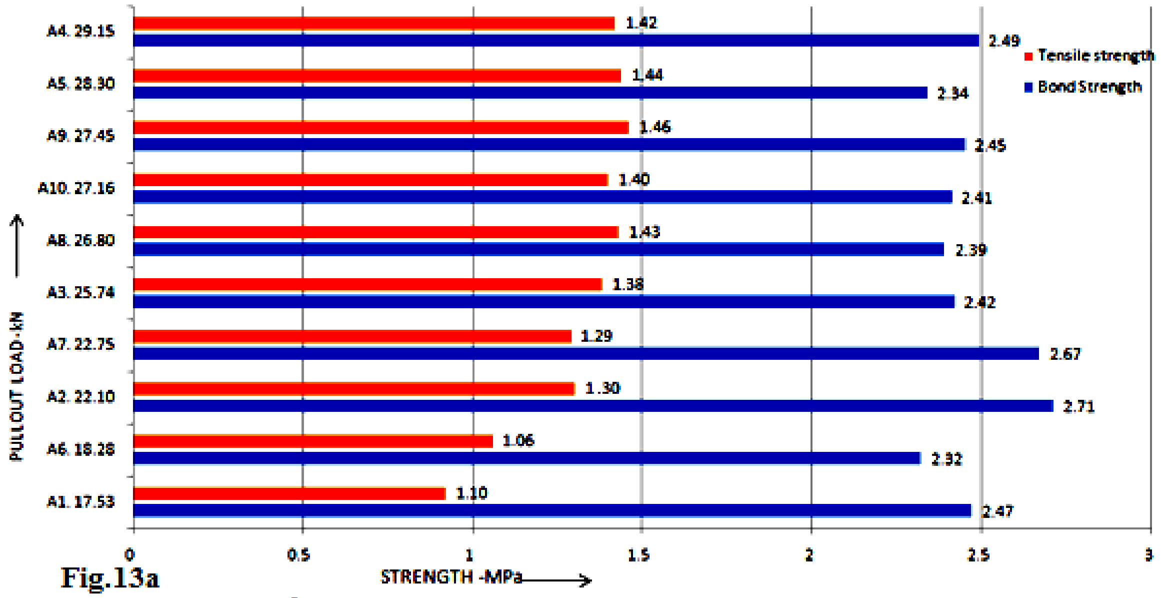


Fig.13a

LOAD .Vs BOND & TENSILE STRENGTH OF CONCRETE- IMPACTC PULL OUT TEST: 12mm. ANCHORAGE

TABLE .4
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}	Pu /ΔL_{12}	ε_{12}	Pu	ΔL_{16}	Pu /ΔL_{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 90^0 Bend	L_{A2-16}	29.40	19.44	1.51	–	35.30	19.56	1.80	–
2b	Retrofitted 90^0 Bend	L_{A7-16}	33.20	23.46	1.40	+20.67%	36.10	21.85	1.65	+11.71 %
3a	Conventional 180^0 Hook	L_{A3-16}	36.20	33.12	1.09	–	49.70	36.48	1.36	–
3b	Retrofitted 180^0 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 : Bar slip (mm), ε: Percentage bar slip against conventional anchorage,
% slip : + ve : Indicates increase , - ve : Indicates decrease

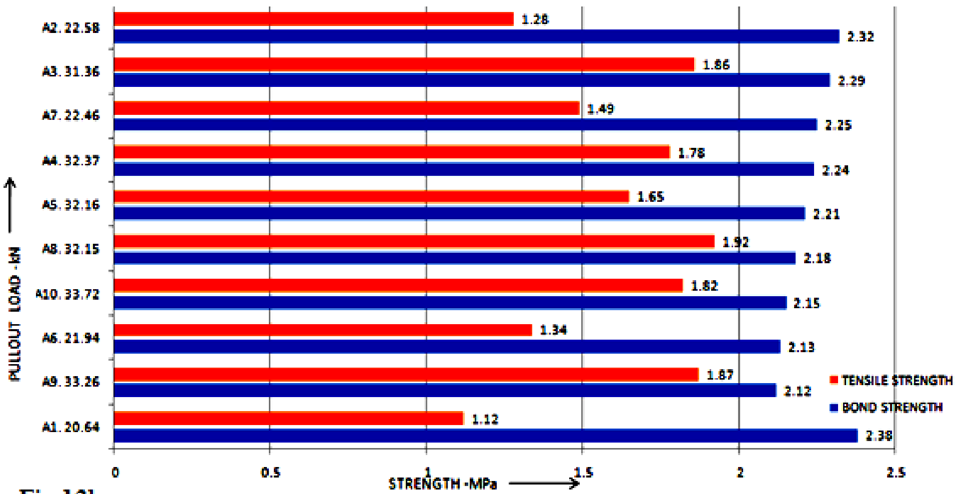


Fig.13b
LOAD .Vs BOND & TENSILE STRENGTH OF CONCRETE: IMPACT PULL OUT TEST: 16mm ANCHORAGE

7.2.2 Effect of bar size on strength

Fig.13a & Fig.13b shows size effect of anchored bar size on bond and tensile strength of concrete.The following observations are.

- There is a significant improvement in strength of anchorage system with increment size anchored bar. Also variation in contribution of bond and tensile strength of anchorage system significantly decreased with increased size of anchored bar.
- Use of large size anchored reinforcement demands more tensile strength of concrete and increased at par with bond strength. This concept was more significant when using retrofitted anchorage system of A8,A9 and A10.

Use of small size reinforcement as rebar anchorage shows requirement of high bond strength and minimum tensile strength of concrete. PISA technique as retrofitting measure of anchorage is more effective when large size bars used in structural anchorage. Its effect is size of bar was reduced.

7.2.3 Effect of bar size on concrete contribution

Fig 14 shows size effect of anchored bar size on concrete contribution since it plays a vital role against ductile performance of the system.The following observations are drawn under impact loading conditions.

- Substantial contribution of concrete was observed in rebar anchorage of A3, A4, A5, A8, A9 and A10. Concrete contribution is minimum in rebar anchorage of A1, A2, A6 and A7.
- Mechanical anchorage by using headed bars shows good contribution of concrete in A4, A5, A9, and A10. It is a noted observation and useful to proceed ductile performance of anchorage.
- No significant improvement on concrete contribution was observed in A1 and A2 anchorage systems by using PISA as retrofitting measure.

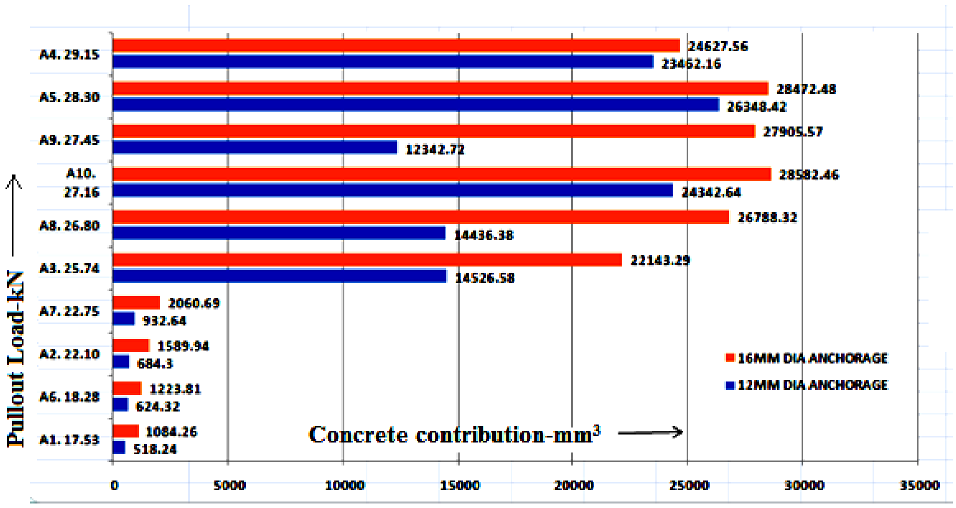


Fig.14 CONTRIBUTION OF CONCRETE IN 12MM & 16MM DIA ANCHORED BAR. IMPACT TEST

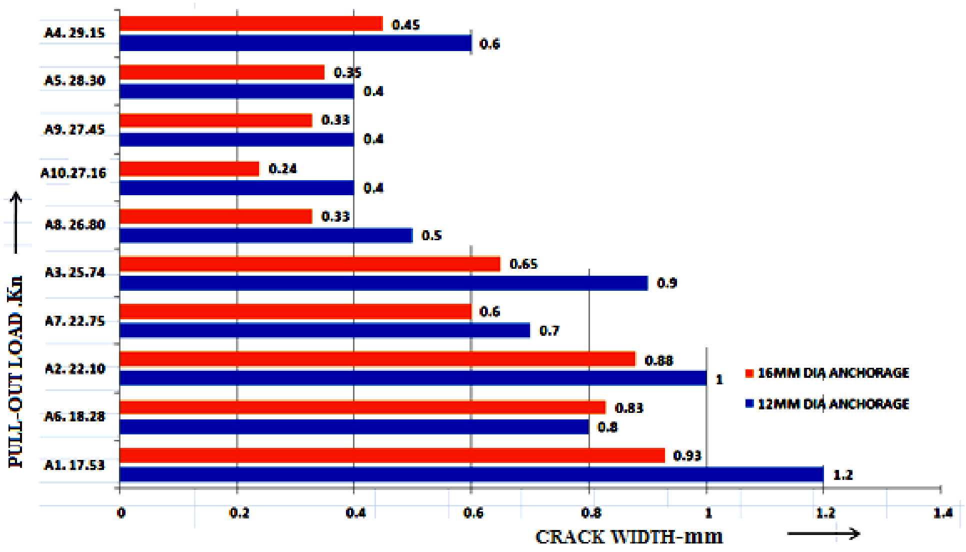


Fig.15 CRACK WIDTH OF 12mm & 16mm SIZE ANCHORED BAR-IMPACT LOAD

7.2.4 Effect of bar size on crack formation

Fig 15 shows size effect on crack width of anchorage system under impact loads. The following observations are drawn.

- Maximum crack width observed in anchorage systems of A1, A2, and A3. The rebar size shows no significance when PISA used as retrofitting measure by the above anchorage systems.
- Anchorage systems A4, A5, A8, A9 and A10 shows minimum crack width and allowing large pullout loads. This indicates a substantial improvement of load transfer when an anchorage subjected to impact loads.
- Retrofitting of hooked anchorage system by PISA technique shows more effective in hooked anchorage system (A3) since it reduce crack width and provides substantial improvement in shear and bond strength of rebar anchorage under dynamic impact loading conditions.

8. CONCLUSIONS

A comprehensive study was conducted on retrofitted anchorage system of structural concrete. Both experimental and numerical studies are conducted on different configurations of anchorage system that was retrofitted by “Post-Installation of Supplementary Anchorage” (PISA) for its implicit strengthening. Due to its versitality and good perfrmance under impact loads, PISA technique shall provide efficient retrofitting measures in discrete RC members subjeced to dynamic impact loads such as blast load, earth quake conditions, ect. The principle observations of retrofitted anchorage system are detailed as folllows.

1. A good improvement of strength (bond, tension) and ductility was observed in retrofitted anchorage systems with Post Installation of Supplementary Anchorage (PISA).The technique shows good prominenence when large diameter bars used in structural anchorage system .
2. PISA retrofitting technique may significantly enhance the contribution of concrete in single head (A9) and double head (A10) anchorage systems that leads to show good improvement of ductility.
3. A substantial improvement of bar-slip observed by supplementary anchorage that was installed hardened concrete. For a given bar diameter (12mm) the maximum increment of bar-slip (48.04%) was observed in straight rebar (A6) and minimum increment of bar-slip (8.42%) observed in retrofitted rebar of double head anchorage (A10).
4. A good control over crack formation and crack width was observed in retrofitted anchorage systems. In this context 180 degree hook anchorage (A8) exhibit maximum reduction of crack width (43%) by supplementary anchorage. But its influence was less significant in double headed anchorage (A10).
5. Experimental results of retrofitting technique (PISA) shows good acceptance to limit inelastic strains developed in deep anchorage system. This is due to predominant influence of local bond stress rather than bond stress.
6. Except straight anchorage (A1) and 90 degree bend (A2), the brittle failure of rest of conventional systems transformed to ductile mode by PISA technique.

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