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STRENGTH AND MODES OF FAILURE OF ADHESIVE ANCHORS IN CONFINED CONCRETE UNDER DIRECT TENSILE LOADING

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Abstract: Bonded anchors are used in several civil engineering applications, whose performance needs to be investigated. This paper discusses some experimental investigations on the strength and failure modes of bonded anchors in concrete, without and with confinement reinforcement. The effect of strength of concrete, embedment length and diameter of anchors has been studied. The important parameters influencing the strength of anchorage system are compressive strength of concrete and the embedment depth of anchors. Three different concrete strengths of 25, 40 and 60MPa were adopted along with three embedment lengths of 150mm, 200mm and 250mm. The anchorage strength increases as the compressive strength of concrete increases. As the embedment length of anchor increases, the anchorage strength also increases. The diameter of the anchor does not show much influence on the strength of anchorage. The strength of bonded anchors was observed to coincide with the strength estimated as per both CCD design method and ACI 349 method. Bonded anchor load carrying capacity has been observed to closely match with that of the post-installed anchors. It has been observed that concrete cone failure was predominant in all the specimens without confinement reinforcement. The confinement reinforcement alters the mode of failure from concrete cone failure to ductile failure of concrete with distributed cracking.

1. INTRODUCTION

Anchorage in concrete can be adopted in one of the following two ways i.e. (i). cast-in-place and (ii). post-installed. In the post-installed method, anchors may be classified as mechanical or bonded anchors. Use of these anchors in connection of structural system is of recent origin. Use of mechanical anchors in concrete construction is well established. Though, bonded anchors are used extensively in practice but the design guidelines for the use f bonded anchors are not yet standardized. The anchors transfer the loads to concrete through mechanical interlock, friction, chemical bond or combination thereof.

The anchorages may be adopted for attachment of piping systems, lightweight suspended ceilings, etc., and are also widely employed for the attachment of metal deck to steel framing. Anchorage system needs to be designed to ensure durability and robustness, and with sufficient load carrying capacity and deformability. Consequently, these systems require studies to understand for standard specifications. Fastenings may be used for less critical applications such as securing lightweight duct, lighting, and wiring, can be selected based on the function without serious analysis or structural review.

2. REVIEW OF LITERATURE

Eligehausen and Clausnitzer [1]

investigated the tensile behavior of expansion anchors. The nonlinear behavior for smeared cracks in concrete over the width of the element was assumed. The behavior of concrete in tension, size of the element and number of load increments to ultimate load has been studied. The ultimate load increased as the element size increases with decrease in number of load increments.

Fuchs et al. [2] reported the concrete capacity design (CCD) approach for the design of post-installed mechanical anchors and cast-in-place headed studs or bolts. A data bank containing about 1200 European and American tests was evaluated. Cook, Kunz and Fuchs [3] reported that *a* constant bond stress develops over the embedment depth and the bond strength is independent on the embedment depth. Procedure for evaluation of the ultimate bond failure in adhesive anchor was set.

Cook [4] investigated the effect of factors influencing the bond strength of adhesive anchors; installation conditions of hole (wet, damp, cleaned, uncleaned), difference of concrete strength, difference in aggregate, and in post-installation process include curing and loading at elevated temperature. Eligehausen [5] compared the model proposed for the concrete cone breakout failure by Fuchs [2] for single cast-in-anchors and post-installed mechanical anchors with that of Cook et al. [3] for the uniform bond stress model. It has been reported that the failure of adhesive anchors can be compared to the concrete cone break out failure of the post-installed mechanical anchors. The actual bond stress distribution along the embedment length at the peak load is nonlinear with low bond stress at the concrete surface and high bond stress at the embedded end of the anchor. However, comparison of the proposed models with the database for single adhesive anchor indicates that the failure load is best described by uniform bond stress model incorporating the nominal anchor diameter, d with mean bond stress, τ associated with the adhesive [3]. Eligehausen et al. [5] reported that the failure load of a single bonded anchor is limited by the load corresponding to the concrete cone break out failure. The uniform bond stress model for adhesive anchors is given by,

$$N_u = \tau \pi d\, h_{ef} \tag{1}$$

Where d = diameter of anchor rod in mm, τ = average bond stress, and h_{ef} = embedment depth in mm,

According to *ACI 349*, a 45° failure cone and a constant tensile stress over the projected failure surface are selected. The calculated failure loads correlate with the results of tests with a limited range of embedment depths. In CCD Method [2], the capacity of a single anchor in tension is calculated based on 45^0 inclination of the failure surface of concrete. This corresponds to the assumption that the failure surface is about twice the effective embedment depth of the anchor. The failure load, N (kN), corresponding to the concrete cone breakout, of a single anchor is given by

$$N_u = k\ f_{cc}^{'0.5}\ h_{ef}^{1.5} \tag{2}$$

Where k = 13.5, for post-installed anchors, k = 15.5, for cast-in situ headed anchors bolts, f_{cc}’ = concrete compressive strength measured on cubes and h_{ef} = effective embedment depth, mm.

The strength of a single anchor in tension as per ACI 318 [6] is as follows

$$N_u = (4\ f_c^{'0.5})\ A_N \tag{3}$$

Where A_N = Projected area of a single anchor = $A_N = \pi h_{ef}^2 \left(1 + \frac{d}{h_{ef}}\right)$

In SI units, the capacity of the anchor is given by

$$N_u = 0.96 f_c^{'0.5} \, h_{ef}^2 (1 + \frac{d_u}{h_{ef}}) \, , N \qquad (4)$$

The splitting of concrete occurs when the size of concrete is small, the anchor is installed close to an edge or a line of anchors are installed in close proximity to each other. The failure load associated with the splitting of concrete is reduced relative to that corresponding to concrete cone break out failure. Failure of steel bolt or stud represents an upper value of the highest load carried by an anchor. Fracture of steel rarely happens except in high-strength concrete. Splitting of concrete during anchor installation can be avoided by providing minimum spacing between anchors and minimum edge distance

$$N_u = \frac{\pi d^2}{4} f_y \qquad (5)$$

Where d = diameter of the anchor, and f_y = yield strength of steel

Table 1: Strength of Post installed anchors, in tons, based on CCD /ACI 349.

S. No	Embedment depth (mm)	Grade of concrete (MPa)		
		25	**40**	**60**
1	150	12.4/13.0	16.0/16.7	19.2/20.1
2	200	19.1/22.0	24.7/28.6	29.6/34.2
3	250	26.7/33.6	34.5/43.6	41.3/52.0

3. STRENGTH ESTIMATE

According to the previously mentioned methods of calculating the capacity of anchors based on the capacity of concrete, the capacity of steel and the capacity of the bond is as tabulated below. The relation between the load capacity of the anchor with the embedment depth according to the concrete cone design (CCD) method and the ACI-318 is shown in the Figures 1 to 3 for various grades of concrete.

Table 2: Bond strength of Anchors

S.No	H_{ef} (mm)	Bond capacity (tons)
1	150	21.20
2	200	28.27
3	250	35.34

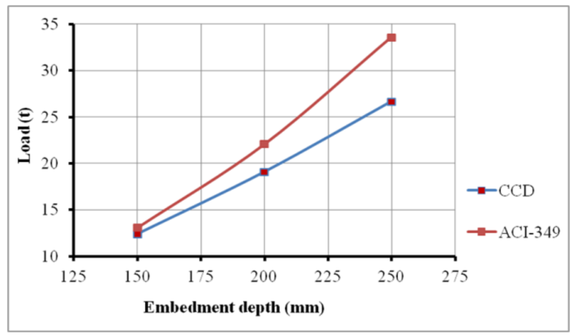

Figure 1: Load vs. Embedment Depth in 25 MPa Concrete.

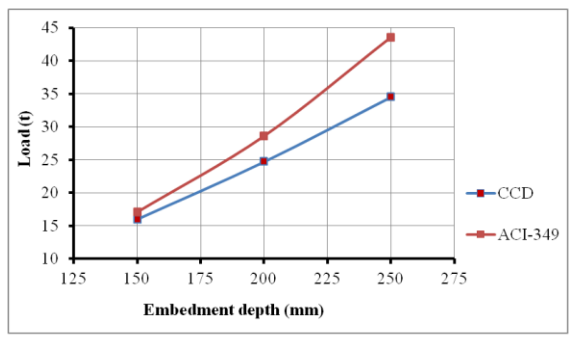

Figure 2: Load vs. Embedment Depth in 40 MPa Concrete.

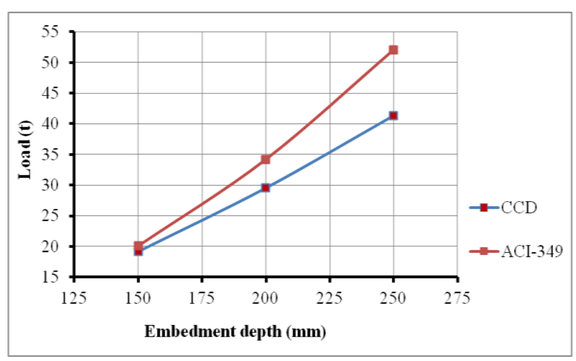

Figure 3: Load vs. Embedment Depth in 60 MPa Concrete.

The steel failure is well documented. Therefore attempt was made for the failure to be that of concrete cone, therefore 30mm diameter steel anchors were used so as to rule out the steel failure mode. The capacity of steel = $f_y . A_{st}$ = 640 * 706.85 = 451940 N = 45 Tons.

The capacity of bond $N_u = \tau\ \pi\ d\ h_{ef}$

The design strength of anchors is to be determined experimentally and relation between the load and displacement to be obtained and analyzed. Also the effect of varying embedment depth, diameter of reinforcement and grade of concrete on the capacity of anchors is to be studied.

4. EXPERIMENTAL PROGRAM

4.1. Concrete Mixes

In this experimental study, concretes of three different strengths were designed and produced to understand the effect of strength of concrete on strength and behaviour of adhesive/bonded anchors. 43 grade ordinary Portland cement was used throughout the programme. 20mm nominal maximum size aggregate was used. The three different strengths of concrete achieved in this study were 25, 40 and 60 MPa. The details of the design concrete mix proportions are as follows.

a. Mix Proportion 25MPa Strength

Cement Content = 360 kg
Mix Proportion = 1: 1.70: 3.15: 0.48

b. Mix Proportion for 40MPa Strength

Cement Content = 420 kg
Mix Proportion = 1: 1.45: 2.65: 0.42

c. Mix Proportion for 60MPa Strength

Cement Content = 450 kg
Mix Proportion = 1: 1.33: 2.44: 0.36

4.2. Steel: The steel anchor rods were supplied by Hilti. Two different diameters of anchors namely 30mm and 20mm were used in this study. The anchors had nominal yield strength of 640 N/mm^2.

4.3. Adhesive

Adhesive was used to grip the anchors with the surrounding concrete. The adhesive used was the injection type which used RE500 adhesive and has mean bond strength of 15.0 N/mm^2. In these plastic cartridges containing pre-measured amounts of resin and hardener allow controlled mixing of polymer components. The components are typically mixed through a special mixing nozzle, as they are dispensed, or are completely mixed within the cartridge immediately before injection.

4.4. Casting of RC Anchors Specimens

To study the influence of various factors on the strength and behaviour of bonded anchors, a total of thirty RC specimens embedded with anchors were cast. The actual strengths of concrete achieved in the laboratory were 25 MPa, 42 MPa, 60 MPa. Three specimens were cast and the average of three is reported. Typical RC embedded with anchor is shown in Figure 4. Since the failure of anchor (steel failure) is well documented, such failure was avoided by selecting the diameter of anchors in all the specimens as 30 mm. Parameters varied in this study are:

- Concrete Grades = M25, M40 and M60
- Embedment depth = 150mm, 200mm and 250mm
- Lateral reinforcement = 8mm diameter bar spaced at 60mm, 90mm & 120mm

Figure 4: Reinforced Concrete Specimen with Anchor Rod

4.5. Test Programme

The load was applied to the anchors by the actuator through a pulling bracket which was fitted in front of the actuator. Displacement was increased incrementally to the anchors to prevent any dynamic effect. Three concrete cubes were tested to determine the concrete compressive strength.The actuator was supported by the testing frame. The concrete block was fixed by a reaction frame anchored to the strong floor thus preventing the pulling of the concrete block. The anchor specimens were made in three embedment depths of 150mm, 200mm and 250mm.

4.6. Preparation of Test Specimen

The moulds were prepared using steel channel placed back-to-back with required specimen dimensions. Three different sizes of specimens with three different embedment depths were prepared. The reinforcement as per calculations was provided by carrying out bar-bending as designed, as shown in Figure 5. The mould was lubricated with oil on the inner faces for easy demolding of concrete specimens. Fresh concrete was poured carefully from the top without any segregation. Needle vibrator was used to compact the concrete. After 24 hours the concrete specimens were demolded from the formwork, duly designated and cured for 28 days.

Figure 5: Anchor Specimens with reinforcement detail.

After achieving sufficient strength of concrete, the specimens were drilled with required hole depth and diameter. Three embedment depths of 100mm, 150mm, 250mm were made using 35mm drill bit to embed 30mm diameter anchor rods. The holes were cleaned with hand pumps to blow the concrete dust in the hole and wire brushes were also used. Subsequently, the hole was washed with water and allowed the cleaned specimens for dry under shade for about two days. The anchor rods were mounted with electrical resistance strain gauges at about half the embedment depth. The hole was filled about 2/3rd depth with RE-500 adhesive using the injection type installation. Subsequently, the test specimens were cured properly. The specimens were allowed for curing for forty eight hours for the adhesive to set.

4.7. Experimental Set-up and Testing

The experimental set-up was prepared for testing the anchored specimens under displacement control as shown in Figure 6. A 100 kN capacity actuator was fixed laterally with an existing A-frame which can withstand 2000 kN loading. Another frame was fabricated and anchored to the floor slab to hold the specimen and provide adequate reaction against the pull of the actuator. Two LVDTs were fixed at the base of the steel bolt embedded in the concrete block to monitor the slip of the anchor, which was connected with the data logger which continuously records the reading at a frequency of 0.5Hz. Under monotonic loading effect, the rate of displacement control was 1.0mm/min.

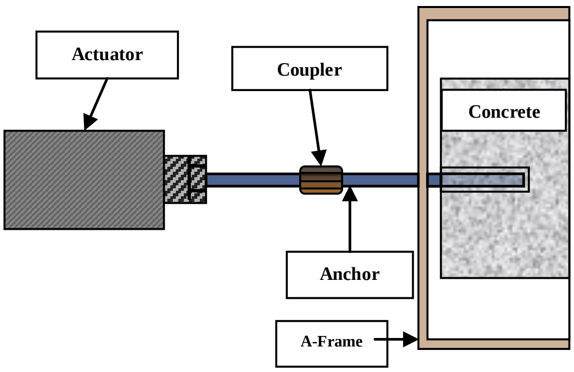

Figure 6: Experimental set-up.

5. RESULTS AND DISCUSSIONS

The strength of concrete adopted in this study was 25 MPa, 40 MPa and 60 MPa. The three embedment depths were 150mm, 200mm and 250mm maintaining the diameter of the anchor bars as 30mm. Three specimens without reinforcement anchored with 250mm embedment depths were also tested in order to compare the load carrying capacity and also to understand the failure modes. The specimens were tested for the ultimate load carrying capacity under monotonic load in tension. The variation of the load carrying capacity with compressive strength and embedment depth is studied. The load versus displacement responses are drawn considering the load as well as the displacement recorded.

5.1. FAILURE MODES

Under the action of monotonic tension on the anchored reinforced concrete, concrete splitting failure, as shown in Figure 7, in most of the specimens was observed. The tensile load was gradually applied under displacement control. As the load was applied, the initial load versus displacement response was appeared to be approximately linear. As the load increased further, a reduction in stiffness was observed. In plain concrete anchor specimens, there has been a sudden drop in the load carrying capacity due to sudden failure of concrete along the plane of cone cracking, while in RC anchor specimen, the load capacity was increased with the increase in the slip. As soon as the load the ultimate load, there has been a marginal drop in the load up to the ultimate deformation followed by a sudden drop in the load in all the cases due to concrete splitting failure. The behavior is virtually linear elastic up to ultimate load. However, in the post-peak region ductile behaviour was observed up to the ultimate deformation. The ultimate load carrying capacity has been found to increase and also matched well with that of the post installed mechanical anchors in almost all the cases.

Figure 7: Typical concrete splitting failure.

5.2. TEST RESULTS

Table 3 shows the ultimate load carrying capacity of anchors obtained in the experiments when loaded in tension. Figures 8 to 10 show the ultimate load carrying capacity of the anchors with 30 mm diameter with various strengths of concrete i.e. 25, 40, and 60 MPa. Figures 11 to 13 show the ultimate load carrying capacity of the adhesive/bonded anchors with 30 mm diameter bars with the variation of embedment depth i.e. 150, 200and 300 mm.

5.2.1. Influence of Strength of Concrete

Three different concrete strengths of 25MPa, 40 MPa and 60 MPa were adopted in this study. Figures 8 to 10 and Table 3 show the comparison of load carrying capacity with concrete strength at different embedment depths. As the strength of concrete increases, the load carrying capacity of the anchor increases. It is also known that the compressive strength of concrete is directly proportional to the tensile strength of concrete.

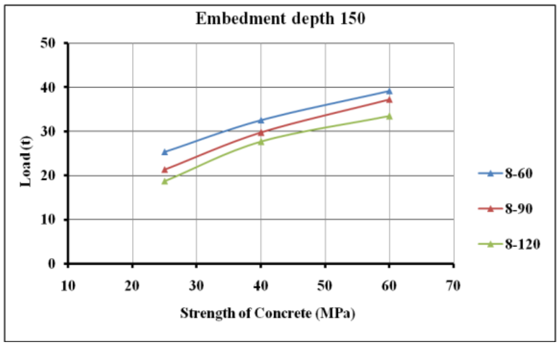

Figure 8: Load carrying capacity v/s strength of concrete at embedment depth 150mm.

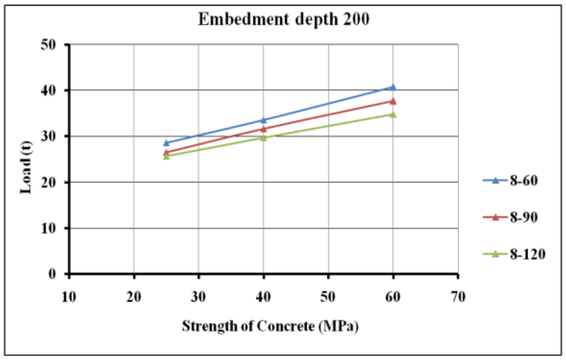

Figure 9: Load carrying capacity v/s strength of concrete at embedment depth 200mm.

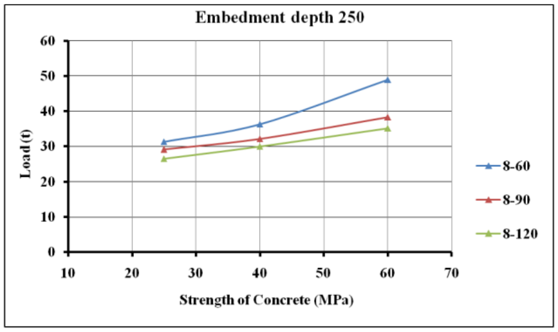

Figure 10: Load carrying capacity v/s strength of concrete at embedment depth 250mm.

5.2.2. Influence of Embedment depth

The embedment depths considered in this study were 150mm, 200mm and 250mm. As the embedment depth increases so does the magnitude of tensile load that can be resisted increases and therefore the load carrying capacity of the anchor increases. According to the CCD method, the load carrying capacity of anchors increases as a function of $h_{ef}^{1.5}$. As per the ACI 349, the load carrying capacity increases as a function of h_{ef}^{2}.The comparison of the experimental results with the CCD method as compared with the ACI code has been very similar. There is no significant difference in the stiffness with regards to the embedment depth.

Figures 11 to 13 show the effect of embedment depth on the load carrying capacity of adhesive anchors for a given concrete. In order to generalize the trend, the stress versus relative embedment depth was plotted as shown in Figures 14 to 16.

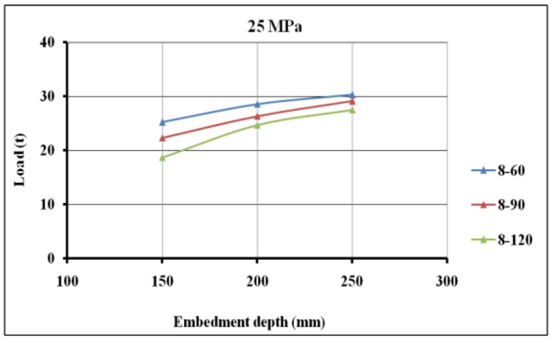

Figure 11: Effect of embedment with concrete strength 25 MPa.

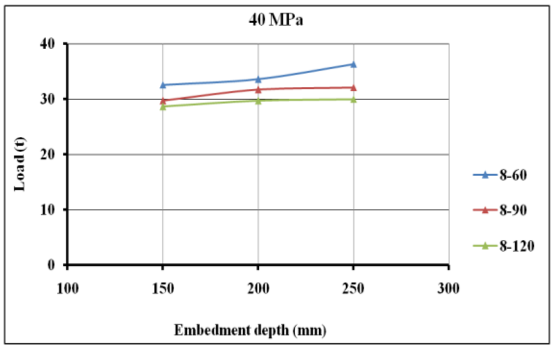

Figure 12: Effect of embedment depth with concrete strength 40 MPa.

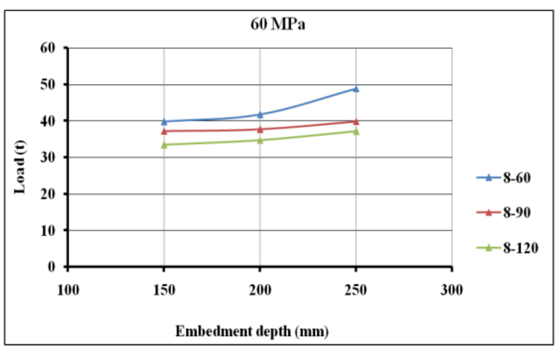

Figure 13: Effect of embedment depth with concrete strength 60 MPa.

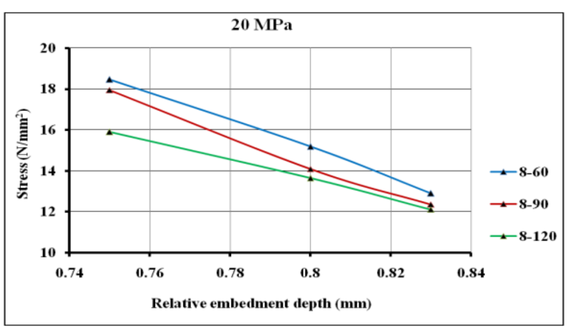

Figure 14: Stress v/s. Relative embedment depth with concrete strength 20 MPa

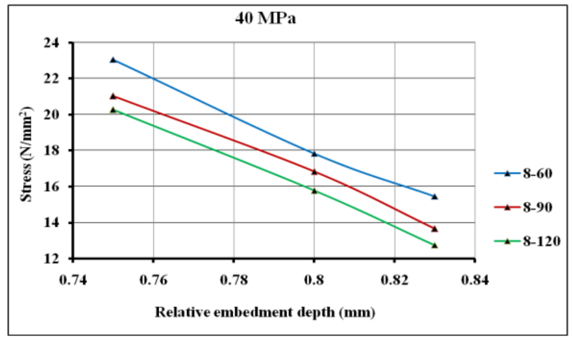

Figure 15: Stress v/s Relative embedment depth with concrete strength 40 MPa

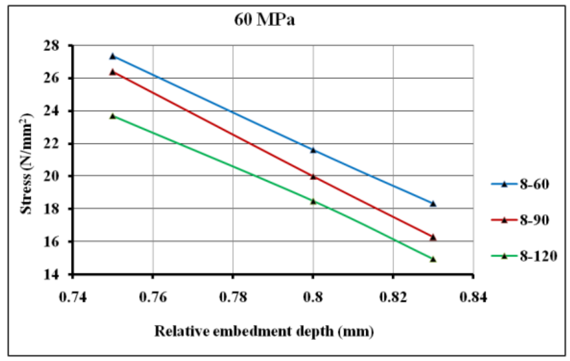

Figure 16: Stress v/s Relative embedment depth with concrete strength 60 MPa

5.2.3. Effect of Lateral Reinforcement

The quantity of lateral reinforcement was varied by varying the spacing of 8mm diameter bar. The three different values spacing of 8mm bars were 60mm, 90mm and 120mm. In plain concrete specimens, there has been a sudden drop in the load carrying capacity due to sudden failure of concrete along the plane of cone cracking. Figure 17 shows the load versus displacement response of the anchor specimen without reinforcement with embedment depth of 250mm loaded monotonically in tension. The lateral reinforcement enhances the confinement of the anchor block thereby preventing the cracking of concrete leading to cone failure. As the quantity of lateral reinforcement increased, the load carrying capacity of the anchor has also increased.

In reinforced concrete, the load increases proportionately with the increase in the slip. As soon as the load was reached its ultimate value, there has been a marginal drop in the load up to the ultimate deformation followed by a sudden drop in the load in all the cases due to concrete splitting. The behavior is virtually linear elastic up to ultimate load however following the peak load a ductile behavior is observed up to the ultimate deformation. The slip-stick region in graphs depicts the ductile behavior of anchor specimens.

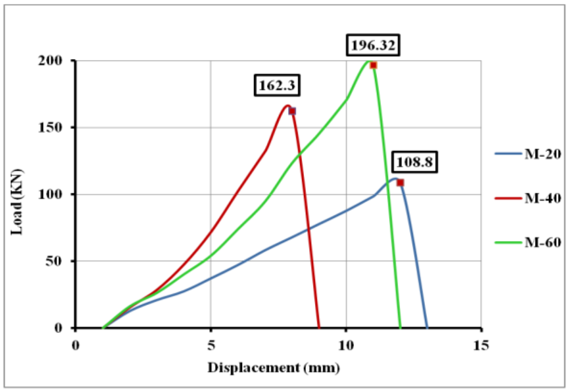

Figure 17: Load versus displacement for plain concrete anchor

Figures 18 to 20 show the load versus displacement response of the anchor loaded monotonically in tension with variation in the quantity of lateral reinforcement in 25 MPa concrete.

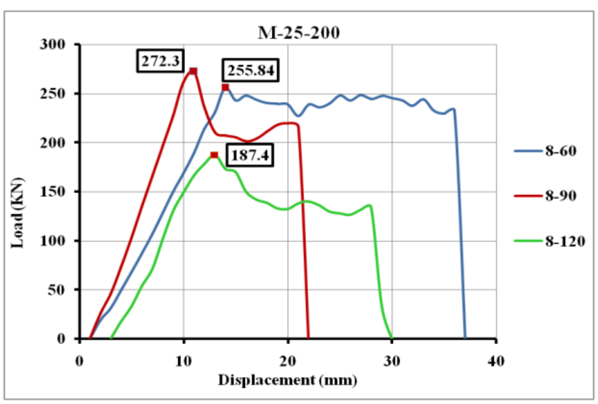

Figure 18: Load versus displacement for 25Mpa at 150mm embedment.

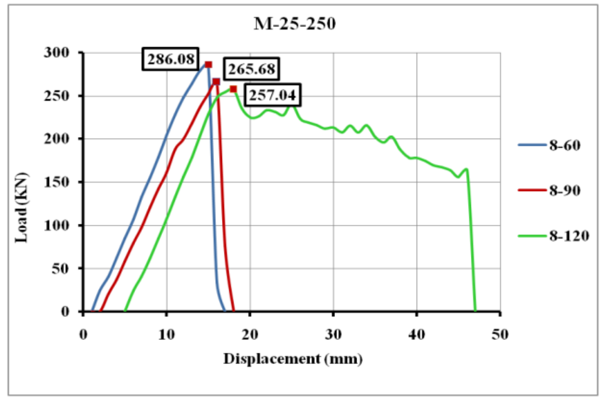

Figure 19: Load versus displacement for 25Mpa at 200mm embedment

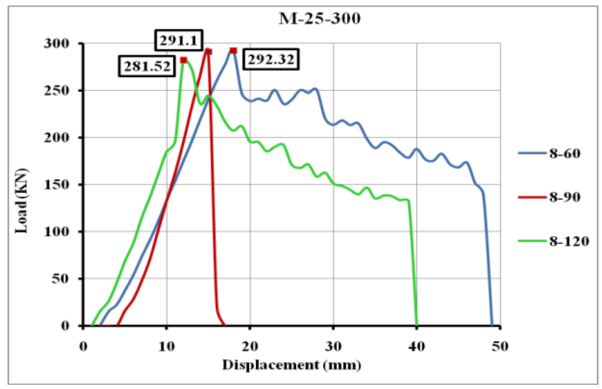

Figure 20: Load versus displacement for 25Mpa at 250mm embedment.

Figures 22 to 24 show the load versus displacement response of the anchor loaded monotonically in tension with variation in the quantity of lateral reinforcement in 60 MPa concrete.

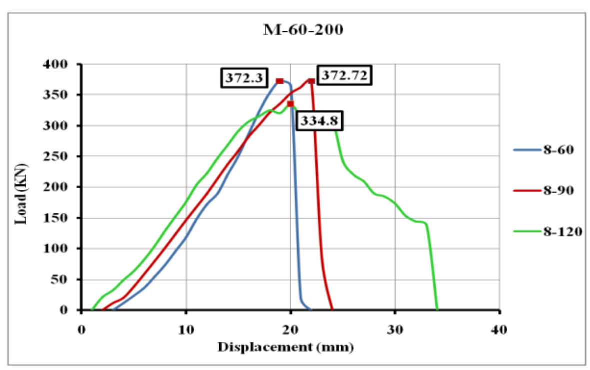

Figure 21: Load versus displacement for 60Mpa at 150mm embedment

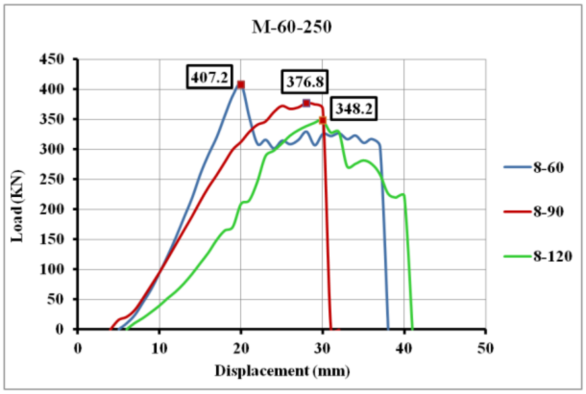

Figure 22: Load versus displacement for 60Mpa at 200mm embedment

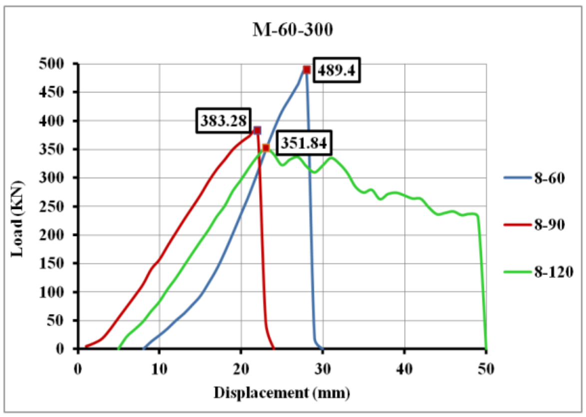

Figure 23: Load versus displacement for 60Mpa at 250mm embedment.

6. CONCLUSION

Following conclusions can be drawn from the experimental studies.

1. In plain concrete anchor specimens, there has been a sudden drop in the load carrying capacity due to sudden failure of concrete along the plane of cone cracking.
2. The lateral reinforcement provided has improved the confinement thereby increased the load carrying capacity of reinforced adhesive anchors to about 250% as compared to plain adhesive anchors.
3. Under the action of monotonic tension on the anchored reinforced concrete, concrete splitting failure in most of the specimens was observed.
4. The load carrying capacity increased proportionately with the increase in the slip. As soon as the load reached its ultimate stage, there has been a marginal drop in the load up to the ultimate deformation followed by a sudden drop in the load in all the cases due to concrete splitting.
5. The reinforced anchor specimen showed increase in the load carrying capacity with the increase in the strength of concrete and embedment depth.
6. The experimental observations were very close with the CCD design method as compared to the ACI-349 Code method with regards to the tensile load carrying capacity.

7. REFERENCES

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Table 3: Experimental observations (Capacity of anchors in tons).

S. No	Embedment depth (mm)	Strength of concrete (MPa)								
		25			40			60		
		8-60	8-90	8-120	8-60	8-90	8-120	8-60	8-90	8-120
1	150	25.24	25.37	18.7	32.58	29.71	28.63	37.23	37.27	33.48
2	200	28.60	26.56	25.70	33.61	31.70	29.72	407.2	37.68	34.82
3	250	29.32	29.11	28.52	36.38	32.16	300.2	489.4	38.32	35.18