Strength of bonded anchors in concrete in direct tension

G. Appa Rao
Associate Professor, Department of Civil Engineering
Indian Institute of Technology Madras, Chennai - 600 036, India
Email. garao@iitm.ac.in
B. Sundeep
Research Student, Department of Civil Engineering
Indian Institute of Technology Madras, Chennai - 600 036, India

Abstract

Bonded anchors are being used in several civil engineering applications, whose performance needs to be investigated. This paper discusses the experimental investigations made on the strength and failure modes of bonded anchors in concrete. 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 strengths of concretes namely 45 MPa, 52MPa and 52MPa were used along with three embedment lengths of 50mm, 100mm and 150mm. It has been observed that concrete cone failure was predominant in all the specimens. 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 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.

Keywords: Bonded anchors, direct tension, split and pullout failure, concrete.

1. Introduction

Anchorages to concrete can be classified in to two i.e. (i). Cast-in-place and (ii). Post-installed. Post-installed anchors may be either mechanical or bonded anchors, which are developed recently. Bonded anchors are used extensively in practice but have not yet been incorporated into the design provisions. An adhesive or bonded anchor is simply a reinforcement bar or a threaded rod inserted into a predrilled hole in the hardened concrete, whose diameter is slightly greater than the diameter of the anchor. Typically the drill hole diameter is only 10 to 25 percentage larger than the diameter of the reinforcing bar or threaded rod. The gap between the drill hole surface and the anchor surface is filled with an adhesive to be acting as a bonding agent between the concrete and the steel after setting and hardening. The adhesive for this type of anchors are available prepackaged in glass capsules or in dual-cartridge injection system. The anchors transfer the loads to concrete through mechanical interlock, friction, chemical bond or combination thereof. The anchorages facilitate 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 must be designed to ensure durability and robustness, and should also exhibit 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. The design of anchorages using cast-in-place and post-installed mechanical anchors is discussed in ACI 318-08 in Appendix D.

2. Review of literature

Under the loads, when the tensile stress on a critical plane in concrete exceeds its tensile strength, the failure occurs due to concrete cone breakout *(Eligehausen, 1984)*. The theoretical estimates of the load-bearing capacity of fastenings are initially based on the assumption that the concrete behaves elastically in compression and tension, which results in the principal compressive and tensile stresses considerably higher than the uni-axial compressive and tensile strength of concrete *(Weyerhaeuser, 1977; Pusill-Wachtsmuth, 1982)*. This is due to the fact that relatively small load transfer area, high deformation gradients and stresses occur locally, that lead to micro cracking in concrete. Therefore, the load bearing capacity of anchors can be described with sufficient accuracy by using nonlinear response of concrete. *Elfgren et al. (1982)* investigated numerically the behavior of headed stud with an embedment depth h_{ef} = 300 mm in tension in concrete through displacement control using discrete crack approach. At low load levels, circumferential tensile cracks form in concrete initiating at the head of the stud. The cracks form along conical plane and the incremental crack growth transects an ever larger area as the length increases. For this reason crack growth remains stable up to the ultimate load. At the ultimate load, the length of the crack is approximately 50% of the total length of the final concrete cone. As the deformation at the ultimate load exceeds, the crack becomes unstable, which leads to final concrete cone. *Eligehausen and Clausnitzer (1983)* 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.

Peier (1983) investigated the behavior of headed studs, expansion and bonded anchors in tension using a nonlinear finite element program. Simulated was a pullout test with large spacing between fastener and support. When the tensile strength in a finite element was reached, a zero stress crack was initiated in that element, smeared across the width of the element. *Seghezzi (1986)* described the failure of torque-controlled expansion anchors. A hydrostatic pressure condition in concrete was established in a small zone around the expansion shell of the anchor. A system of circumferential tension cracks run from the load transfer zone to the surface of the concrete. Radial cracks also form at the surface. If the expansion sleeve is sufficiently large and thick, then a concrete cone failure is the result when the circumferential tension cracks reach almost to the surface of the concrete. If the expansion shell is too small and/or too thin, then concrete outside the pulverised zone fails in compression and the anchor is pulled out.

Sawade (1994) developed a model for describing the process of cracking in concrete in tension in which the crack propagation and the crack widening are considered as time-dependent associated with energy dissipation. The specific surface energy is a function of the crack width and deformation zone, crack trajectory, crack width and plastic deformation as the mechanical variables. *Fuchs (1995)* 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. The comparison showed that the CCD method predicts the concrete failure load very well, which also included the adhesive anchors. *DeVries (1999)* conducted several tests on headed reinforcement with low ratios of embedment depth-to-edge distance (shallow embedment) and studied the effect of several variables on anchorage behavior. Based on the results, a design procedure was proposed. *Cook, Kunz and Fuchs (1998) reported that a* constant bond stress develops over the embedment depth and the bond strength is independent on the embedment depth. Procedure for the evaluation of the ultimate bond failure in adhesive anchor was set.

Cook (2001) 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 (2006)* compared the model proposed for the concrete cone breakout failure by *Fuchs (1995)* for single cast-in-anchors and post-installed mechanical anchors with that of *Cook et al. (1998)* 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 *(Cook et al. 1998). Eligehausen et al. (1999) reported* that the failure load of a single bonded anchor is limited by the load corresponding to the concrete cone break out failure. This is confirmed through experimental and numerical studies (*Meszaros and Mc Vay et al. 1999***).** 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,

In concrete cone breakout failure, the slope measured from the horizontal surface and averaged over the circumference lies between 30° and 40°. It increases with increasing embedment depth *(Zhao,* 1993). Compressive or tensile stresses acting in concrete perpendicular to the direction of the anchor load cause the slope of the failure surface to be steeper or shallower, respectively. Noting that the effective embedment depth, h_{ef} designates the distance between the surface of the concrete and the end of the force transfer zone, the depth of the concrete breakout surface varies between $0.8h_{ef}$ *to* h_{ef} for mechanical expansion anchors. According to *ACI 349 (1990),* 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. Yield theory was employed by *Braestrup, Nielsen, Jensen, Bach (1976)* to calculate the concrete cone breakout load of headed studs. However, concrete in tension does not exhibit the elasto-plastic behavior as assumed in this theory. Therefore, an artificial low concrete tensile strength is used to calibrate the calculated failure loads based on the test results.

In CCD Method (Fuchs, 1995), 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 Committee 349 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

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

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

$$N_u = \frac{\pi d^2}{4} f_y \tag{5}$$

Where d = diameter of the anchor, and $f_{y\,=}$ yield strength of steel

Strength of anchor in terms of failure of steel is well documented. In this attempt, the design of anchor specimens was based on only concrete cone break out using 30mm diameter anchors. Strength of Anchor corresponding to steel fracture, $f_y A_{st}$ = 640 x 706.85 = 451940 N = 45 T. Strength of anchor due to bond failure, $N_u = \tau \pi d\, h_{ef}$. Table 1 shows the bond strength of anchors for different embedment depths.

Table 1. Bond strength of Anchors at various embedment depths

S.No.	h_{ef} *(mm)*	*Bond Strength (Tons)*
1	*50*	*7.07*
2	*100*	*14.14*
3	*150*	*21.21*

3. Experimental program

43 grade ordinary Portland cement was used for this study. 20mm nominal maximum size coarse aggregate was used. The mix proportions for the above three concretes are given below. The strengths of concrete adopted were 45 MPa, 52 MPa and 62 MPa and the three embedment depths were 50mm, 100mm and 150mm maintaining the diameter of the anchor bars as 30mm. With three embedment depths in three different concretes, total twenty seven specimens were produced. For each result, average of three specimens is reported. Two specimens were tested with 52 MPa concrete at 150mm embedment depth using 20mm diameter anchors. In order to study the influence of anchor

diameter, 52 MPa strength concrete was used with 20mm diameter anchors at 150 mm embedment depth.

Two different diameters of anchors i.e. 30mm and 20mm were used in this study. The nominal yield strength of the anchors was 640 N/mm^2. Adhesive material was used to fill the clearance between the anchor bar surface and the surrounding concrete. The adhesive was injection type RE500 adhesive and has mean bond strength of 15N/mm^2. In plastic cartridges containing pre-measured amounts of resin and hardener allow controlled proportion and 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.

3.1. Preparation and testing of specimen

The wooden moulds were prepared to cast three different sizes of concrete specimens to maintain three different embedment depths. The mould inner surfaces were lubricated with oil for easy demolding. Fresh concrete was poured vertically from the top without segregation. Needle vibrator was used to compact the fresh concrete. After 24 hours the specimens were demolded from the formwork and cured for 28 days. The drill holes for 30mm and 20mm diameter anchors were made in the concrete up to the embedment depths of 50mm, 100mm and 150mm using 35mm and 24mm drill bits respectively. The drilled holes were cleaned with hand pump to blow out the concrete dust in the hole and wire brushes were also used to remove the dust on the concrete surface. Subsequently, the drilled hole was washed with potable water and cleaned to dry under shade for about two days. The anchor rods were mounted with electrical resistance strain gauges at the middle of the embedment length as shown in Figure 1. The drilled hole was filled with adhesive using injection type installation up to 2/3rd depth. The adhesive was cured and allowed for 48 hours for it to set.

Figure 1. Concrete specimens, anchors and mounting of strain gauges.

The three specimen sizes are; 300mm x 300mm x 200mm, 500mm x 500mm x 250mm and 500mm x 500mm x 300mm with embedment depths of 50mm, 100mm and 150mm respectively. Since two sets of the specimens were identical in plan dimensions, only two reaction frames were used to test the specimens. In addition on the day of testing, three concrete cubes were also tested to determine its compressive strength. The parameters studied in this programme are strength of concrete, embedment length and diameter of anchor bar i.e. 30mm, 20mm.

All the anchorage specimens were tested under monotonic tensile loading until failure. Displacement was increased through actuator to prevent the dynamic effect. The load was applied to the anchors by the actuator. The actuator was supported to a strong testing frame. The concrete block was fixed by a reaction frame anchored to the strong floor thus preventing the uplifting of the concrete block. The experimental set-up was fabricated for testing the anchored concrete specimens through displacement controlled actuator as shown in Figure 2.

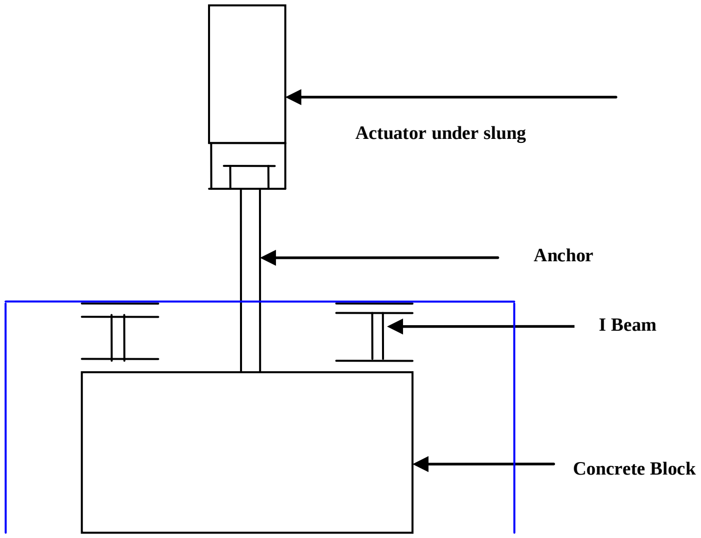

Figure 2. Experimental set-up.

A 500 kN capacity actuator was used to apply the load in the anchor rod. Two LVDTs were fixed at the base of the steel bolt embedded in the concrete block to monitor the anchorage slip. LVDTs and strain gauge were connected with a data logger to continuously record the reading at a frequency of 0.5Hz. Under monotonic loading, the rate of stroke control was 1.51mm/min (i.e. 0.025mm/sec).

4. Results and discussions

4.1. Failure modes

The monotonic load was increased to measure the slip of the anchor. At the ultimate load, there has been a sudden drop in the load in all the specimens due to concrete cone break out failure. The ultimate strength of the bonded anchors matches with that of the post-installed mechanical anchors estimated from the theoretical expression available. At 50mm embedment depth, the ultimate load carrying capacity was found to be greater than that of the post-installed mechanical anchors. There has been an increase of about 20 to 30% of the ultimate load at this embedment depth. At larger embedment depths, the ultimate load carrying capacity of the bonded anchors matches well with the load carrying capacity of the post-installed mechanical anchors. The bonded anchors exhibited concrete cone break out failure as shown in Figure 3.

Figure 3. Concrete cone break out failure at an angle of 45 degrees at 50 mm embedment depth.

Out of twenty nine tests, only three tests with 150mm embedment depth exhibited combination of concrete cone and splitting failure. The angle of cone with the failure surface is about 45 degrees with 50mm embedment depth. At 100mm and 150mm embedment depths, the angle of failure plane was varied between 30-40 degrees. No traces of bond slip failure were found up to 150mm embedment depths.

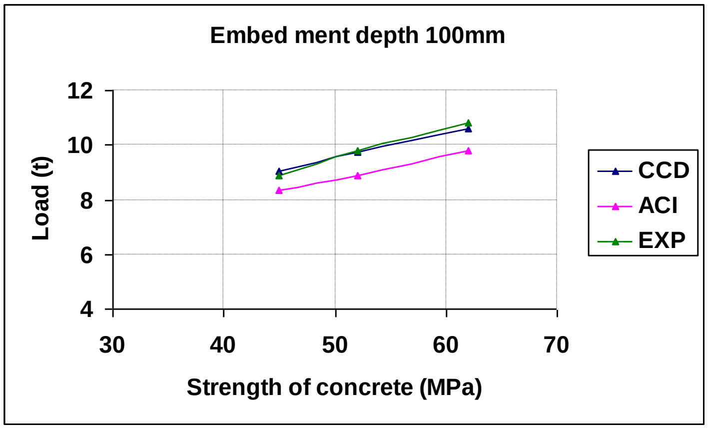

Figure 4. Load vs. Strength of concrete at embedment depth 50mm

.

4.2. Influence of strength of concrete

The results are correlated with three different concrete strengths of 45MPa, 52 MPa and 62 MPa. As the strength of concrete increases, the load carrying capacity of the anchor increases. The compressive strength of concrete is directly proportional to the tensile strength of concrete. The load carrying capacity with concrete cone failure can be estimated by both the CCD method and the ACI-349 method, which provide design expressions as directly proportional to $f_{cc}^{0.5}$. Figures 4 to 6 show the capacity of anchors with different concrete strengths with different embedment depths of 50mm, 100mm and 150mm respectively.

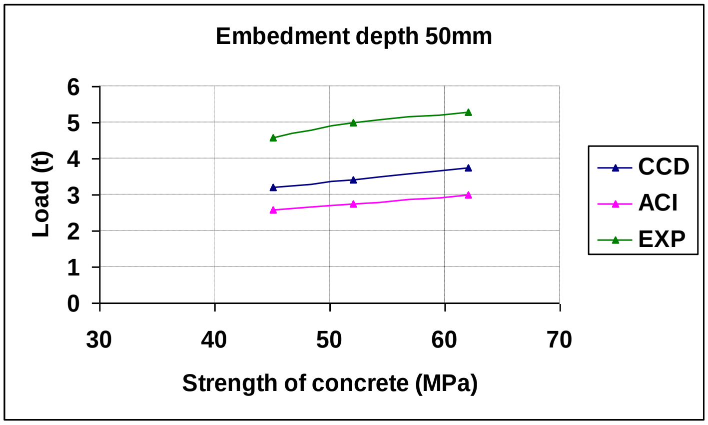

Figure 5. Load vs. Strength of concrete at embedment depth 100mm.

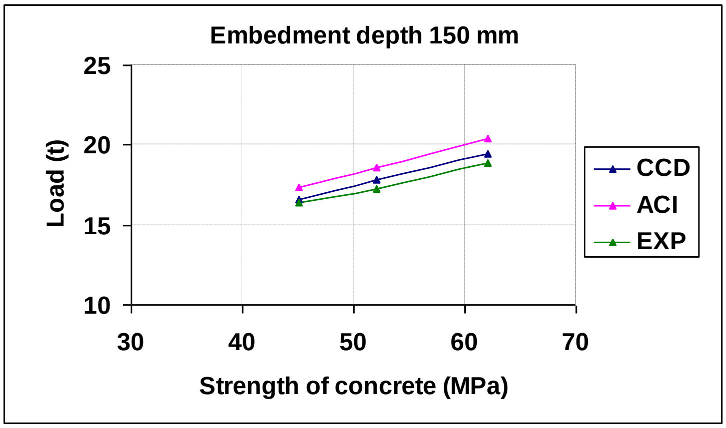

Figure 6. Load vs. Strength of concrete at embedment depth 150mm.

4.3. Influence of embedment length

Three embedment lengths of 50mm, 100mm and 150mm were adopted. As the embedment length 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 method, the load carrying capacity increases as a function of h_{ef}^{2}. The comparison of the experimental results with both the CCD method and the ACI 349 method has been observed to be very similar. This shows that the variation of concrete cone strength is more close to the proportion of $h_{ef}^{1.5}$ given by the CCD method. At small embedment depth i.e. 50mm, the strength is higher than those given by the CCD method and the ACI-349 report. However, the experimental results are very closer to that of the CCD method. The ACI-349 report underestimates the strength by about 40-45%, whereas the CCD method underestimates the load carrying capacity by about 25-30%. At larger embedment depths, the strength of anchors was much closer to the CCD method with a deviation of 2 to 5%, whereas the deviation from ACI-349 method is 7 to 10%. The comparison of the experimental results with the existing methods shows that there has been no significant difference in the stiffness with regards to the embedment depth. Figures 7 to 9 show the capacity of anchors with different embedment depths of 50mm, 100mm and 150mm respectively at various concrete strengths of 45 MPa, 52 MPa and 62 MPa. At larger embedment depth failure mode may change to fracture of steel or bond failure, the diameter of the anchor is expected to influence the tensile capacity of the anchor.

4.4. Effect of bar diameter

Anchors were tested with embedment depth of 150mm in 52 MPa concrete using 20mm and 30mm diameter anchor bolts. There has been no significant influence of bar diameter on the capacity of the bonded anchor. The CCD method does not mention the influence of anchor diameter on the anchor capacity, whereas the ACI 349 method for determining anchor capacity includes the anchor diameter.

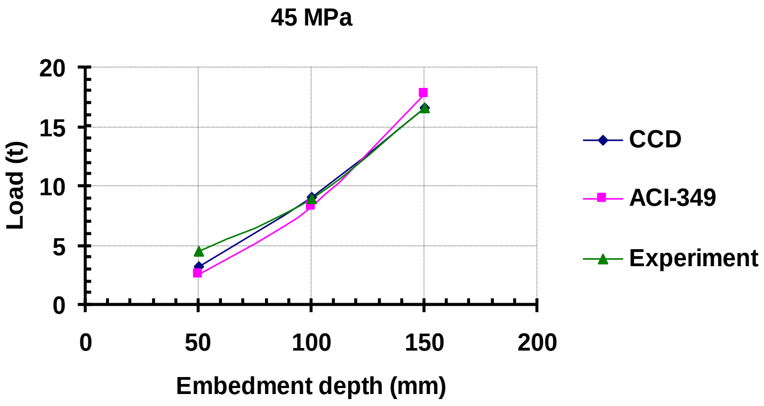

Figure 7. Load vs. Embedment with 45 MPa concrete.

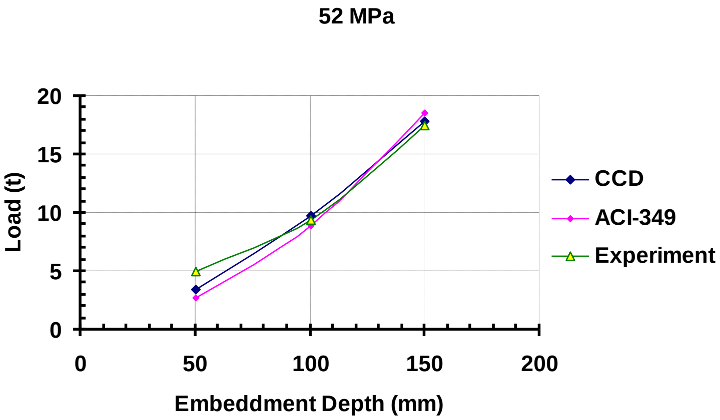

Figure 8**.** Load vs. Embedment depth with 52 MPa concrete.

Figures 7 to 9 show the ultimate carrying capacity of the bonded anchors with 30 mm diameter at various embedment depths of 50, 100and 150 mm. The tension in the anchor was gradually applied under stroke control. As the load was applied the initial load versus displacement response was linear. As the load increased further, a reduction in stiffness was observed. There has been a sudden drop in the load carrying capacity due to sudden failure of concrete along the plane of concrete cone break out. The displacement at the ultimate load was very small and a minor reduction in the displacement at ultimate load was observed as the strength of concrete increased at a given embedment depth.

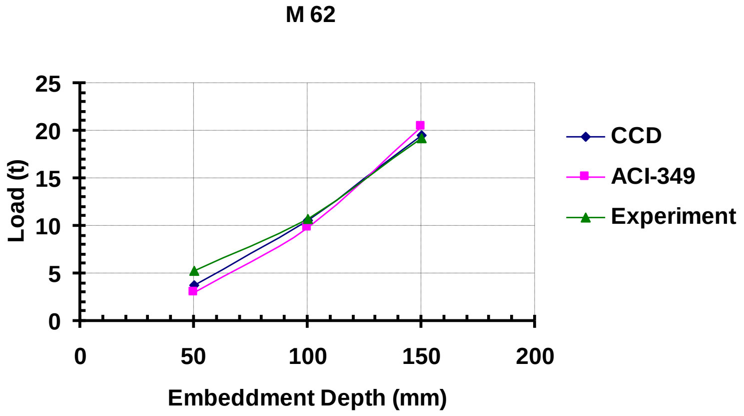

Figure 9. Load vs. Embedment depth with 62 MPa concrete.

5. Conclusion

The failure load on the bonded anchors was limited by the concrete cone break out failure. The load carrying capacity and the behavior of the bonded anchors is comparable with that of the post-installed mechanical anchors estimated as per both CCD and ACI 349 methods. As the strength of concrete increases, the anchorage carrying capacity was also found to increase. As the embedment depth of the anchor increases, the load carrying capacity of the anchorage has been observed to increase. The effect of diameter was not significant on the limited study on two anchor diameters of 30mm and 20mm on the load carrying capacity of the anchor. The load carrying capacity of the bonded anchors has been observed to be very close to that of the CCD design method as compared to the ACI-349 method.

References

Eligehausen R., Clausnitzer (1983), "*Tensile behavior of expansion anchors",* ACI Journal, Report No. 1/4-84/1.

Eligehausen R., (1993), "*Design and Testing of Anchors in cracked concrete*", ACI SP 130-5, Editors Senkin G. A., Lancelot H. B. , pp. 123-144.

Fuchs, W ,Eligehausen ,R and Breen, J.E. (1995), "*Concrete Capacity Design (CCD) approach for Fastening to Concrete*", ACI Structural Journal, V. 92, N. 1, Jan-Feb, 1995, pp 73 - 94.

Cook, R.A., Kunz, J., Fuchs, W. (1998), “*Adhesive anchor under tensile loading*”, ACI Journal, Jan –Feb 1998, pp. 9 - 25.

Cook, R.A. and Konz, R.C. (2001), “*Factors Affecting Bond Strength of Adhesive Anchors*”, ACI Structural Journal, V. 98, N. 1, pp. 76 - 86.

ACI Committee 355 Report (2001): “Evaluating the Performance of Post-Installed Mechanical Anchors in Concrete”, ACI, Farmington Hills, Michigan.

ACI 318 (2005), “*Building Code Requirement for Structural Concrete (ACI-318-05) and commentary (318R-05*)”, ACI, Farmington Hills, Michigan

Eligehausen, R., Mallee, R., Silva, J. (2006), “*Anchorages in Concrete*”, Ernst and John, ISNB13, ISNB10.