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Tensile Behavior of Cast-in-Place and Undercut Anchors in High-Strength Concrete

  

by Eric J. Primavera, Jean-Paul Pinelli, and Edward H. Kalajian

This paper deals with the pullout capacity, the failure cone geometry, and the load deformation behavior for both cast-in-place and post installed undercut anchors embedded in high-strength concretes with compressive strengths of 7500 and 12000 psi. Cast-in-place anchors where embedded at depths of 4, 6, and 8 in., whereas the undercut anchors were only embedded at a depth of 8 in.. Shallow cone failure angles, ranging from 21 to 28 deg, occurred consistently for all cases regardless of embedment depth, contradicting the 45 deg cone assumed in many design methods. For cast-in-place anchors, current design methods (such as CCD, ACI 349, TVA, TRW-Nelson) over predicted anchor pullout capacity. Over prediction of pullout capacity increased with increasing concrete compressive strength. For the post-installed anchors, the CCD model under predicted anchor pullout capacity, whereas the ACI model over predicted anchor pullout capacity.

Keywords: anchors; anchorage; failure cone; embedment; fasteners; high-strength concrete; pullout capacity; tensile capacity (strength);

INTRODUCTION

One of the most essential parts of any structural system are the connections which transfer load between members. Anchors embedded in concrete, cast-in-place or post-installed, are one of the most prominent examples. They can be used to attach structural elements to a concrete foundation. Steel beams may be attached to a concrete column or wall. Headed anchors with couplers can be utilized to splice conventional rebars for connections of reinforced concrete beams and columns, and for precast elements. Anchors can be fabricated from reinforcing bars, bolts, studs, shear lugs, and many variations of structural shapes and fabricated steel sections.[1]

Previous tension test data presented in the ACI Tension Data Base, which includes both American and European results, TRW-Nelson test reports,[2] and the recent deep anchor investigation conducted at Bucknell University[3] have been conducted with compressive strengths which typically do not exceed 5000 psi (34.5 MPa). However, although the use of high-strength concrete is becoming common practice, the behavior of anchors embedded in high-strength concrete has not been fully investigated. In an effort to remedy this situation, the performance of cast-in-place and post-installed anchors embedded in high-strength concrete with compressive strengths of 7500 psi (51.7 MPa) and 12000 psi (82.7 MPa), subjected to direct tension without shear, have been evaluated. The results of this research are presented in this paper.

RESEARCH SIGNIFICANCE

Prior to this study, limited tests had been conducted to determine the pullout capacity of anchors embedded in high-strength concrete (> 5000 psi). The data obtained in this program correlates pullout capacity for both cast-in-place anchors and undercut anchors to concretes with a compressive strength of 7500 to 12000 psi using calcareous limestone aggregate without the addition of pozzolanic material.

SCOPE

The objective of this study was to investigate the direct tensile behavior, particularly the pullout capacity, of both single cast-in-place anchors with embedment lengths varying from 4 to 8 in. (102 to 203 mm) and single post-installed undercut anchors with an 8 in. (203 mm) embedment, utilizing high-strength concrete. This investigation contributes to the discussion of current procedures utilizing anchors embedded in high-strength concrete. Pullout capacity, load deformation, failure cone geometry, and the validity of common design methods, particularly ACI 349 and the Concrete Design Capacity (CCD) methods,[4] are presented.

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Eric J. Primavera *is a structural engineer at Gee & Jenson, E.A.P. Inc.. He received his MS and BS in Civil Engineering at the Florida Institute of Technology. His masters research utilizing cast-in-place and undercut anchors in high-strength concrete was the foundation of this publication.*

Jean-Paul Pinelli *is an Assistant Professor in the Civil Engineering Program at the Florida Institute of Technology. He studied at the University of Buenos Aires, and received his PhD from the Georgia Institute of Technology in 1992. He has published several papers related to precast cladding connections.*

Edward Kalajian *is a Professor in the Civil Engineering Program, and Director of the Division of Engineering Sciences at the Florida Institute of Technology. He received his PhD from the University of Massachusetts in 1971.*

TESTING PROGRAM

Testing Methodology

In order to investigate the strength of the concrete for anchors in direct tension, the tensile strength of the steel in these anchors was designed to be greater than the predicted concrete strength to ensure that a cone failure occurred in the concrete section. Anchor testing was accomplished after the concrete had cured for a minimum of 28 days and the minimum spacing and edge distance requirements as designated in the revised version of ASTM E488[5] were satisfied. Steel reinforcing bars were only utilized along the bottom of each test slab, away from the test anchor, to prevent a premature failure of the concrete section. The thickness of each test slab was three times the embedment depth.

Material properties of concrete

The initial intent was to test anchors installed in three distinct commercially available concrete compressive strengths, referred to as target strengths. Table 1 summarizes the concrete mix design proportions for each case. Although the mix design parameters varied for each case, the final values for the compressive strengths at the time of testing were approximately 7500 psi (51.7 MPa) for the first mix, and 12000 psi (82.7 MPa) for the remaining two mixes.

Cast-in-place and post-installed anchors

Anchors which are installed prior to the placement of concrete are considered to be cast-in-place. Typical examples of cast-in-place anchors are structural bolts like A490 standard high-strength bolts (see Fig. 1[a]). Other typical cast-in-place anchors include flush mounted anchors, internally threaded for a bolt, like the SAE 3 anchors (see Fig. 1[b]). These anchors are commonly secured to the formwork.

Anchors that are installed in pre-drilled holes after the concrete has cured to the desired compressive strength can be adhesive, expansion, or undercut anchors. Undercut anchors have mechanical parts which spread as the fastener is installed, conforming to a wedge cut at the desired depth within the pre-bored concrete hole. A typical undercut anchor is the post-installed Swedge Bolt, shown in Fig. 1(c), with an inverted conical undercut (ICU). Adhesive and expansion anchors were not included in this study.

A total of 75 anchors were tested, including 60 cast-in-place and 15 undercut (post-installed). Table 2 details the type of anchors tested and the corresponding embedment depths which varied between 4 (102 mm), 6 (152 mm), and 8 in. (203 mm).

TESTING PROCEDURE

Loading equipment

The testing apparatus shown in Fig. 2 was used to simulate a pure tension load for a particular concrete section. A mechanical coupler, shown in Fig. 3, was constructed from steel plates to transfer the applied load from a loading rod to the test anchor. The tensile load was applied by a 100 ton (890kN) capacity hollow cylinder jack. Hydraulic pressure was supplied by an electric pump.

Instrumentation

A pressure transducer was connected to the hydraulic jack to determine the applied load. Displacement was determined by a spring loaded linear variable differential transducer (LVDT) positioned directly over the test anchor by an equal

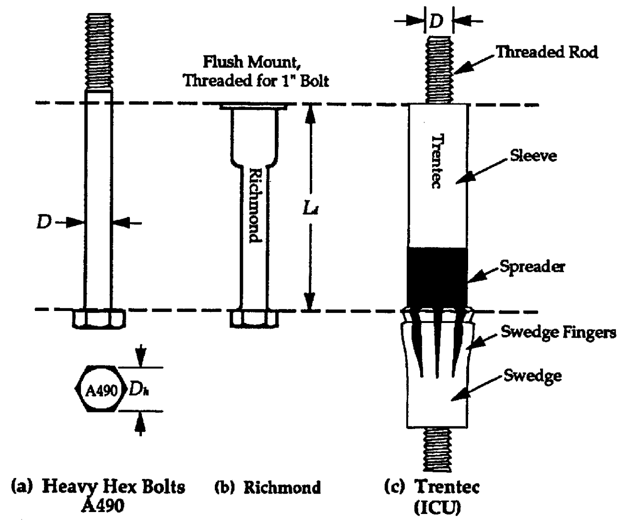

Fig. 1—Types of anchors tested

Table 1—Concrete mix design proportions

Mix design parameters per cubic yard		Compressive strength for each test group, psi (MPa)		
	Target	4000 to 5000 (28 to 34)	7000 to 8000 (48 to 55)	≥ 10000 (≥ 69)
	Actual	7500 (51.7)	12000 (82.7)	12000 (82.7)
		A,H,I	C,F,G	B,D,E
Portland cement Type I/II, lb (kg)		580 (263)	846 (384)	987 (448)
Coarse aggregate, lb (kg)		1530 (694)	1650 (748)	1650 (748)
Fine aggregate, lb (kg)		1307 (593)	1240 (562)	1050 (476)
Water reducer, fl. oz. (cc)		41 (1212)	34 (1005)	39 (1153)
High range water reducer, fl. oz. (cc)		3 (88)	NA	NA
Air entrainment agent, fl. oz. (cc)		NA	118 (3489)	138 (4081)
Water, lb (kg)		300 (136)	267 (121)	275 (125)
Water-cement ratio by weight		0.52	0.32	0.28

NA = Not applicable for this concrete mix design
† Florida pearock calcareous limestone with ASTM No. 89 gradation (approx. maximum particle size of 3/8 in. (9.5 mm)

leg angle (see Fig. 3). The angle was supported away from the expected failure cone, and was not in contact with any other structural member which could have produced inaccurate displacement readings. Both the pressure transducer and LVDT were excited by a strain gage conditioner and amplification unit. Digital data was acquired by a computer data acquisition system.

EXPERIMENTAL RESULTS

Failure modes

All embedment failures in this investigation were brittle concrete failures, meaning abrupt failures with no prior noticeable or significant amount of yielding of the anchoring system. In each case, a distinct popping noise accompanied the rupture point. For each test, the peak load corresponded to a rupture of a conical section of the concrete. This peak load defined the pullout capacity of the anchor. Table 2 (AtoF) lists all the test results. The mean pullout capacities and COVs were obtained for each test group and are also given in Table 2.

Load deflection results

The load deformation behavior of each anchor tested was defined by a load-deflection curve. A thorough presentation and discussion of the load deformation behavior is presented by Primavera.[6] The results were evaluated with respect to concrete strength, stiffness, embedment length, and anchor type, and they were compared to test data from other sources. The load deflection results are summarized in Tables 3 to 5. Representative load deflection curves are also presented in Fig. 4 to 8.

Influence of Concrete Strength

Table 3 summarizes the influence of concrete strength on the load deflection behavior of specific anchor types, for different embedment lengths. The load deflection curves are plotted in Fig. 4 to 6 for the 8 in. (203 mm) A490, flush mounted, and ICU anchors respectively. It should be noted

Table 2 (A)—Summary of test results

Test anchor	Ultimate deflection, in.	Ultimate load, lb
ICU: f'_c = 7375 psi; f'_{sp} = 604 psi; L_d = 8 in.; D_h = 2.75 in.; D = 1.25 in.		
A-1	0.079	85544
A-2	0.071	82587
A-3	0.107	94575
A-4	0.079	74545
A-5	0.082	84216
Mean	0.084	84293
Std. dev.	0.012	6407
COV, percent	14.7	7.6
A490: f'_c = 7375 psi; f'_{sp} = 604 psi; L_d = 8 in.; D_h = 2 in.; D = 1.25 in.		
A-6	0.08	76318
A-7	0.062	72626
A-8	0.055	73819
A-9	0.081	81195
A-10	0.096	80228
Mean	0.075	76837
Std. dev.	0.015	3394
COV, percent	19.6	4.4
Flush Mount: f'_c = 7375 psi; L_d = 8 in., D_h = 1.75 in.; D = 1 in.		
A-11	0.07	68036
A-12	0.073	72128
A-13	0.068	72855
A-14	0.101	71127
A-15	0.057	69079
Mean	0.074	70645
Std. dev.	0.015	1821
COV, percent	19.8	2.6

Table 2 (B)—Summary of test results

Test anchor	Ultimate deflection, in.	Ultimate load, lb
ICU: f'_c = 11722 psi; L_d = 8 in.; D_h = 2.75 in.; D = 1.25 in.		
B-1	0.068	87058
B-2	0.082	96356
B-3	0.068	85007
B-4	0.072	87424
B-5	0.072	92307
ICU: f'_c = 11234 psi; L_d = 8 in.; D_h = 2.75 in.; D = 1.25 in.		
C-1	0.081	92078
C-2	0.079	88104
C-3	—	—
C-4	0.081	94907
C-5	0.099	106037
Mean†	0.078	92142
Std. dev.	0.009	6810
COV, percent	11.2	7.4

† The mean, standard deviation, and COV consider both of the above groups since they essentially have the same compressive strength.

Table 2 (C)—Summary of test results

Test anchor	Ultimate deflection, in.	Ultimate load, lb
A490: f'_c = 11722 psi; L_d = 8 in.; D_h = 2 in.; D = 1.25 in.		
B-6	0.043	85895
B-7	0.051	81900
B-8	0.044	78058
B-9	0.051	84763
B-10	0.038	71811
A490: f'_c = 11234 psi; L_d = 8 in.; D_h = 2 in.; D = 1.25 in.		
C-6	0.05	91742
C-7	0.045	86737
C-8	0.046	93381
C-9	0.05	89038
C-10	0.045	87814
Mean†	0.046	85114
Std. dev.	0.002	2500
COV, percent	5.1	2.9

† The mean, standard deviation, and COV consider both of the above groups since they essentially have the same compressive strength.

Table 2 (D)—Summary of test results

Test anchor	Ultimate deflection, in.	Ultimate load, lb
Flush Mount: f'_c = 11722 psi; f'_{sp} = 684 psi; L_d = 8 in.; D_h = 1.75 in.; D = 1in.		
B-11	0.055	78070
B-12	0.065	82114
B-13	0.082	81857
B-14	0.068	78763
B-15	0.063	77219
Flush Mount: f'_c = 11234 psi; f'_{sp} = 750 psi; L_d = 8 in.; D_h = 1.75 in.; D = 1in.		
C-11	0.109	87769
C-12	0.086	84241
C-13	0.102	85623
C-14	0.066	81583
C-15	0.102	86438
Mean†	0.080	82368
Std. dev.	0.018	2625
COV, percent	22.9	3.2

† The mean, standard deviation, and COV consider both of the above groups since they essentially have the same compressive strength.

Table 2 (E)—Summary of test results

Test anchor	Ultimate deflection, in.	Ultimate load, lb
A490: f'_c = 11951 psi; L_d = 4 in.; D_h = 1.25 in.; D = 0.75 in.		
D-1	0.019	26021
D-2	0.021	26547
D-3	0.016	25126
D-4*	0.014	18361
D-5	0.017	26146
D-6	0.025	24783
A490: f'_c = 12042 psi; L_d = 4 in.; D_h = 1.25 in.; D = 0.75 in.		
F-1	0.02	24458
F-2†	0.025	25240
F-3†	0.021	23050
F-4*†	0.042	20975
F-5†	0.061	25450
F-6†	0.044	26175
Mean‡	0.027	24361
Std. dev.	0.014	2448
COV, percent	52.8	10.0
A490: f'_c = 7451 psi; f'_{sp} = 719 psi; L_d = 4 in.; D_h = 1.25 in.; D = 0.75 in.		
H-1	0.026	25336
H-2	0.034	27703
H-3	0.046	28475
H-4*	—	—
H-5	0.033	26780
H-6	0.042	27186
Mean	0.036	27096
Std. dev.	0.008	1170
COV, percent	21.8	4.3

* This anchor is a galvanized A325 bolt. Except as indicates, all other anchors are A490.
† Deflection values for these test anchors are questionable. The mean and standard deviation for deflection only consider anchors D-1 to D-6 and F-1
‡ The mean, standard deviation, and COV consider both of the above groups since they essentially have the same compressive strength.

Table 2 (F)—Summary of test results

Test anchor	Ultimate deflection, in.	Ultimate load, lb
A490: f'_c = 11951 psi; L_d = 6 in.; D_h = 1.625 in.; D = 1 in.		
E-1	0.024	49321
E-2	0.028	49932
E-3	0.028	51650
E-4	0.028	49115
E-5	0.035	52365
A490: f'_c = 12042 psi; L_d = 6 in.; D_h = 1.625 in.; D = 1 in.		
G-1	0.027	52432
G-2	0.029	53899
G-3	0.028	51351
G-4	0.028	52684
G-5	0.027	53510
†Mean	0.028	51626
Std. dev.	0.003	1686
COV, percent	9.7	3.3
A490: f'_c = 7451 psi; f'_{sp} = 719 psi; L_d = 6 in.; D_h = 1.625 in.; D = 1 in.		
I-1	0.034	46886
I-2	0.045	47640
I-3	0.066	51573
I-4	0.055	49800
I-5	0.04	45329
Mean†	0.048	48246
Std. dev.	0.013	2460
COV, percent	26.4	5.1

† The mean, standard deviation, and COV consider both of the above groups since they essentially have the same compressive strength.

that in the case of the flush mounted anchors, anchors in Groups B and C yielded, while in the case of the ICU anchors, one anchor in Group C yielded (Table 5).

All the anchors experienced an increase in pullout capacity with increasing concrete strength, except for the A490 anchors with an embedment depth of 4 in. (102 mm). No satisfactory explanation was found for this discrepancy.

The higher 12000 psi (82.7 MPa) concrete consistently produced lower ultimate deformation for all ranges of embedment depths for A490 anchors. The stiffness, a measure of load with respect to deformation, is greater for A490 anchors embedded in the higher strength concrete. Both effects, lower deformation and increased stiffness are most likely due to less crushing under the head of the anchor in the higher strength concrete. Load deflection curves for the 12000 psi (82.7 MPa) concrete are quite linear, and show a well defined ultimate load. Load deflection curves for the 7500 psi (51.7 MPa) are non linear with a varying curvature. The load deflection behavior of the flush mounted anchors was very similar to that of the A490 anchors.

There was no apparent difference in deformation at failure between the two concrete strengths for the ICU anchors, where the load deflection curves are very similar, almost overlapping. All ICU curves increase linearly until the peak load.

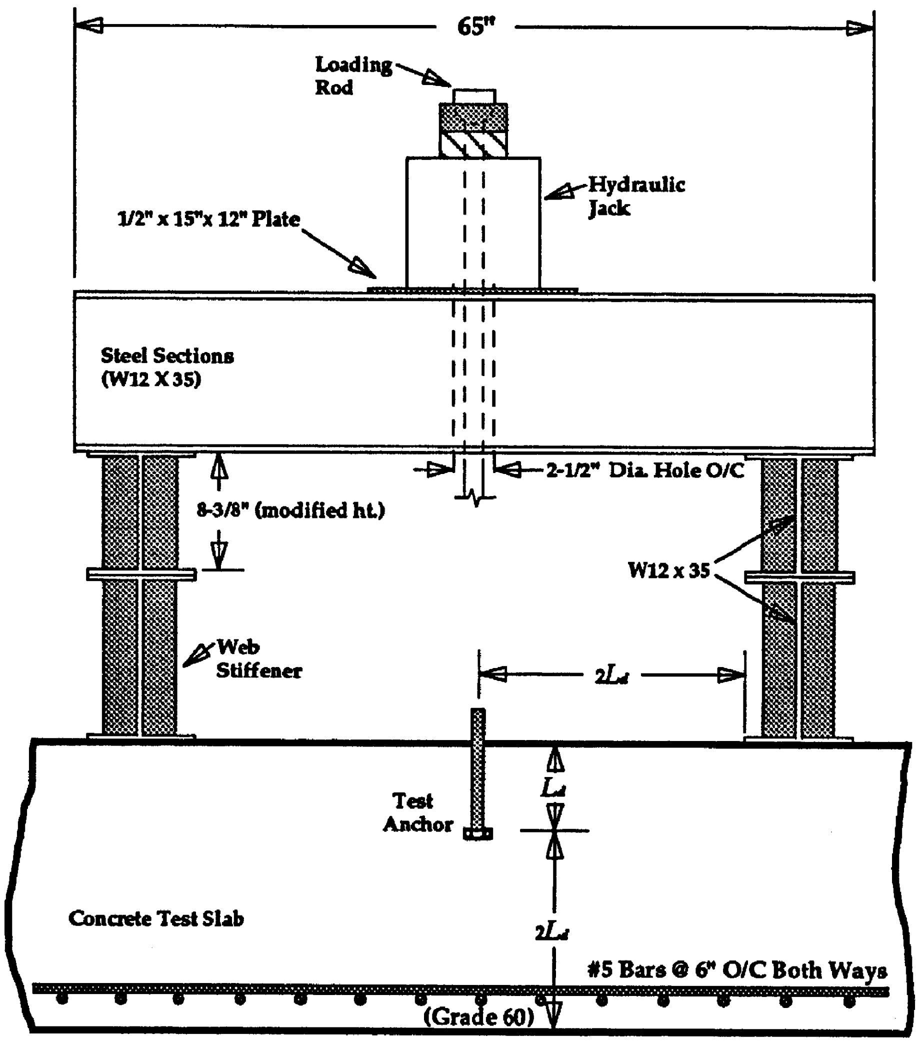

Fig. 2—Elevation view of test frame and concrete test slab

Table 3—Comparison of load and deflection data for different concrete strengths

Anchor group	Anchor type	L_d, in.	Nominal compressive strength, psi	Mean ultimate load P, lb	Change in mean ultimate load,* percent	Mean ultimate deflection Δ, in.	Change in mean ultimate deflection,† percent
H	A490	4	7500	27096	—	0.36	—
D/F	A490	4	12000	24361	–10.1	0.019	–47.2
I	A490	6	7500	48246	—	0.048	—
E/G	A490	6	12000	51626	7.0	0.028	–41.7
A	A490	8	7500	76837	—	0.075	—
B/C	A490	8	12000	85114	10.8	0.046	–38.7
A	ICU	8	7500	84293	—	0.084	—
B/C	ICU	8	12000	92142	9.3	0.078	–7.1
A	Flush Mount	8	7500	70645	—	0.074	—
B/C	Flush Mount	8	12000	82368	16.6	0.080	8.1

* Percent change in mean ultimate load = $\frac{P_{f_c = 12000\text{ psi}} - P_{f_c = 7500\text{ psi}}}{P_{f_c = 7500\text{ psi}}} x 100$

† Percent change in mean ultimate Δ = $\frac{\Delta_{12000\text{ psi}} - \Delta_{7500\text{ psi}}}{\Delta_{7500\text{ psi}}} x 100$

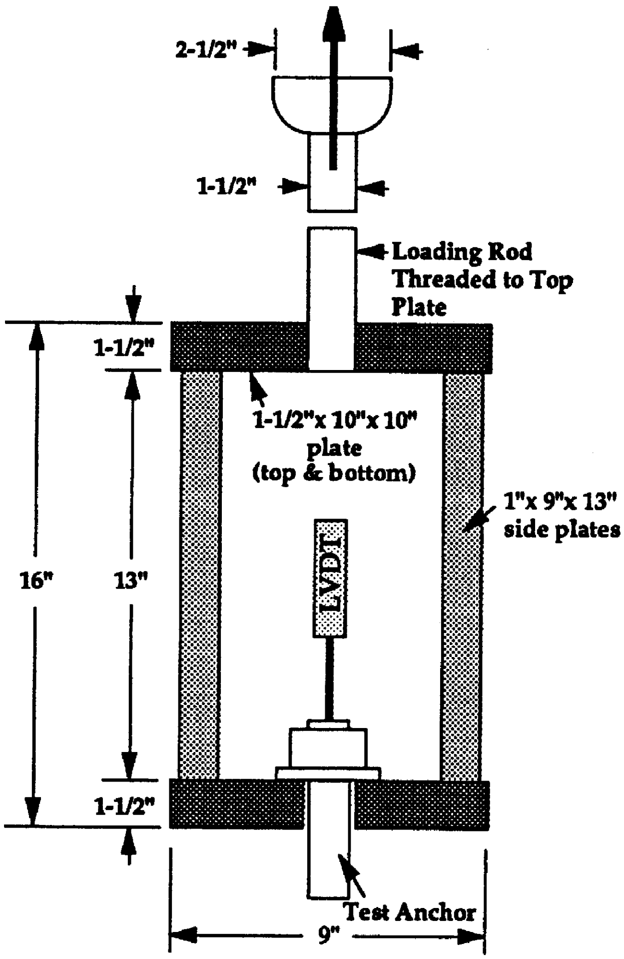

Fig. 3—Mechanical coupler

Influence of the embedment length

Table 4 summarizes the influence of the embedment length on the load- deflection behavior of an A490 anchor, for different concrete strengths. The load-deflection curves are plotted in Fig. 7 and 8 for the case of the 12000 psi (82.7 MPa) concrete (in this case, none of the anchors plotted yielded). Table 4 shows that the embedment depth is the most important parameter for increasing pullout capacity. The stiffness and deformation is also slightly greater for anchors with a longer embedment length for a given concrete.

Influence of the anchor type

Table 5 shows a consistent pattern in ultimate loads achieved for the different anchors with the same concrete compressive strength. The ICU anchors consistently provided the greatest peak loads, followed by the A490 anchors, and then the flush mounted anchors. This trend partly reflects the fact that higher load capacities are achieved in the case of the cast-in place anchors with greater anchor head diameter. In other words, the effective tensile area will increase with an increasing anchor head diameter, allowing for greater pullout capacity. Other differences between the anchors, in addition to the diameter of the anchor head, include methods of installation, material type, and physical geometry. In particular, the effect of the pre-setting load,90000 lb. (400 kN) used in this study for the installation of undercut anchors will increase the stiffness and make the results linear to failure. The exact influence of the preload requires further investigation.

Table 4—Comparison of load and deflection data for cast-in-place A490 anchors with different embedment depths

Anchor group	Ld, in.	Nominal compressive strength, psi	Mean ultimate load P, lb	Percent increase in P with respect to 4-in. anchors*	Mean ultimate deflection Δ, in.	Percent increase in Δ with respect to 4-in. anchors†
A	8	7500	76837	184	0.075	108
I	6	7500	48246	78	0.048	33
H	4	7500	27096	—	0.036	—
B	8	12000	80485	229	0.045	137
E	8	12000	50477	106	0.029	53
D	4	12000	24497	—	0.019	—
C	8	12000	89742	270	0.047	135
G	6	12000	52775	118	0.028	40
F	4	12000	24225	—	0.020	—

* Percent increase in mean ultimate load = $\frac{P_{L_d = 6 \text{ or } 8 \text{ in.}} - P_{L_d = 4 \text{ in.}}}{P_{L_d = 4 \text{ in.}}} x\, 100$

† Percent increase in mean ultimate Δ = $\frac{\Delta_{L_d = 6 \text{ or } 8 \text{ in.}} - \Delta_{L_d = 4 \text{ in.}}}{\Delta_{L_d = 4 \text{ in.}}}$

Table 5—Comparison of load and deflection data for different anchor types

Anchor group	anchor type	L_d, in.	D_h, in.	Nominal compressive strength, psi	Mean ultimate load P, lb	Increase in mean ultimate load,* percent	Mean ultimate deflection Δ, in.
A	ICU	8	2.75	7500	84293	19.3	0.084
A	A490	8	2	7500	76837	8.8	0.075
A	Flush Mount	8	1.75	7500	70645	—	0.74
B	ICU	8	2.75	12000	89630	12.6	0.072
B	A490	8	2	12000	80485	1.1	0.045
B†	Flush Mount	8	1.75	12000	79605	—	0.067
C†	ICU	8	2.75	12000	95282	11.9	0.085
C	A490	8	2	12000	89742	5.0	0.047
C†	Flush Mount	8	1.75	12000	85131	—	0.093

* Percent increase in mena ultimate load = $\frac{P_{\text{ICU or A490}} - P_{\text{Flush Mount}}}{P_{\text{Flush Mount}}} x\, 100$

† Steel anchor yielded

Concrete failure geometry

Most current design methods, (ACI 349, TVA, PCI, TRW) predict the pullout capacity for a given anchor utilizing an idealized failure cone with a 45 degree failure plane, based upon the principal stress orientation due to diagonal tension.[1] The proposed Concrete Capacity Design Method (CCD) pre-

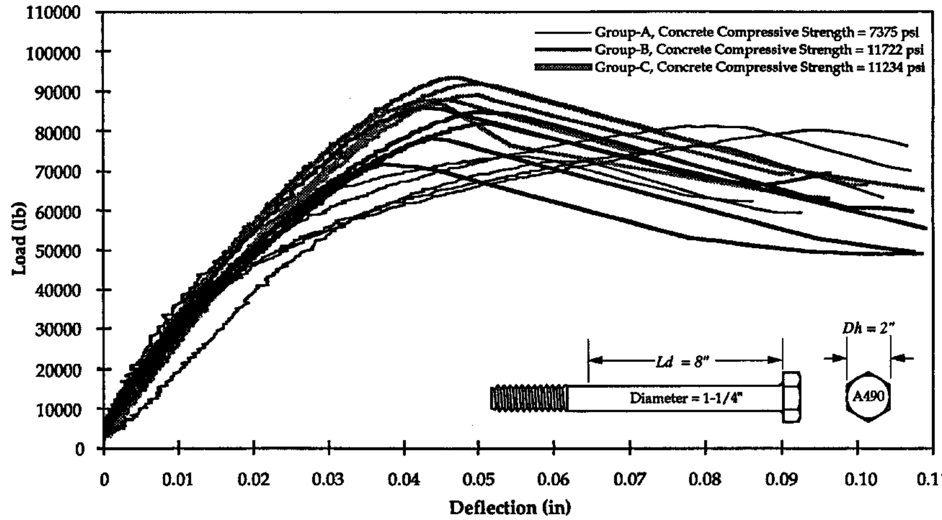

Fig. 4—Comparison of load deflection curves for cast-in-place A490 anchors with different concrete strengths

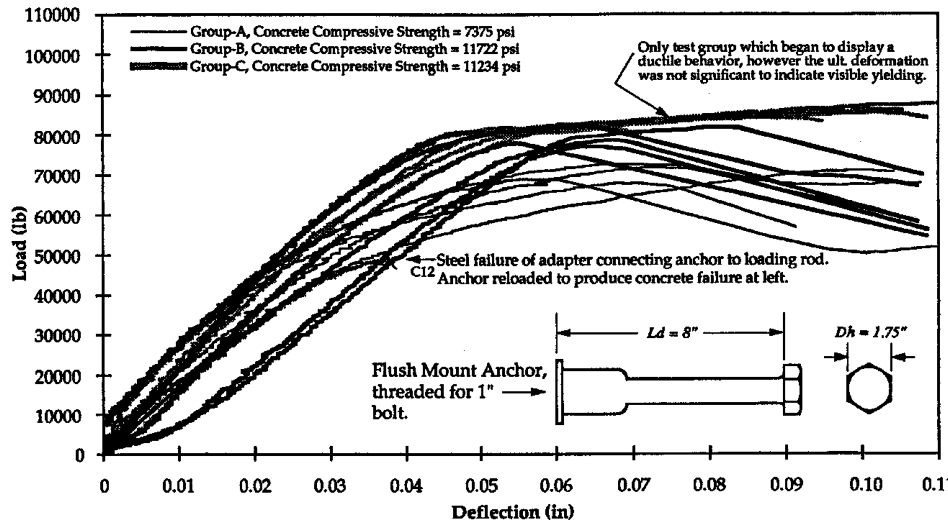

Fig. 5—Comparison of load deflection curves for flush mounted anchors with different concrete strengths

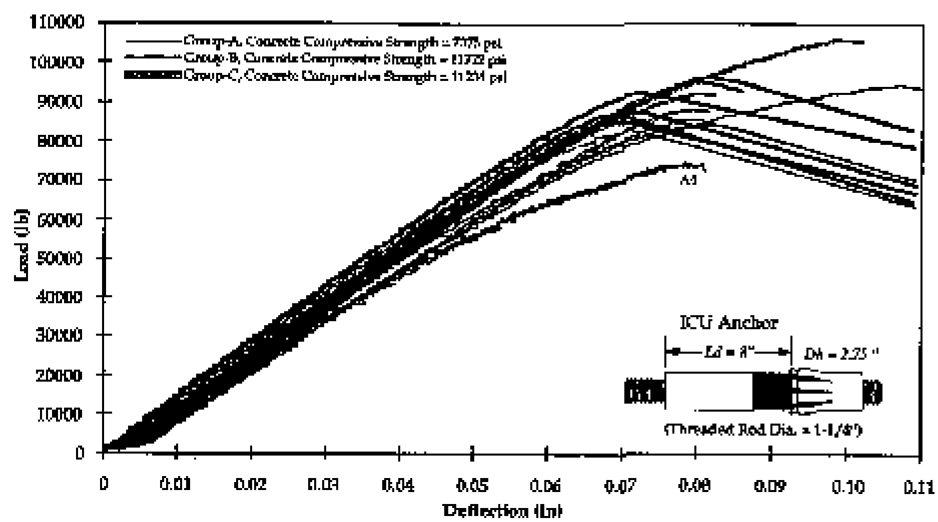

Fig. 6—Comparison of load deflection curves for post-installed inverted conical undercut anchors with different concrete strengths

dicts the strength of a single anchor based on a fracture mechanics model. However, for closely spaced anchors a pyramid shaped failure is utilized with a 35 degree failure plane.[4]

The ACI 349 Nuclear Safety Structures Commentary does indicate that anchors with an embedment depth of 5 in. (127 mm) or less tend to produce shallower concrete failure planes at approximately 30 degrees.[1] Similar conclusions are reached in Test Report No. 7 by TRW-Nelson[2] for cast-in-place headed steel anchors with an embedment length of 4 in. (102 mm) and compressive strength of 3000 psi (20.7 MPa).

These results coincide with the observations of the ACI 349 Commentary[1] and TRW-Nelson[2] concerning shallow embedments (less than 5 in. [127 mm]), and extend their validity to embedment depths up to at least 8 in. (203 mm).

Visually, the failure geometry appeared to be quite similar for each anchor group, and all cone failures consistently occurred through the calcareous limestone aggregate, as opposed to acementitious-bond failure around the aggregate.

The cast-in-place embedments, A490 and flush mounted anchors, predominantly have two very distinct failure planes. The post-installed undercut anchors predominantly had three distinct failure planes. Both failure cone profiles are shown in Fig. 9(a) and (b) respectively. For comparison, a recent deep anchor test series at the University of Bucknell[3] observed both two and three failure planes for cast-in-place and post-installed anchors. Failure geometry does not appear to be limited to a specific type of anchor.

COMPARISON OF DESIGN METHODS WITH EXPERIMENTAL RESULTS

There are currently five main design methods (PCI,[7,8] TRW,[9] TVA,[10] ACI 349,[1] and CCD[4]) available in North America to compute pullout capacity of embedded anchors. The equations of the first four are closely related to each other, and the ACI 349 is the most representative. Therefore only the ACI 349 and the CCD equations were retained in this study for comparison purposes. They are:

for the CCD method, $$N_{no} = k_{nc} \cdot \sqrt{f_c'} \cdot h_{ef}^{1.5} \qquad (1)$$

with k_{nc} = 40 for cast-in-place anchors, and k_{nc} = 35 for post-installed anchors;

for the ACI method, $$P_c = 4\sqrt{f_c'}[\Pi \cdot L_d \cdot (L_d + D_h)] \qquad (2)$$

(in both cases, L_d and h_{ef} are the embedment length)

The mean ratio of the experimental to predicted capacity is presented in Table 7 for the ACI 349 and CCD design procedures, for both the undercut and the cast-in-place (A490 and flush mounted) anchors. The first row of the table gives the statistics for the case of the 7500 psi (51.7 MPa) concrete. The second row of the table gives the statistics for the case of the 12000 psi (82.7 MPa) concrete. The last row of the table gives the statistics for both cases considered together. Predicted loads are computed without applying a strength reduction factor (Ø) or factor of safety. Ratios greater than unity represent under predictions, and ratios less than unity depict over predictions. The comparison of experimental results to design predictions shown in Table 7 are also represented graphically in Fig. 10, 11, and 12.

From Table 7, and Fig. 10 and 11, it can be seen that in the case of cast in place anchors, both the ACI and the CCD models tend to overpredict the pullout capacity by similar amounts on the average, as the concrete strength increases. The overprediction goes from 3 percent for f_c' = 7500 psi to 20 percent for f_c' =12000 psi. The coefficients of variations vary in opposite directions with an increase in COV with f_c' for the CCD model, and a decrease for the ACI model.

In the case of the undercut anchors, the ACI model consistently overpredict the pullout capacity while the CCD model consistently underpredict it (by as much as 25 percent on the average for f_c' = 7500 psi). In this case, the COVs are identical and reflect only the COV of the data itself.

Fig. 12 plots the same data in terms of the ultimate load (normalized with respect to the square root of f_c') as a function of the embedment length. The plots of Eq. (1) and (2) are also superimposed to the data. In the case of the ACI curve, the effect of the anchor head diameter is

Table 6—Average failure plane results for each test group

Ancor type	Nominal compressive strength, psi (MPa)	L_d, in. (cm)	Number of cross-sections measured	Mean failure plane θ*, deg	COV, percent
ICU	7500 (51.7)	8 (20.32)	9	26.8	18
Flush Mount	7500 (51.7)	8 (20.32)	9	22.7	11
A490	7500 (51.7)	8 (20.32)	9	21.5	6
A490	7500 (51.7)	6 (15.24)	9	21.2	5
A490	7500 (51.7)	4 (10.16)	9	21	13
ICU	12000 (82.7)	8 (20.32)	18	27.7	13
Flush Mount	12000 (82.7)	8 (20.32)	18	23.1	8
A490	12000 (82.7)	8 (20.32)	18	23.4	7
A490	12000 (82.7)	6 (15.24)	18	23.9	10
A490	12000 (82.7)	4 (10.16)	18	21.9	11

*Defined in Fig. 11

Table 7—Summary comparison of X_{exp}/X_{pred} for CCD and ACI 349

Nominal compressive strength	Undercut anchors				Cast-in-place anchors			
	CCD		ACI		CCD		ACI	
	Mean	COV	Mean	COV, percent	Mean	COV, percent	Mean	COV, percent
7500 (51.7 MPa)	1.24	8.50	0.91	8.50	0.96	5.28	0.97	14.70
12000 (82.7 MPa)	1.09	7.62	0.80	7.62	0.80	11.47	0.81	7.82
All tests	1.14	10.19	0.84	10.19	0.85	12.81	0.86	14.13

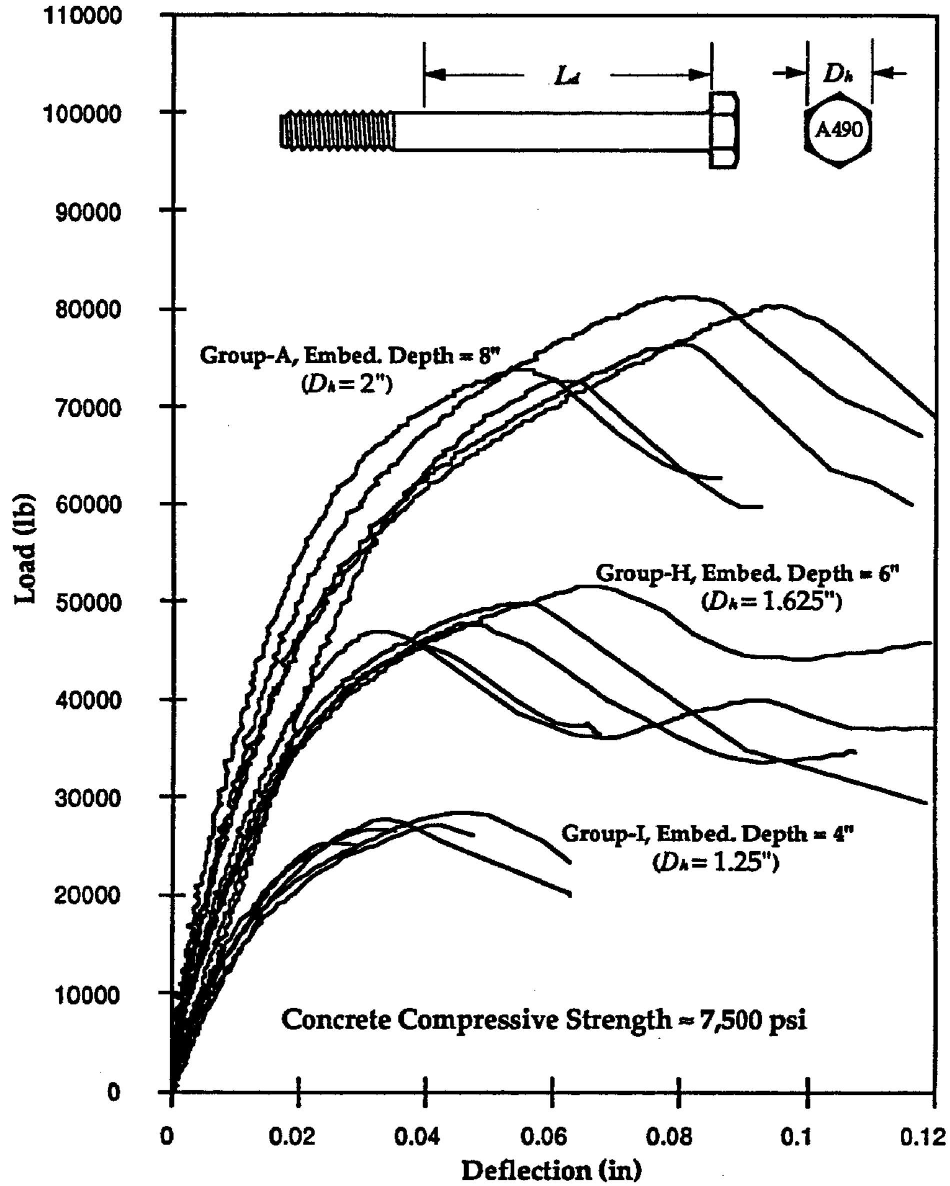

Fig. 7—Comparison of load deflection curves for cast-in-place A490 anchors with different embedment depths, Test Groups A, H, and I

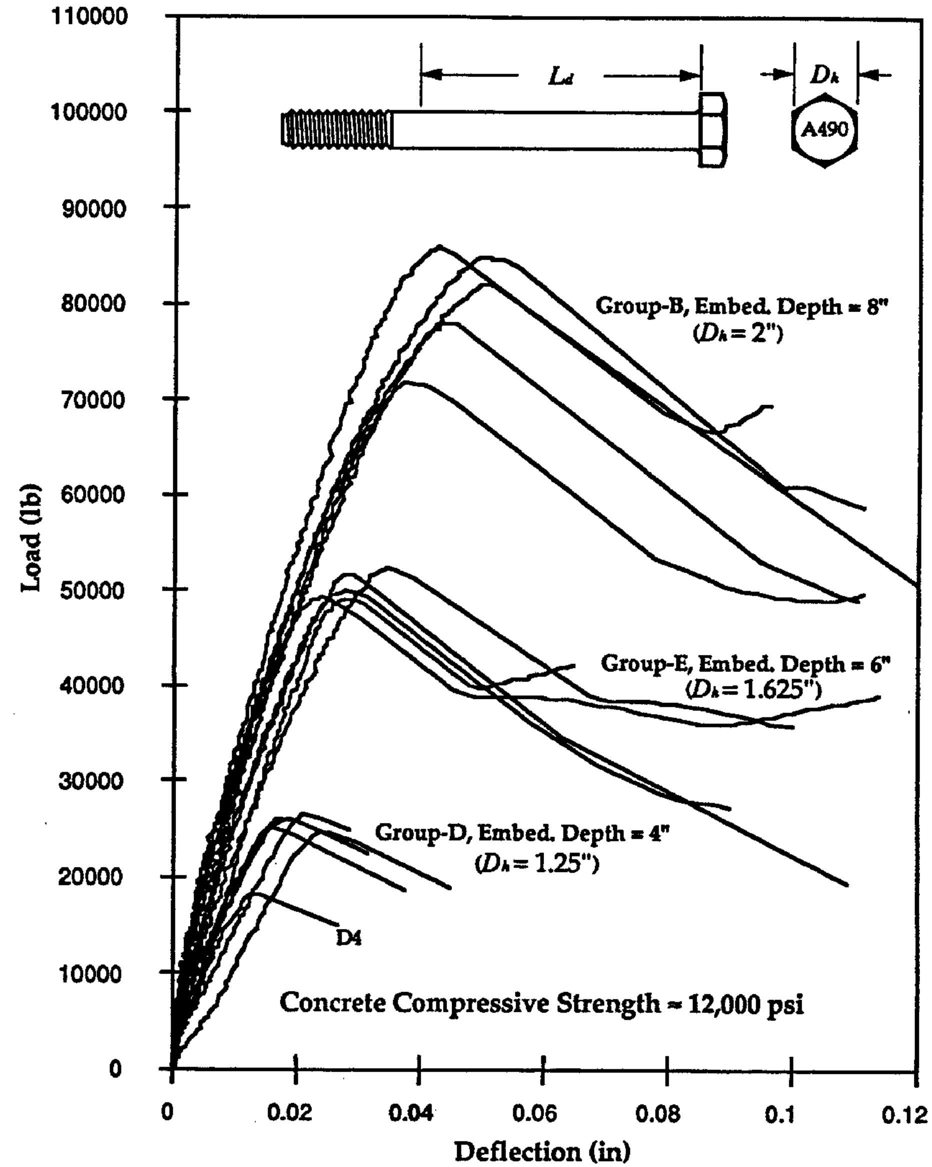

Fig. 8—Comparison of load deflection curves for cast-in-place A490 anchors with different embedment depths, Test Groups B, D, and E

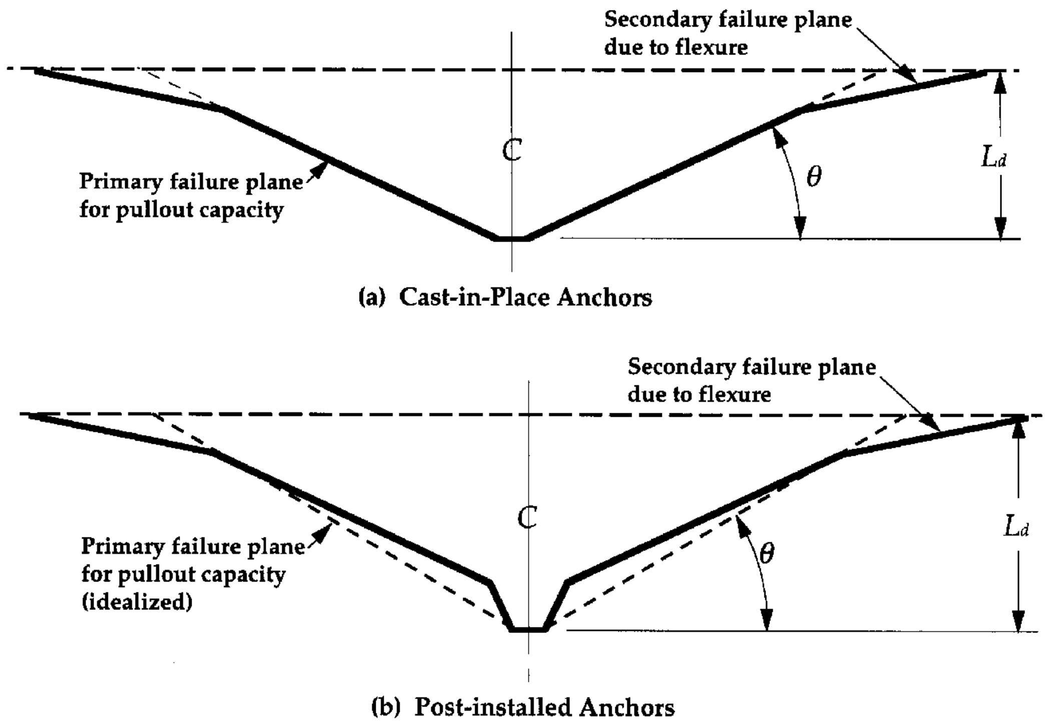

Fig. 9—Typical failure plane geometries

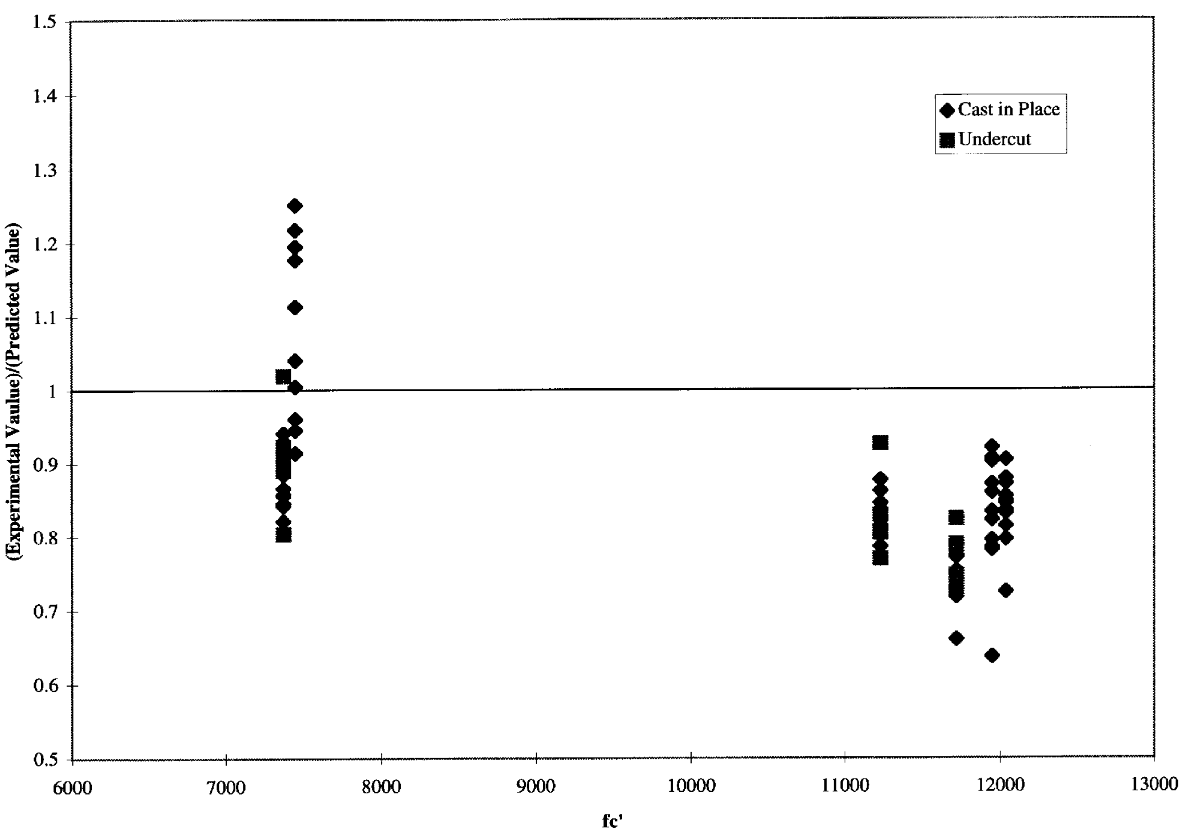

Fig. 10—Distribution of (experimental)/(ACI-predicted) values

included in the curve. The same conclusions as above can be drawn from this graph. However, it should be noted that in the case of the shorter anchors (embedment = 4 in.) the ACI model does underpredict the pullout capacity for f_c' = 7500 psi.

CONCLUSIONS

In this study the pullout capacity of cast in place and post-installed anchors embedded in high-strength concrete has been investigated. The following conclusions can be drawn from the investigation:

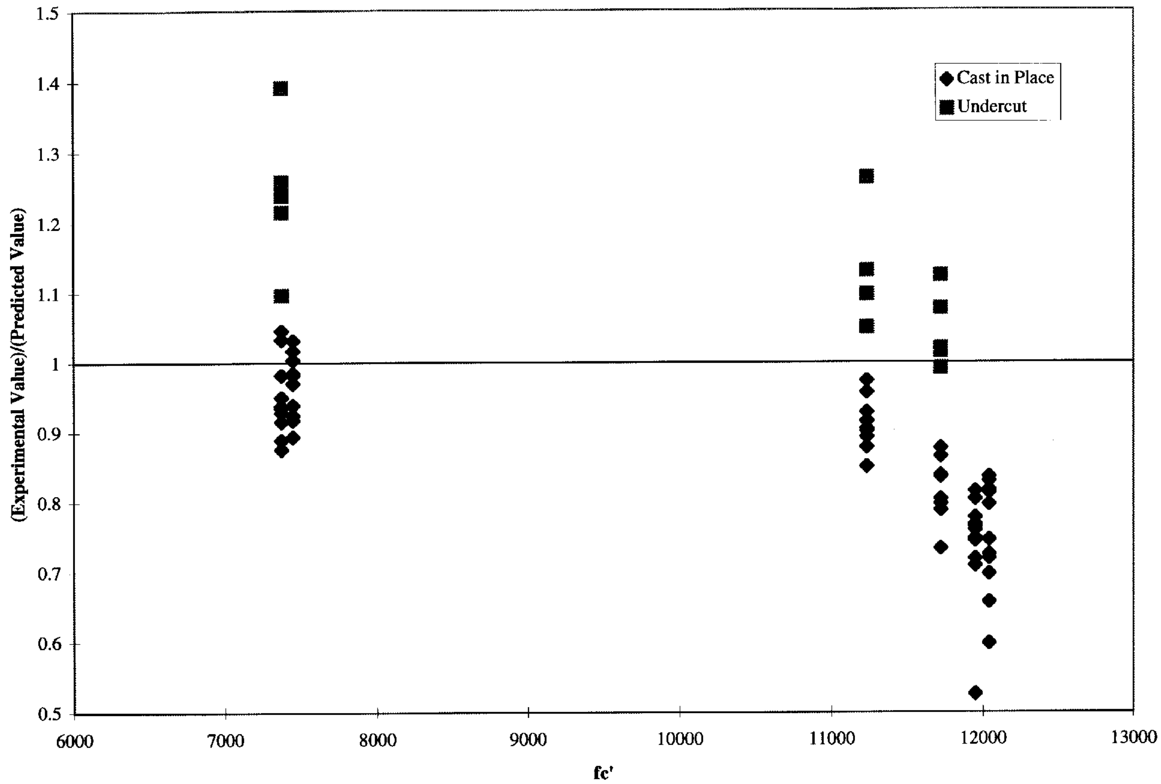

Fig. 11—Distribution of (experimental)/(CCD-predicted) values

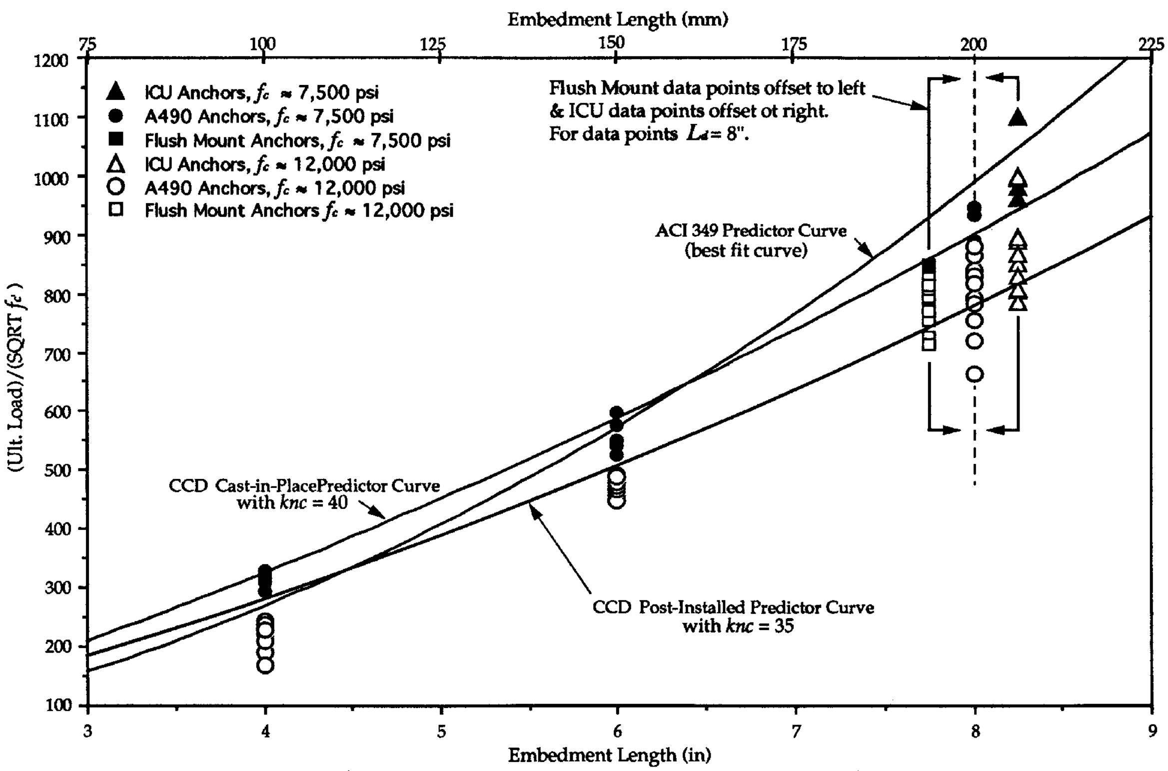

Fig. 12—Comparison of cast-in-place experimental results for Florida Technological University, showing both cast-in-place and post-installed anchors

1. For cast-in-place and post-installed anchors with an embedment depth of 6 and 8 in. (152 and 203 mm) there was a general trend indicating the pullout capacity of the concrete increased with higher compressive strength concrete. For the 4-in. (102-mm) cast-in-place anchors the pullout capacity did not increase with higher compressive strength concrete.

2. Shallow angle cone failures were obtained for all anchors tested, even with embedment depths of 8 in. (203 mm).

Therefore, results of this investigation contradicted the established 45 deg idealized failure cone model.

3. When comparing only cast-in-place A490 anchors installed in the same concrete strength, the embedment length (4, 6, and 8 in.) was the most important parameter for increasing the pullout capacity.

4. A comparison of the different 8 in. (203 mm) anchors shows a consistent pattern in ultimate loads achieved, when installed in the same concrete. The undercut anchors consistently provided the greatest peak loads, followed by the A490 anchors, and then the flush mounted anchors.

5. In general, the CCD and ACI 349 design procedures without an applied strength reduction factor (ϕ) tend to over predict concrete pullout capacity for cast in place anchors. Over prediction of pullout capacity increased with increasing concrete compressive strength.

RECOMMENDATIONS FOR FUTURE RESEARCH

Further studies are warranted to fully understand the behavior of embedded anchors in high-strength concrete. Future research should address the following topics.

1. The original purpose of this research was to study similar anchors in normal, high, and very high-strength concrete with the same aggregate. However the concrete mixes turned out to be only high and very high strength. To complete the comparison, a study of the anchors described in this paper should be carried out for normal strength concrete (f_c' = 5000 psi) with the same aggregates.

2. A study for both normal and high-strength concrete is needed to understand the effects of different aggregate types such as a soft calcareous limestone, conventional crushed aggregate, and a smooth rounded river gravel for anchors both in tension and shear.

3. High strength concrete in this investigation only incorporated the use of portland cement Type I/II. High strength concretes may also incorporate the addition of other pozzolanic materials such as fly ash and silica fume. Therefore, one additional variable to be investigated is the effect of pozzolanic additions to high-strength concrete.

4. Further study is needed to determine both pullout and shear capacity of anchors embedded in lightweight concretes, for different lightweight aggregates and compressive strengths, which includes high-strength lightweight concretes.

5. Post-installed undercut anchors are typically installed at a specific pre-setting load which induces a stressed zone between the anchor head and concrete surface. Thus, an investigation to determine the effect of the pre-setting load on the concrete pullout capacity is recommended.

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