Tensile behavior and design of adhesive anchors embedded in thin concrete members

Ahmad N. Tarawneh, Brandon E. Ross, and Thomas E. Cousins

- This paper presents an experimental test program for adhesive anchors embedded in precast concrete sandwich panels. The program was conducted to evaluate the behavior, capacity, and failure modes of single tension-loaded adhesive anchors embedded in thin concrete members.
- Test results were used to create a design model for adhesive anchors postinstalled in thin concrete members. The model's accuracy and variability are similar to code-based models for other applications.

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Precast concrete sandwich wall panel systems have been used in the construction industry for the past 50 years because of their structural and thermal insulation efficiency.[1] Precast concrete sandwich panels consist of two thin concrete layers separated by a thermal insulation layer. The concrete layers are commonly made structurally composite using shear connectors. The thickness of the layers typically ranges from 2 to 5 in. (50.8 to 127 mm). Postinstalled anchors are used in these panels for purposes including beam supports, repairing alignments, and installation of canopies and signs. However, anchorage in precast concrete sandwich panels can be challenging because of the thinness of the concrete layers and the lack of research and code provisions regarding anchorage in such members. In addition, codes and specifications impose limits on the minimum concrete member thickness and minimum anchor embedment depth. These limitations further hamper the use of postinstalled anchors in sandwich panels.

Concrete anchors come in many categories. The general categories are cast-in place anchors, which are installed before the concrete cures, and postinstalled anchors, which are installed in cured concrete.[2] Postinstalled anchors can be divided into subcategories based on load transfer mechanisms. Mechanical anchors transfer loads through mechanical interlock. Bonded anchors transfer load through a bonding agent between the anchor and the concrete.

The use of postinstalled anchorage systems has increased due to the growing demand for more flexibility in planning and construction.[3] Postinstalled anchors have the advantage of being more flexible on jobsites because their location can be easily adjusted to ensure proper alignment and facilitate retrofits of buildings.

Adhesive anchors are commonly used in the concrete industry and are viewed as a practical and economical fastening system.[4,5] Accordingly, there is a desire to evaluate the capacity and behavior of adhesive anchors in precast concrete sandwich panels. This paper presents an experimental program that evaluates the effects of concrete member thickness, anchor diameter, concrete compressive strength, and anchor brand on the tensile behavior and capacity of adhesive anchors. The effect of full-thickness drilling (penetration) on back-face blowout is also investigated. The experimental results are then used to verify a design approach for adhesive anchors in sandwich panels based on the 5% fractile of the mean value.

Limitations on anchoring to thin concrete members

Current codes and specifications include limitations that affect the use of anchors in thin concrete members. According to International Code Council's ICC-ES AC193,[6] the minimum allowable concrete thickness required for the use of mechanical anchors is twice the effective embedment depth unless acceptable test data are provided. In addition, acceptance criteria for both mechanical and adhesive anchors specify a minimum member thickness not less than the hole depth plus twice the hole diameter or 1.25 in. (31.75 mm), whichever is larger.[7] Product design tables from anchor suppliers specify minimum member thickness values that are larger than the embedment depth. These limitations prohibit full-thickness embedment of anchors; that is, anchor depth is equal to member thickness.

Acceptance criteria for mechanical and adhesive anchors[6,7] also specify a minimum embedment depth of 1.5 in. (38.1 mm), whereas anchor manufacturer specifications specify a minimum embedment depth greater than 2 in. (50.8 mm). These provisions on minimum member thickness and minimum embedment depth prevent the use of anchors in thin concrete layers and in applications with full-thickness embedments.

According to the American Concrete Institute's (ACI's) *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)*[8] chapter 17, "Anchoring to Concrete," the embedment depth for expansion and undercut of postinstalled anchors must not exceed two-thirds of the member thickness or the member thickness minus 4 in. (101.6 mm), whichever is greater. Limitations on the maximum embedment depth are intended to prevent splitting failures and concrete back-face blowout during drilling.[8] These limitations restrict full-thickness embedment, which effectively prevents engineers from designing postinstalled anchors in thin concrete members.

Background

An adhesive anchor is a threaded rod or reinforcing bar inserted into a drilled hole with an adhesive (bonding agent) that attaches the anchor to the concrete. The applied loads are transferred from the anchor to the adhesive through the mechanical interlocking between the threads and the adhesive and then to the concrete through the adhesion or microinterlock between the adhesive and the concrete (**Fig. 1**).[5]

The capacity of an anchor in concrete is a function of its failure mode. More specifically, postinstalled anchors can exhibit several failure modes under tension load, including steel anchor failure, concrete cone breakout, bond (pullout) failure, or a combination of bond and concrete cone breakout failure (**Fig. 2**). In the design process of an anchor, the capacity for each failure mode is calculated, and the mode with the lowest capacity governs the design.

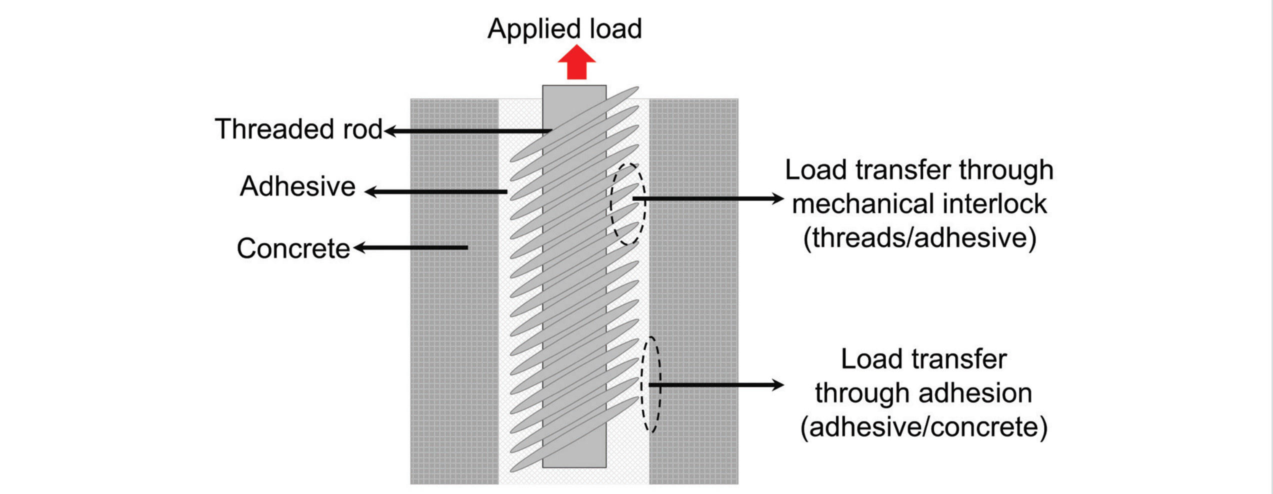


Figure 1. Adhesive anchor load transfer mechanism.

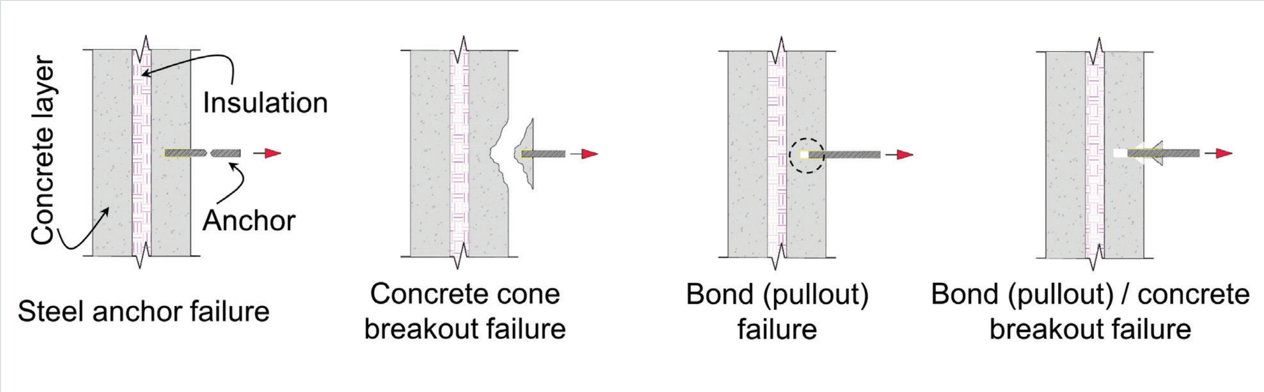


Figure 2. Failure modes for anchors embedded in one layer of precast concrete sandwich panel system.

PCI Design Handbook: Precast and Prestressed Concrete[3] refers to ACI 318 or to proprietary manufacturers for designing postinstalled anchors. The design provisions of ACI 318-14[8] for each failure mode are summarized in the following paragraphs.

Equation (1) gives the nominal capacity of an anchor against steel failure N_{sa} according to ACI 318-14.[3] The tensile strength of the steel is limited to 1.9 times the yield strength or 125,000 psi (860 MPa), whichever is smaller.

$$N_{sa} = A_{se,N} f_{uta} \tag{1}$$

where

$A_{se,N}$ = anchor effective cross-sectional area

f_{uta} = tensile strength of the steel

Concrete cone breakout capacity is determined using the concrete capacity design (CCD) model proposed by Fuchs et al.[9] It is based on concrete failure of a 35-degree cone failure originating at the end of the anchor (**Fig. 3**), where h_{ef} is the effective embedment depth. This model has been extended to include multiple anchor and edge effects and was adopted by ACI 318 as the design model for concrete breakout failures. The calculated capacity of an anchor based on the CCD model is a function of the embedment depth and the compressive strength of concrete.

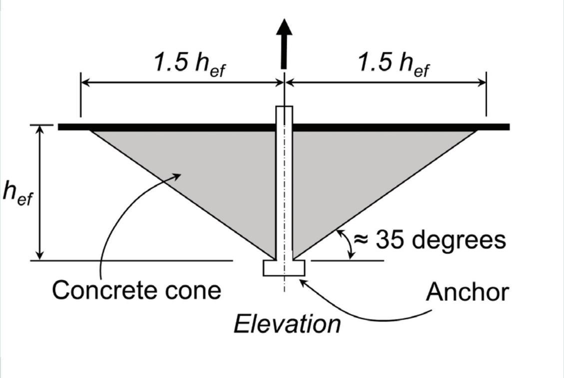


Figure 3. Concrete capacity design model. Note: h_{ef} = effective anchor embedment depth.

Equation (2) gives the CCD strength of postinstalled anchors in uncracked concrete.

$$N_{cb} = k_c \sqrt{f_c'} h_{ef}^{1.5} \tag{2}$$

where

N_{cb} = concrete breakout capacity

k_c = coefficient for basic concrete breakout strength in tension (ACI 318-14)

f_c' = concrete compressive strength

Concrete cone failure is common for shallow embedment depths; however, bond failure may occur with deeper embedment depth.[3] Experimental results discussed in Eligehausen et al.[10] show that bond stress distribution along the embedment depth is nonlinear. However, based on work by Cook et al.,[4] a uniform bond stress can be practically used in design. Equation (3) gives the anchor bond failure capacity N_{ba} assuming a uniform stress distribution.

$$N_{ba} = \tau \pi d h_{ef} \tag{3}$$

where

τ = mean bond stress associated with each product based on the 5% fractile

d = anchor diameter

In 2020, Tarawneh et al.[11] investigated the behavior and capacity of screw anchors in thin concrete members. Screw anchors are postinstalled anchors that transfer loads through mechanical interlock. It was shown that drilling through the thickness of the concrete layer using a rotary-hammer drill will cause the concrete to blow out as the drill bit approaches the back face (**Fig. 4**). It was observed that holes drilled with smaller drill bits tended to create narrower blowout cones. Blowout width ranged from 3.5 to 5.0 in. (88.9 to 127 mm). Depth of the blowout cones ranged from 0.70 to 0.95 in. (17.78 to 24.13 mm). It was observed in these tests that the blowout depth was not a function of the drill bit diameter.

Based on 100 pull-out tests in uncracked concrete, Tarawneh et al.[11] presented a design model for screw anchors in thin concrete layers. The model is based on the CCD approach in Eq. (2) but uses a reduced effective embedment depth that accounts for the back-face blowout (Eq. [4]).

$$h_{ef} = 0.75(h_{nom} - h_b) \tag{4}$$

where

h_{nom} = nominal length of the anchor

h_b = blowout depth, taken as 0.95 in. (24.13 mm)

When using Eq. (2) for screw anchors, k_c is specified as 13.5 (SI units) or 32 (U.S. customary units, computed by the authors), a value similar to the expansion anchor model.

The results also indicate that screw anchors can exhibit different behaviors based on their thread configuration and their ability to provide mechanical interlock with the concrete. Anchors with greater undercut—defined as the difference between the outer diameter of the screw anchor and the diameter of the hole in which the anchor is installed—have higher capacity and more consistent breakout failure. Anchors with small undercut values have less capacity and may fail in pull-out failure mode.

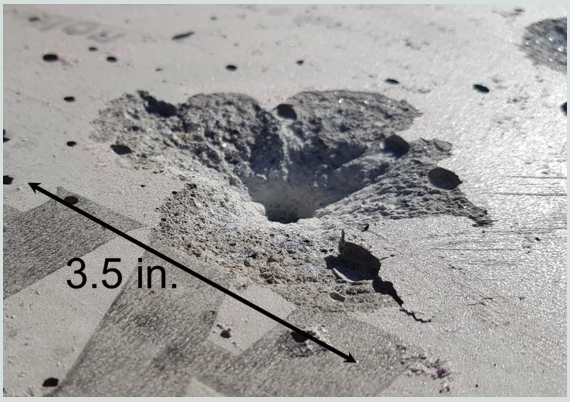


Figure 4. Back-face concrete blowout due to drilling.
Note: 1 in. = 25.4 mm.

The current paper builds on the earlier research by Tarawneh et al.[11] and extends the research on postinstalled anchors in thin concrete to include adhesive anchors.

Experimental program

An experimental program of 89 pull-out tests on adhesive anchors embedded in sandwich panels was conducted to evaluate the behavior, capacity, and failure modes of single tension-loaded adhesive anchors embedded in thin concrete members. All tests were conducted in plain uncracked concrete away from concrete edge. Variables in the experimental program included concrete thickness, anchor diameter, embedment depth, and anchor brand (**Table 1**). Four to five repetitions were tested for each combination of variables considered. Variable values were chosen based on common industry practice and on recommendations from precast concrete and anchor suppliers. Also based on supplier recommendations, the threaded rod in each test was extended into the insulation layer by approximately 1 in. (25.4 mm). Of the 89 tests, 40 were conducted using 2 in. (50.8 mm) thick concrete, 40 using 4 in. (101.6 mm) thick concrete, and 9 using 3 in. (76.2 mm) thick concrete.

With the 89 tests for the experimental program, anchors were typically installed and tested vertically; however, 12 additional tests of horizontally installed anchors were also conducted to ensure that strength is not affected by the direction of installation. The variables associated with the horizontal installation tests are reported later in this paper.

Test specimens

Eleven 3 ft × 9 ft × 8 in. (0.9 m × 2.7 m × 203.2 mm) precast concrete sandwich panels were fabricated by a precast concrete manufacturer. The concrete layers were either 4 and 2 in. (101.6 and 50.8 mm) or 3 and 3 in. (76.2 and 76.2 mm) and were separated by a 2 in. insulation layer (**Fig. 5**). Adhesive anchors were installed and tested in each of the concrete layers. After the tests on one side of a panel were completed, the panel was flipped and anchors were installed and tested on the other side. The testing area in the panels was unreinforced; however, reinforcement was provided at the perimeter to support the lifting points. All panels had a concrete compressive strength of 5.5 ksi (38 MPa) and size 67 aggregate

Table 1. Test matrix summary

Concrete compressive strength, ksi	5.5
Adhesive brands	3 (A, B, C)
Anchor diameters, in.	⅜ and ½
Embedment depths, in.	2, 3, and 4
Test repetitions	4 to 5
Total number of tests	89

Note: 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.

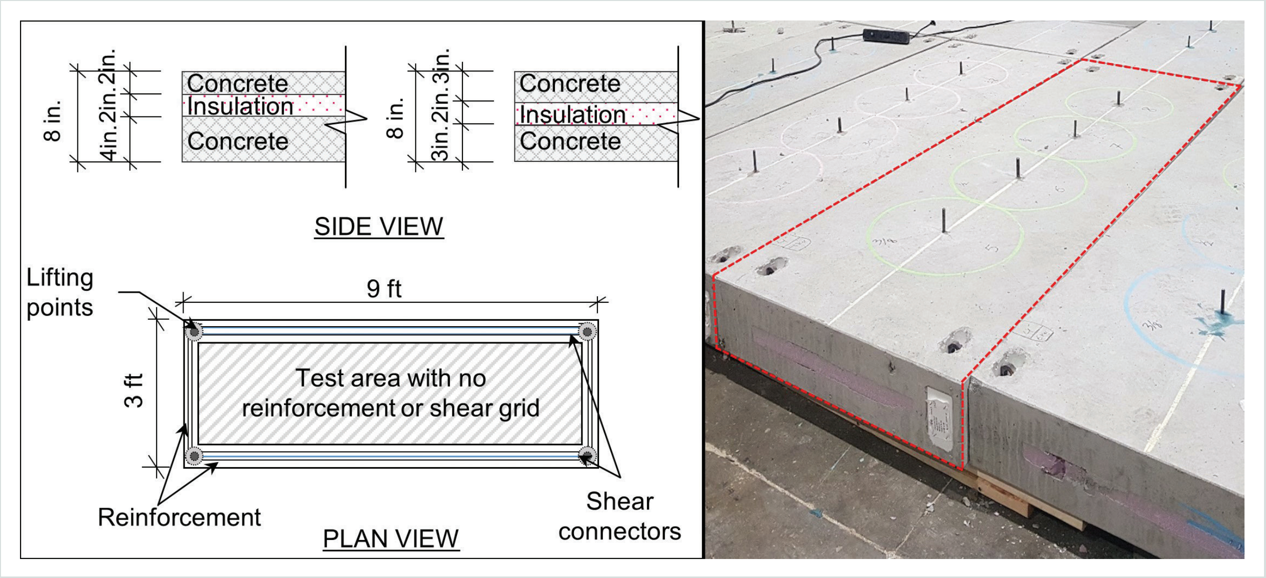


Figure 5. Side and plan view for the tested precast concrete sandwich panels. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

Typically, four tests were conducted on each side of each panel. To prevent interaction between adjacent tests, the clear distance between the tested anchors was at least five times the embedment depth, which is greater than the minimum distance specified by ASTM E488[12] for unconfined pull-out tests. The distance between the anchors and the perimeter reinforcement also complied with ASTM E488. Threaded rods were grade B7 steel with 125 ksi (860 MPa) tensile strength that met or exceeded ASTM A193.[13] The B7 grade was chosen to mitigate steel anchor failures.

Setup, procedure, and measurements

Holes for anchors were drilled using carbide drill bits and a rotary-hammer drill. Because rotary-hammer drills combine the rotary mechanism with a hammering action that produces a pounding force, they are efficient and effective for drilling in concrete and masonry. Rotary-hammer drills also lead to back-face blowout, as previously discussed. Holes were drilled through the entire thickness of the concrete layer.

Before injecting the adhesive, the holes were cleaned with compressed air and a brush according to the product specifications. The hole was filled with the adhesive and the threaded rods were then installed through the full thickness of concrete layer and extended approximately 1 in. (25.4 mm) into the insulation layer (**Fig. 6**). The adhesive cured for at least 24 hours, which exceeds the time required by the product specifications.

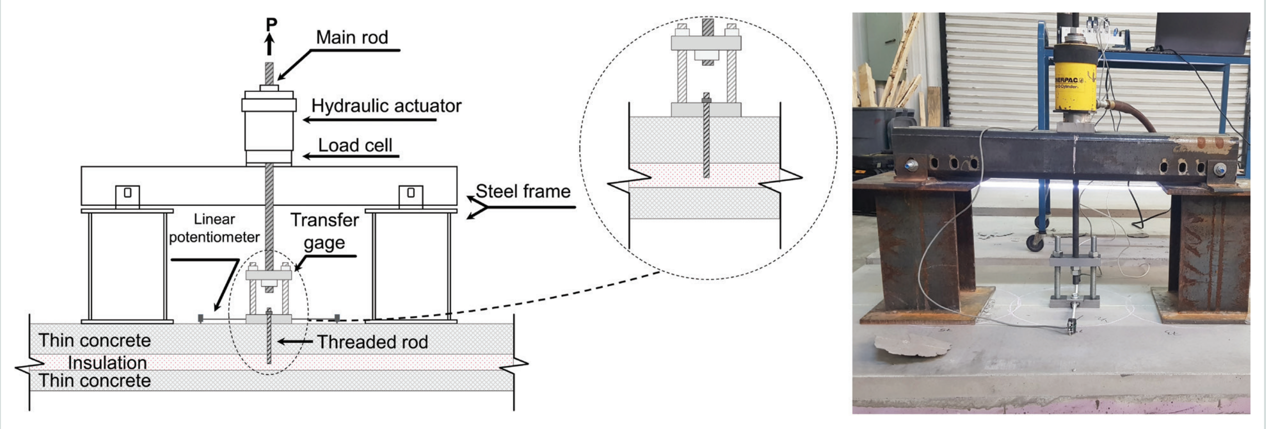


Figure 6. Test apparatus. Note: P = applied load. 1 in. = 25.4 mm.

The testing apparatus (Fig. 6) was designed to meet the requirements of ASTM E488, including the required distance between supporting points for unconfined pull-out tests. The tension load was applied perpendicular to the panel by a hand-operated hydraulic jack. Load was recorded using a calibrated load cell and checked using a pressure gauge installed in the hydraulic line. The loading rate was adjusted to ensure that failure occurred within one to three minutes after the beginning of the test, as specified by ASTM E488.[12]

Two calibrated displacement transducers recorded the displacement of the anchor relative to the concrete surface, and the average displacement was considered as recommended by

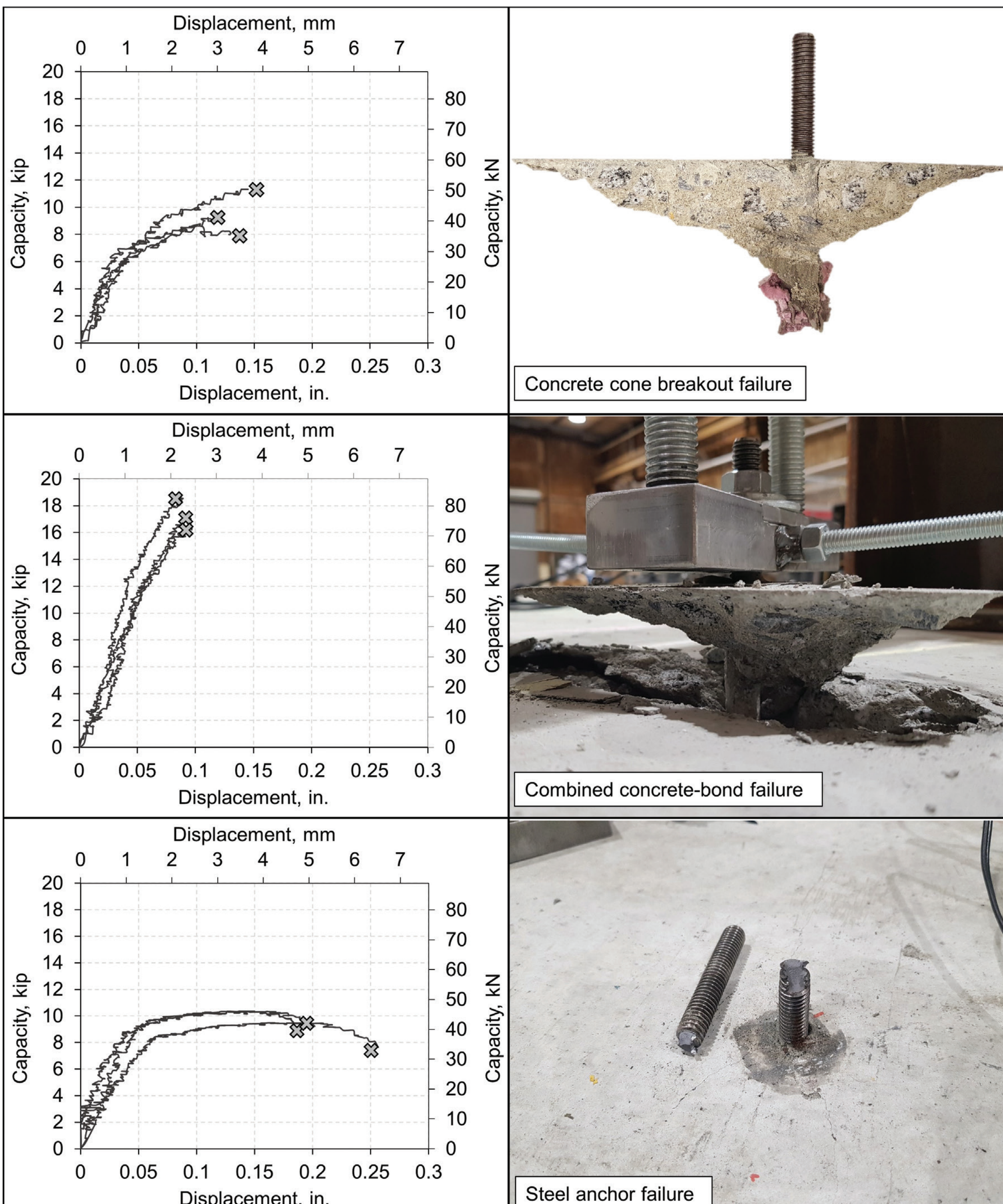


Figure 7. Load-displacement and failure mode for concrete cone breakout failure, combined concrete-bond failure, and steel anchor failure.

ASTM E488.[12] Data were continuously monitored and logged using a computer-based data acquisition system.

Tests results

The following section presents the results of the 89 pull-out tests. Results are discussed in terms of the failure modes and the associate load-deflection response, back-face blowout effect, and the effect of the variables on the capacity of adhesive anchors.

Failure modes and load-displacement response

Figure 7 shows the three observed failure modes: steel anchor failure, concrete cone breakout, and concrete cone/pullout, as well as the load-displacement response associated with each failure mode.

Anchors embedded in 2 and 3 in. (50.8 and 76.2 mm) thick concrete layers failed in concrete cone breakout failure regardless of the anchor diameter. The cone depth was equal to the concrete layer depth, as will be discussed in the following section. Figure 7 shows the load-displacement response for typical anchors embedded in a 2 in. concrete layer. Load and displacement increased linearly until cracks began to form in the concrete cone. Cracks formed when the displacement reached approximately 0.05 in. (1.27 mm). Initial cracking in the concrete led to a reduction of stiffness but not to immediate failure. In the example, the load continued to increase until it reached a peak near 9 kip (40 kN) with a corresponding displacement of 0.1 to 0.15 in (2.54 to 3.81 mm).

Anchors embedded in 4 in. (101.6 mm) concrete experienced anchor steel failure for the ³⁄₈ in. (9.525 mm) anchors and a combined failure concrete cone/pullout for ½ in. (12.7 mm) anchors (Fig. 7). This general behavior was consistent with the adhesive anchor behavior described in Cook et al.,[4] where shallow embedment anchors typically result in concrete cone failure, whereas anchors with deeper embedment depths experience combined failure mode.

Figure 7 shows that anchor steel failure is a ductile failure that exhibits the highest deformation of 0.2 to 0.25 in. (5.08 to 6.35 mm), which is almost twice the deformation associated with other failure modes. This behavior is due to the ductile nature of the steel.

The combined failure mode (½ in. [12.7 mm] anchors in 4 in. [101.6 mm] concrete thickness) experienced the smallest deformation (0.09 in. [2.3 mm]) and had the highest stiffness due to the higher bond embedment depth (Fig. 7).

Effects of variables

The experimental program included two anchor diameters, ³⁄₈ and ½ in. (9.525 and 12.7 mm). **Figure 8** presents the relationships between the capacity and the anchor diameter for each concrete thickness. The trend line showed that the effect of the diameter became more noticeable as the concrete thickness increased. This can be seen by the increase of the trend line slope, which was smallest at 2 in. (50.8 mm) concrete thickness and greatest at 4 in. (101.6 mm) concrete thickness. This behavior was consistent with the behavior of screw anchors embedded in thin concrete layers where the effect of anchor diameter and concrete strength were negligible in 2 in. concrete thickness but increased when the thickness increased.[11]

Figure 9 shows the effect of the concrete thickness on the capacity, comparing anchor capacity with concrete thickness for ³⁄₈ and ½ in. (9.525 and 12.7 mm) diameter anchors.

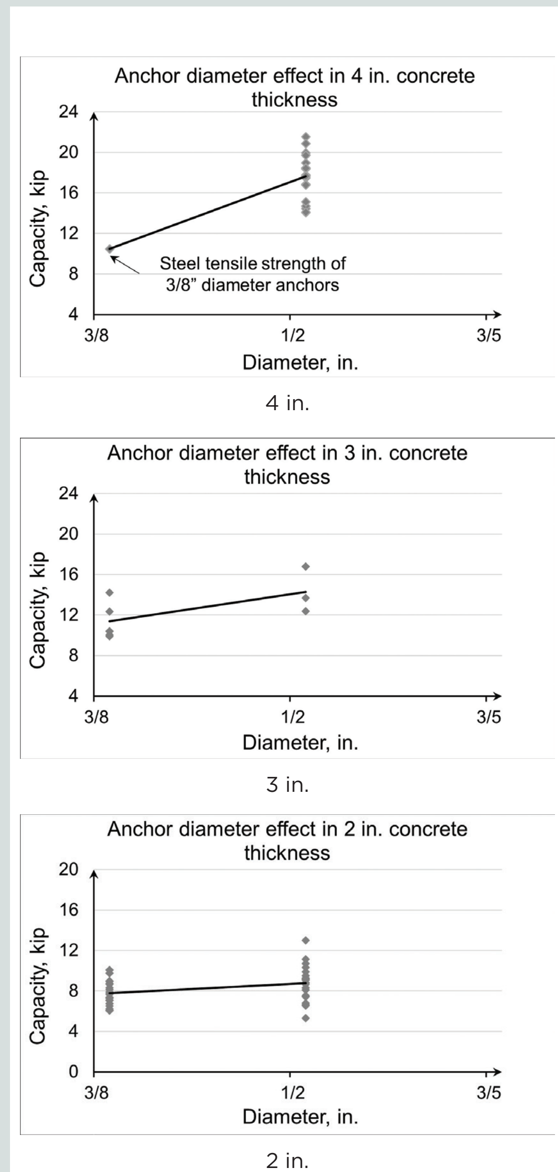


Figure 8. Anchor diameter effect in 4, 3, and 2 in. concrete thickness. Note: 1" = 1 in. = 25.4 mm; 1 kip = 4.448 kN.

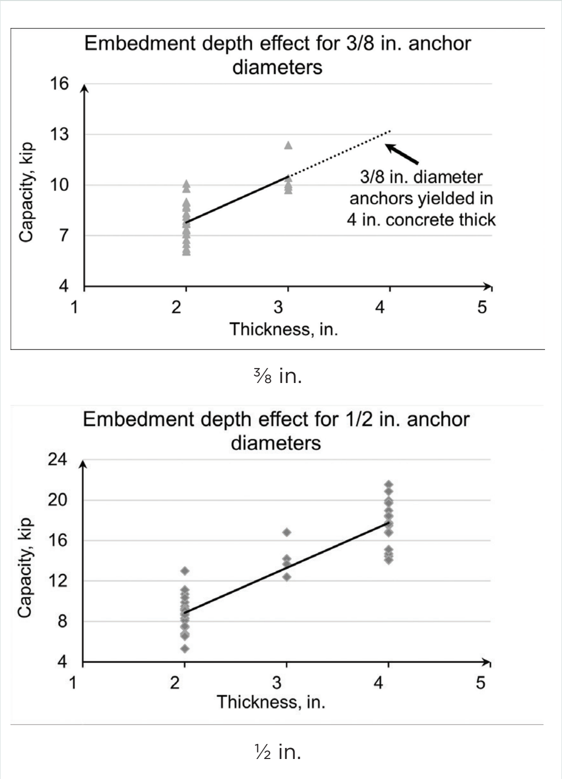


Figure 9. Concrete thickness effect on anchor capacity for ⅜ and ½ in. diameter anchor. Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN.

A three-way analysis of variance with a 95% confidence level was conducted to determine the effects and correlation of anchor diameter, concrete thickness, and adhesive product manufacturer on anchor capacity. The coefficient of correlation is a value that ranges from -1 for maximum negative correlation to +1 for maximum positive correlation; a 0 value represents no correlation. The result showed that the adhesive product had no correlation (correlation value -0.05) to the capacity, which meant that changing the product manufacturer did not affect the capacity. Note that the same supplier was used for all steel threaded rods and the adhesive came from three different suppliers. The analysis of variance results showed that there was a statistically significant main effect for anchor diameter (correlation value 0.535) and concrete thickness strength (correlation value 0.910), with P-value less than 0.01.

Furthermore, the analysis of variance showed an interaction between the anchor diameter and concrete thickness, which meant that the effect of the diameter on the capacity was affected by the thickness. This interaction was supported by the results shown in Fig. 8, where the effect of anchor diameter (that is, the slope of the trend line) increased as the concrete thickness also increased.

Comparison of adhesive and screw anchors

In the test program, adhesive anchors embedded in 2 and 3 in. (50.8 and 76.2 mm) thick concrete layers always failed in concrete breakout. Back-face blowout did not affect the failure cone, and the cone depth was equal to the concrete thickness. This result was attributed to the adhesive filling the cracks and fractures caused by drilling. In addition, part of the injected adhesive entered the insulation foam layer and created a base or plug for the concrete cone. This adhesive base helped to create a full-thickness cone. Figure 7 and **Fig. 10** show a concrete cone breakout in 2 in. (50.8 mm) thick concrete. The figures show the injected adhesive between the cracks and the base created by the adhesive. Tarawneh et al.[11] provides a magnified picture of the breakout cone.

Figure 10 compares concrete cone breakout for screw and adhesive anchors embedded in 2 in. (50.8 mm) thick concrete.[11] The breakout cone depth for the adhesive anchor was twice the depth of the screw anchor breakout cone. This

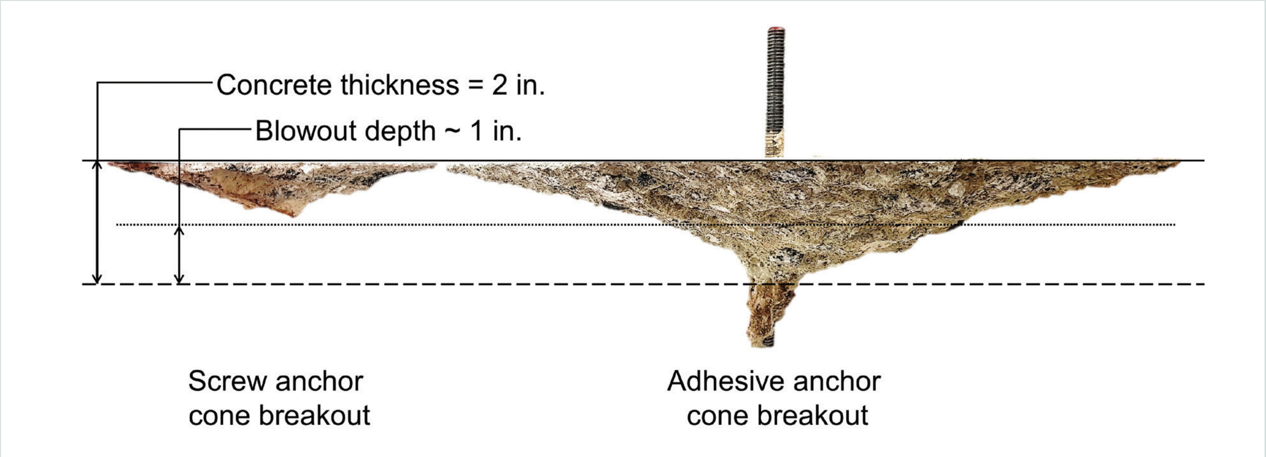


Figure 10. Adhesive and screw anchors concrete cone breakout. Note: 1 in. = 25.4 mm.

Table 2. Adhesive and screw anchor experimental mean capacities

Concrete thickness, in.	Screw anchors		Adhesive anchors	
	⅜ in. diameter, kip	½ in. diameter, kip	⅜ in. diameter, kip	½ in. diameter, kip
2	2.1	2.0	7.8	8.8
3	5.6	6.2	10.3	14.1
4	9	10.2	n.a.	17.5

Note: n.a. = not available. 1 in. = 25.4 mm; 1 kip = 4.448 kN.

increase in size can be attributed to the adhesive that filled the cracks and created a base at the end of the anchor, as previously explained. This increase in cone size led to a significant increase in the capacity. **Table 2** shows the average capacities of screw and adhesive anchors in 2, 3, and 4 in. (50.8, 76.2, and 101.6 mm) thick concrete. Adhesive anchors were tested in concrete with 5.5 ksi (38 MPa) compressive strength, while the screw anchors were tested in concrete with compressive strengths ranging from 5.5 to 8.7 ksi (38 to 60 MPa). For 2 in. thick concrete, the tensile capacity of the adhesive anchors was over four times the capacity of the screw anchors. The additional strength was attributed to the increased effective depth, which was a result of the adhesive mitigating the effects of the concrete blowout cone.

Behavioral and design models for adhesive anchors in thin concrete members

As a standard practice, the CCD model is used to evaluate the capacity of mechanical anchors failing in concrete cone breakout and has been adopted by building codes and design standards. Equation (2) gives the capacity of single-anchor failure in concrete cones with k_c = 13.5 for SI units and k_c = 32 for U.S. customary units (converted by the authors).

The CCD model was used to evaluate the capacity of the adhesive anchors in the test program. For these calculations, the effective depth of the anchor was set equal to the thickness of the concrete. This approach contrasts with the approach used for evaluating screw anchors in thin concrete, where a reduced depth is recommended to account for the effects of back-face blowout (Eq. 4). The experimental data were compared with the CCD model (behavioral model) in **Fig. 11**. Tests have shown that k_c values for adhesive and expansion mechanical anchors are similar.[8] The model has good agreement with the test data (Fig. 11). The average strength ratio (tested capacity/predicted capacity) was 1.1 with a coefficient of variation of 0.2. The accuracy and the fitting of the model can be checked by plotting the ratio between the tested capacity $N_{u\,test}$ and the predicted capacity N_{cb} with respect to thickness and diameter (Fig. 11).

When experimental data are available, it is common practice for concrete anchorage designs to be based on the 5% lower fractile with 90% confidence level of the data. Equation (5) is used to determine the value of k_c that achieves this level of conservatism.[14]

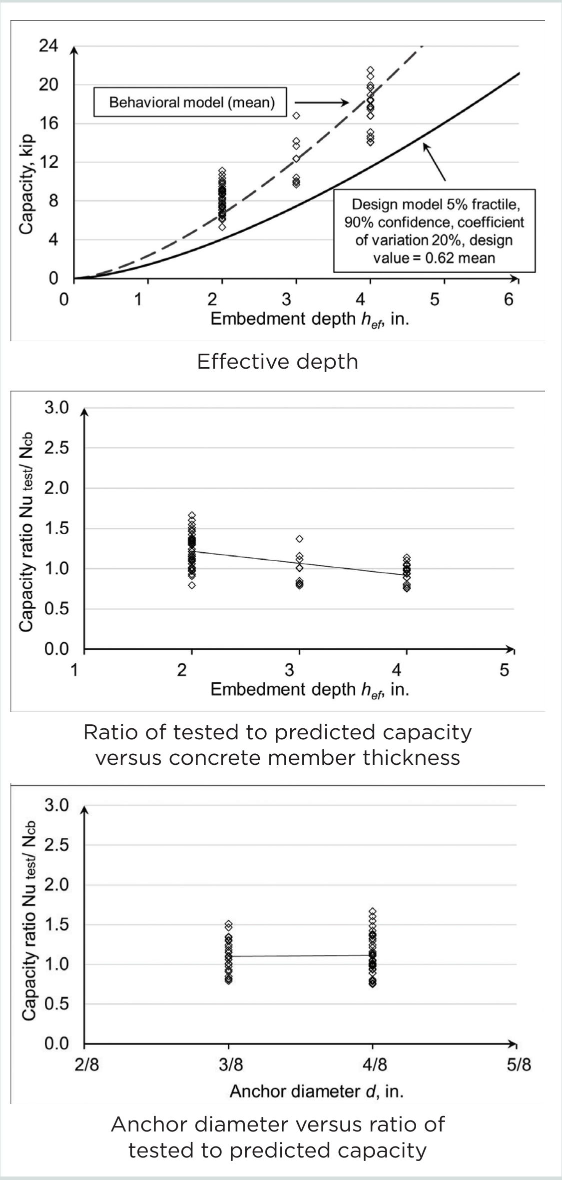


Figure 11. Proposed behavior and design models of adhesive anchors in uncracked thin concrete as function of effective depth, ratio of tested to predicted capacity versus concrete member thickness, and anchor diameter versus ratio of tested to predicted capacity. Note: N_{cb} = concrete breakout capacity; $N_{u\,test}$ = experimental anchor capacity. 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.

$$F_{5\%} = F_m(1 - K\nu) \quad (5)$$

where

$F_{5\%}$ = characteristic capacity at 5% fractile

F_m = mean failure capacity

K = factor for one-sided tolerance limits for normal distributions corresponding to a 5% probability of nonexceedance with a confidence of 90%

ν = coefficient of variation

Following this approach, Eq. (6) gives the proposed design equation. The proposed design model produces conservative results for each of the experimental data points (Fig. 11).

$$N_{cb} = 19.5\sqrt{f'_c}\,h_{ef}^{1.5} \quad (6)$$

Effects of horizontal installation and concrete strength

To verify the adequacy of the proposed model to predict the capacity of anchors installed in higher-strength concrete and for anchors installed horizontally, 12 additional pull-out tests were conducted in 2 and 4 in. (50.8 and 101.6 mm) thick concrete layers with 9.2 ksi (63.4 MPa) concrete compressive strength. The anchors were installed horizontally in the panels. The panels were kept in the upright position during drilling and while installing the anchors. After curing, the panels were placed flat to test the anchors.

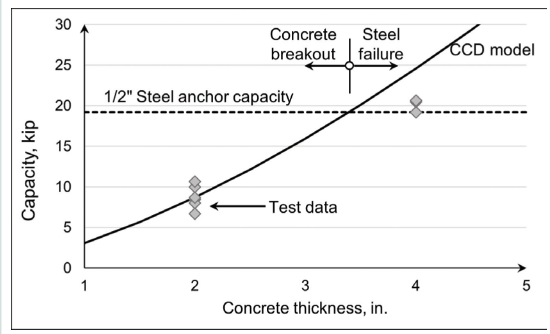
Figure 12 shows the CCD model, steel tensile strength for a ½ in. (12.7 mm) diameter anchor, and test data for anchors embedded in higher-strength concrete with horizontal installation. Anchors embedded in 2 in. (50.8 mm) thick concrete showed a high agreement with the CCD model with a tested/predicted ratio of 1.0. All ½ in. anchors embedded in 4 in. (101.6 mm) thick concrete reached their steel tensile capacity at 80% of the capacity predicted by the model. The results indicate that neither changing the concrete strength nor the orientation of the anchor (vertical or horizontal) affected model prediction accuracy.

Figure 12 shows the effect of concrete strength on ½ in. (12.7 mm) anchors embedded in 2 and 4 in. (50.8 and 101.6 mm) thick concrete. The general trend for both concrete thicknesses was increased capacity as the concrete compressive strength also increased. The effect of concrete strength became more noticeable with greater thickness of concrete, which was consistent with screw anchor behavior.[10]

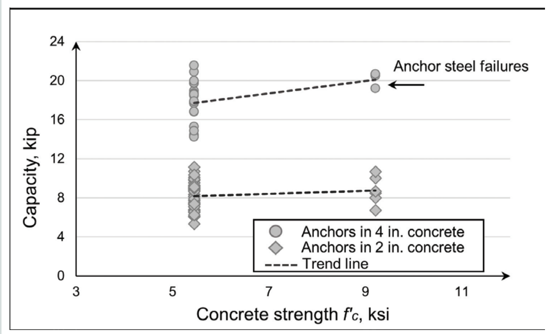
Comparison of behavioral model accuracy and conservatism

As expected, the experimental capacity of adhesive anchors obtained in this study exhibited a degree of variability. Scatter in the experimental data was primarily attributed to variations in concrete tensile capacity.[15] The experimental variability led to variability in the accuracy of the proposed model. To assess the overall conservatism and accuracy of the proposed model, it was useful to compare the current results with those of other test programs (**Table 3**). These comparisons provided context for the degree of scatter observed in the adhesive anchor tests in thin concrete layers and for the accuracy of the behavior model.

The bias and coefficient of variation values for the other anchor types shown in Table 3 are based on CCD and adhesive bond failure models. These models formed the basis of the design models included in ACI 318-14. Bias and coefficient of variation values from other anchor types were used as a threshold to compare with the behavioral model. It was inferred that the behavior model for adhesive anchors in thin concrete was adequate if it had a bias equal to or greater than 1.0 and a coefficient of variation equal to or less than 23%. In all cases, data from the current experiments and model resulted in bias and coefficient of variation values that are within these limits. This suggests that the model for adhesive anchors in thin concrete will provide levels of conservatism and accuracy that are similar to, if



Experimental and predicted capacities for anchors installed horizontally in higher-strength concrete



Effect of concrete strength for ½ in. anchors

Figure 12. Experimental and predicted capacities for anchors installed horizontally in higher-strength concrete (9.2 ksi) and effect of concrete strength for ½ in. anchors. Note: CCD = concrete capacity design model. 1 ″ = 1 in. = 25.4 mm; 1 kip = 4.448 kN. 1 ksi = 6.895 MPa.

Source	Database anchor type	Number of tests	Bias	Coefficient of variation, %
Tarawneh et al. (2020)	Screw anchors in thin concrete	100	1.1	20
Olsen, Pregartner, and Lamanna (2012)	Screw anchors in thick concrete	402	1.1	15
Eligehausen et al. (1992)	Headed studs	318	1.0	18
Fuchs, Eligehausen, and Breen (1995)	Expansion/undercut anchors	519	1.0	23
Cook et al. (1998)	Adhesive anchors (bond failure)	888	1.0	20
Current test program	All tests	101	1.1	20
	Anchors in 4 in. thick concrete	46	1.0	12
	Anchors in 3 in. thick concrete	9	1.3	19
	Anchors in 2 in. thick concrete	46	1.1	17

Table 3. Comparison of current and earlier tests programs.

Note: All data are from tensile tests of single anchors. Bias = average experimental-to-model capacity ratio. 1 in. = 25.4 mm.

not better than, the leading models applied to other anchor types and conditions. Furthermore, the favorable comparison of bias and coefficient of variation values suggests that the strength reduction factors in the ACI code are reasonable for use with the design model for adhesive anchors in thin concrete.

Although the comparisons shown in Table 3 are encouraging, additional research is needed to confirm whether the findings of the current test program can be generally applied. Future research should include testing by multiple organizations, and testing should include a wider range of variables. Variables in future research should include different concrete mixtures (varying aggregate type and size, compressive strength, and thickness), different hammer drill models and users, and interactions among variables. A reliability analysis is also recommended to confirm the validity of the ACI strength reduction factors.

Recommendation

Previous research has shown that screw anchors in thin concrete members can support significant loads;[11] however, it is clear from the current results that adhesive anchors provide superior tensile capacity under similar conditions. For example, in the case of anchors in 2 in. (50.8 mm) thick concrete, adhesive anchors provide approximately four times greater capacity than comparable screw anchors. In addition, adhesive anchors showed consistent performance independent of the adhesive supplier, unlike screw anchors, for which the failure mode and capacity depended on the product itself. Therefore, the authors recommend that adhesive anchors be used in lieu of screw anchors in most situations. Screw anchors are typically more efficient to install and may be reasonable for some temporary fixtures, nonstructural elements, and lightly loaded connections.

Conclusion

This study investigated the tensile behavior of adhesive anchors embedded in thin concrete members. Experimental data were used to verify a design model for single tension-loaded adhesive anchors with full-thickness concrete embedment. Results were also compared and contrasted with a previous study on the use of screw anchors in thin concrete members. The following conclusions are made:

- The CCD model with effective embedment depth equal to the concrete layer thickness can be used to calculate the tensile capacity of adhesive anchors with full-thickness installation in thin concrete members. The average experimental-to-calculated ratio for the test program was 1.1 with a coefficient of variation of 0.2.

- The bias and the coefficient of variation of the proposed model and experimental data are similar to the bias and coefficient of variation reported for widely accepted models applied to other anchor types and conditions. This suggests that the CCD model for adhesive anchors in thin concrete provides a similar level of accuracy and variability.

- The depth of concrete cone breakout for adhesive anchors embedded in 2 and 3 in. (50.8 and 76.2 mm) thick concrete layers was equal to the concrete thickness. The effect of back-face blowout was mitigated because the adhesive filled the cracks that occurred due to drilling. This phenomenon led to a larger failure cone and significantly higher capacity compared with screw anchors.

- The capacity of adhesive anchors was approximately 200% to 400% greater than the capacity of comparable screw anchors. Adhesive anchors exhibited a consistent failure mode in each concrete thickness that was independent of the adhesive product, unlike screw anchors, where the failure mode was affected by the screw geometry.

- The effects of anchor diameter and concrete strength on anchor capacity tend to increase with increasing embedment depth. The adhesive products did not significantly affect anchor capacity. Although the test data for investigating the effects of the installation orientation (vertical or horizontal installation) were limited, there is no evidence that orientation affects anchor capacity.

The results and models in this paper are valid only for the limits of the variables tested. However, these limits are within a practical range of values that are common in many applications.

The following should be considered to be the limits of the design model unless additional testing is provided:

- anchor diameter = ⅜ to ½ in. (9.525 to 12.7 mm)
- concrete strength = 5.5 to 9.2 ksi (38 to 63.4 MPa)
- concrete thickness = 2 to 4 in. (50.8 to 101.6 mm)

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Notation

$A_{se,N}$ = effective anchor cross-sectional area

d = anchor diameter

f_c' = concrete compressive strength at 28 days

f_{uta} = tensile strength of the steel

F_m = mean failure capacity

$F_{5\%}$ = 5% fractile or characteristic capacity

h_b = blowout depth, taken as 0.95 in. (24.13 mm)

h_{ef} = effective anchor embedment depth

h_{nom} = nominal length of the anchor

k_c = per coefficient for basic concrete breakout strength in tension (ACI 318-14)

K = factor for one-sided tolerance limits for normal distributions

N_{ba} = anchor bond failure capacity

N_{cb} = concrete breakout capacity

N_{sa} = steel anchor capacity

$N_{u\ test}$ = experimental anchor capacity

P = applied load

ν = coefficient of variation

τ = mean bond stress associated with each product based on the 5% fractile

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Abstract

This paper presents an experimental program investigating the behavior of single adhesive anchors embedded in precast concrete sandwich wall panel systems under tension loading. Variables included concrete thickness, concrete compressive strength, anchor diameter, and adhesive manufacturer. Anchors were embedded in the full thickness of the concrete member, and the effects of back-face blowout due to drilling were considered. The results showed that the concrete capacity design model with an effective embedment depth equal to the concrete layer thickness can be used to calculate the tensile capacity of adhesive anchors with full-thickness installation in thin concrete members. The average experimental-to-calculated ratio for the test program was 1.1 with a coefficient of variation of 0.2. Based on the experimental results, behavioral and design models are proposed. The proposed model results in levels of accuracy and variability that are consistent with other types of anchorage and the associated models.

Keywords

Adhesive anchor, anchorage, postinstalled anchor, sandwich wall panel, thin concrete member.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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