Tensile Behavior and Design of Adhesive-Bonded Anchors and Dowels

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Adhesive-bonded anchors and reinforcing dowels are frequently used in highway applications. Currently, designers rely on either manufacturers' recommendations or job-by-job testing to determine the capacity of these anchors. The purpose of the research was to develop a rational design procedure for adhesive-bonded anchors. The design recommendations presented are based on a combination of a uniform bond stress model for typical embedment lengths and an elastic bond stress model for deep embedments. The use of the easily applied uniform bond stress model for typical embedment lengths is justified by comparison with an elastic bond stress model that considers compatibility of displacements for the adhesive anchor system. A total of 167 tests were performed using three anchor diameters and 16 adhesive products. Load-displacement data were collected for each test. A series of 144 baseline tests of confined, fully bonded anchors was used to determine the basic bond and stiffness properties of the adhesive-bonded anchors. The results of the baseline test series were used to compare the uniform bond stress model with the rationally based but more complicated elastic bond stress model. Another 23 tests were performed for comparison with the results of the baseline tests. These consisted of unconfined tests with both fully and partially bonded anchors and confined tests with partially bonded anchors.

An adhesive-bonded anchor is a reinforcing bar or threaded rod inserted into a drilled hole in hardened concrete with a structural adhesive acting as a bonding agent between the concrete and the steel. Typically the hole diameter is only about 10 to 25 percent larger than the diameter of the reinforcing bar or threaded rod. Structural adhesives for this type of anchor are available as two-component polyester, vinylester, and epoxy systems typically packaged in glass capsules or in dual-cartridge injection systems.

Adhesive-bonded anchors provide a viable, economical method for adding new concrete sections or attaching steel members to existing concrete structures. Currently, most designers follow the adhesive manufacturer's recommendations, which are based on laboratory testing specific to individual products and applications. In many applications proof-load testing is required for each anchor diameter and embedment length. The increasing amount of retrofit and rehabilitation work encountered today exemplifies the need for a standard specification and design procedure for this type of anchor.

The purpose of the research described in this paper was to study the tensile behavior of adhesive-bonded anchors and to identify bond parameters specific to different types of adhesives. Adhesives used in this research program were packaged as self-mixing, two-component systems composed of an epoxy, polyester, or vinylester resin and a catalyst or curing agent. The diameters and embedment lengths of the anchors were varied to provide a broad range of contact surface areas and length-to-diameter ratios. The embedment lengths were chosen to prevent steel failure and concentrate on the bond strengths of the individual adhesives. Baseline tests were used to determine bond and stiffness characteristics specific to each adhesive. These properties were used to develop a rational design procedure for adhesive-bonded anchors. Other tests were performed to confirm the results from the baseline tests.

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BACKGROUND

Adhesive-bonded anchors transfer load differently than do headed cast-in-place or mechanical anchors. Headed anchors transfer load through bearing of the anchor head on the concrete. Bonded anchors transfer load through bond to the concrete along the entire bonded portion of the anchor.

Failure Modes

Bonded anchors may fail by anchor steel failure, bond failure, or bond failure combined with a shallow concrete cone. Anchor steel failure (characterized by yielding and fracture of the steel) is likely to occur only with sufficiently long embedment lengths. To achieve this failure mode, the tensile strength of the anchor must be less than the strength associated with the embedded portion of the anchor. As shown in Figure 1, the failure modes associated with the embedded portion of the anchor are bond failure or combined cone-bond failure.

In a typical installation, bond failure without a concrete cone may occur if the bonded surface lacks adequate bond strength because of the adhesive itself, improper curing, or inadequate hole preparation. As shown by Doerr et al., bond failure without a concrete cone will occur when the top 51 mm (2 in.) of the embedment length is debonded (*1*). Bond failure without a concrete cone can also be achieved by performing confined tension tests; such tests will be discussed later.

The typical failure mode for unconfined tensile tests is by combined cone-bond failure. Tests by Doerr et al. indicate that the contribution of the shallow concrete cone to the strength of the anchor is insignificant and can be neglected in design (*1*). The results of their tests on anchors with 16-mm (⅝-in.) diameters indicated that the shallow cone [typically about 51 mm (2 in.) deep] only contributed 19 percent to the strength

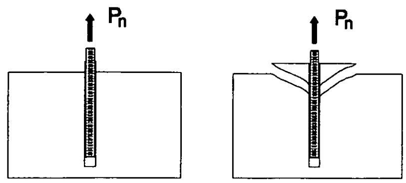

FIGURE 1 Typical embedment failure modes: *left*, bond; *right*, combined cone-bond.

of anchors embedded 102 mm (4 in.) and 7 percent to the strength of anchors embedded 152 mm (6 in.).

Load-Displacement Characteristics

The results of tests performed by Collins et al. indicate that adhesive-bonded anchors behave linearly up to an elastic limit (*2*). After the elastic limit is reached, the load-carrying capacity of an adhesive-bonded anchor is unpredictable. In some tests the strength of the anchor increased after the elastic limit was reached; in other tests the strength decreased after the elastic limit.

Variables Affecting Tensile Strength

Several variables influence the tensile strength of bonded anchors. Among those that may have an appreciable affect are the strength of the components (bonding agent, concrete, steel), hole cleaning, temperature, time of loading, type of loading, moisture in the hole, and cracked concrete. The effect of many of these variables on the tensile strength of bonded anchors has been investigated in previous studies. These studies typically compare the strength of bonded anchors not subjected to specific variables with those that are. Although these studies are very valuable, they would increase in value if a design procedure that adequately predicts the strength of a standard bonded anchor could be developed. The results of these studies could then be used to adjust the predicted strength of the standard bonded anchor in the same manner as development lengths for reinforcing bars are adjusted for various conditions.

The design recommendations for bonded anchors developed in this report are based on a standard bonded anchor. A standard bonded anchor is assumed to be installed in a clean, dry hole in uncracked concrete and tested at 24 hr (±2 hr) under normal laboratory temperatures with monotonically applied tension.

BOND STRESS MODELS

Figure 2 shows two possible bond stress models for bonded anchors: the uniform bond stress model and the linear elastic bond stress model.

Uniform Bond Stress Model

A uniform bond stress distribution relates a tensile load to the product of a bond stress and a surface area. The uniform bond stress model is easy to apply but does not account for compatibility between the concrete, bonding resin, and threaded rod. The following equation is used to predict the strength for a uniform bond stress distribution:

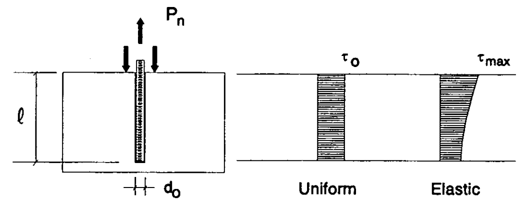

FIGURE 2 Bond stress models.

$$P_n = \tau_0 \pi d_0 \ell \tag{1}$$

where

P_n = nominal tensile strength of adhesive anchor,
τ_0 = maximum bond stress of adhesive based on a uniform bond stress distribution,
d_0 = hole diameter, and
ℓ = embedment length of adhesive anchor.

Elastic Bond Stress Model

The linear elastic bond stress model has been proposed by Doerr et al. (*1*). The model addresses compatibility relationships between the concrete, bonding resin, and threaded rod for the bonded anchor. Figure 3 shows the elastic model for an adhesive-bonded anchor. The full development of the elastic solution is provided elsewhere (*1,3*); only the results used in this paper are presented here. Using the appropriate boundary conditions noted in Figure 3, the final solution for the elastic bond stress model in terms of displacement is found to be

$$w(z) = \frac{P\sqrt{d_0}}{AE\lambda'} \left(\frac{\cosh \dfrac{\lambda' z}{\sqrt{d_0}}}{\sinh \dfrac{\lambda' \ell}{\sqrt{d_0}}} \right) \tag{2}$$

where

$w(z)$ = displacement at a distance z from bottom of anchor,
AE = stiffness property of threaded rod or reinforcing bar,
λ' = elastic constant for adhesive anchor system that is dependent on shear stiffness of adhesive-concrete system and axial stiffness of threaded rod or reinforcing bar (λ' is independent of hole diameter), and
z = distance measured from bottom of anchor.

The solution of the elastic bond stress model in terms of the nominal tensile strength of the anchor is given by

$$P_n = \tau_{max} \pi d_0 \left(\frac{\sqrt{d_0}}{\lambda'} \tanh \frac{\lambda' \ell}{\sqrt{d_0}} \right) \tag{3}$$

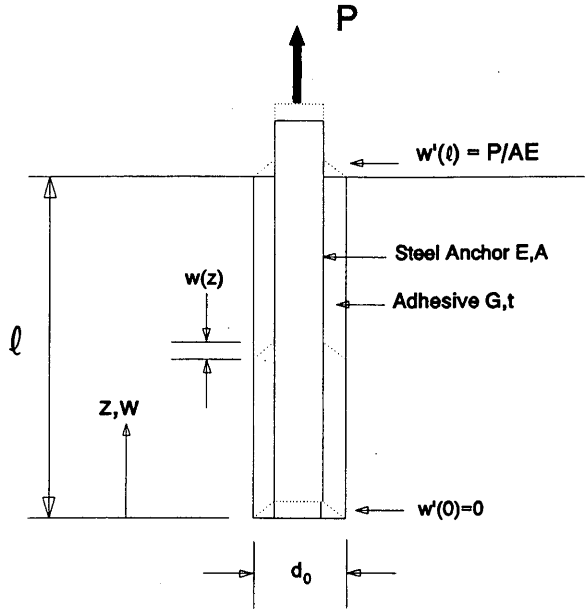

FIGURE 3 Elastic model of bonded anchor: $\epsilon = w'(z)$, $\lambda = w(z)/t$.

where τ_{max} is the maximum bond stress of adhesive based on an elastic bond stress distribution.

Note that the uniform bond stress model represented by Equation 1 is similar to the elastic bond stress model of Equation 3. The only differences are that τ_0 is replaced by τ_{max} and that ℓ is replaced by the last term of Equation 3, which includes an hyperbolic tangent function involving ℓ. The last term of Equation 3 varies between ℓ for short bonded lengths and something less than ℓ at longer bonded lengths.

TESTING PROGRAM

As mentioned, the test program included a series of 144 baseline tests performed with 16 adhesives. The purpose of these tests was to determine bond (τ_0 and τ_{max}) and stiffness (λ') properties specific to each adhesive. These properties were then used to develop design recommendations for adhesive-bonded anchors. An additional 23 supplemental tests were performed to verify the results of the baseline tests.

Test Specimens

ASTM A193 Grade B7 threaded rods were used for all of the adhesive-bonded anchor tests. This high-strength steel with a minimum specified tensile strength of 86 MPa (125 ksi) was used to ensure that the bond would fail before the steel failed. Before installation, the threaded rods were soaked in paint thinner and wiped clean to rid the steel of any oily residue.

Anchors were installed in concrete blocks 1830 × 1370 × 380 mm (72 × 54 × 15 in.). All tests were performed in the top surface of the test blocks. Reinforcing bars were placed in the bottom of the test blocks. The minimum specified 28-day compressive strength of the concrete was 24.1 MPa (3,500 psi). The actual compressive strength of the concrete at the time of testing was 37.0 MPa (5,370 psi) as determined from standard cylinder tests.

Holes were drilled into the concrete using a rotary hammer drill. Drill bit sizes were 14 mm (9/16 in.) for 13-mm (1/2 in.) rods, 19 mm (3/4 in.) for 16-mm (5/8 in.) rods, and 22 mm (7/8 in.) for 19-mm (3/4 in.) rods. The holes were then cleaned out with compressed air. A plastic tube enabled the compressed air to clean the bottoms and sides of the holes until residual dust leaving the holes was no longer noticeable. A stiff bottle brush connected to an electric drill was used to loosen dust along the sides of the holes. Afterward, compressed air was again used to remove any residual dust.

Adhesive products were installed using the manufacturer's recommendations. Anchors were tested after curing for 24 hr (±2 hr).

Baseline Tests

The baseline tests involved confined testing with fully bonded anchors to determine bond (τ_0 and τ_{max}) and stiffness (λ') properties specific to each adhesive. This method of testing prevented spalling at the surface of the concrete and allowed for the study of the bond strength in the absence of the shallow concrete cone that typically forms in unconfined testing. Load-displacement data were recorded for all tests.

Three test series were performed for each of the 16 adhesive products tested. A test series included three repetitions of tensile tests on anchors with the same diameter and embedment length. The anchor diameters tested were 13, 16, and 19 mm (1/2, 5/8 and 3/4 in.), and their respective embedment lengths were 127, 89, and 178 mm (5, 3.5, and 7 in.). These combinations of dimensions were chosen to provide a range in the specimens' $\ell/\sqrt{d_0}$ ratio. This relationship was determined to be important in modeling the behavior of adhesive anchors.

The parameters τ_0, τ_{max}, and λ' were determined using the data from the baseline tests for each adhesive. The maximum uniform bond stress τ_0 was determined by dividing the load at the elastic limit by the bonded surface of the anchor as follows:

$$\tau_0 = \frac{P_{exp}}{\pi d_0 \ell} \quad (4)$$

where P_{exp} is the load at the elastic limit.

The stiffness property λ' of the adhesive anchor system was determined from the slope of the load-displacement diagram. Anchor stiffness (k) is the relationship between axial load and displacement of the anchor at the surface of the concrete.

$$k = \frac{P}{w(\ell)} \quad (5)$$

where k is the stiffness of adhesive-bonded anchor (slope of load-displacement diagram).

Evaluating Equation 2 at $z = \ell$ results in the following:

$$k = \frac{AE\lambda'}{\sqrt{d_0}} \tanh \frac{\lambda' \ell}{\sqrt{d_0}} \quad (6)$$

The product AE was experimentally determined for each anchor diameter. Samples of each diameter of threaded rod were axially loaded in tension using a Tinius Olsen testing machine. Load-displacement data were recorded for each test. The displacement was measured over a gauge length ℓ_g equal to 51 mm (2 in.). Noting that the slope of the load-displacement diagram in the elastic range is the axial stiffness of the anchor over the gauge length (AE/ℓ_g), the value of AE is the slope of the load-displacement diagram multiplied by the gauge length. The experimentally determined values for AE for the 13-, 16-, and 19-mm (½-, ⅝-, and ¾-in.) threaded rods were 17.4, 26.5, and 42.6 kN (3,920, 5,950, and 9,580 kips), respectively.

The value of λ' was determined from Equation 6 using the slope of the load-displacement diagram (k) and the appropriate values of d_0 and AE for the rod diameter tested.

The maximum elastic bond stress τ_{max} was determined from λ' and the load at the elastic limit as follows:

$$\tau_{max} = \frac{P_{exp}}{\pi d_0 \left(\frac{\sqrt{d_0}}{\lambda'} \tanh \frac{\lambda' \ell}{\sqrt{d_0}} \right)} \qquad (7)$$

Supplemental Tests

Four types of supplemental tests were performed. The primary purpose of these tests was to determine if the bond and stiffness properties determined from the baseline tests could be used to predict the strength of anchors that were in some way different from those included in the baseline test series. The four types of supplemental tests were as follows:

1. Six confined, fully bonded tests of 16-mm (⅝ in.) anchors embedded 152 mm (6 in.) using two adhesive products (three tests each).
2. Nine confined, partially bonded tests of anchors with diameters of 13, 16, and 19 mm (½, ⅝, and ¾ in.) embedded 127, 152, and 178 mm (5, 6, and 7 in.), respectively (three tests each). In partially bonded tests, the top 51 mm (2 in.) of the anchors was wrapped with duct tape to debond it before installation. The purpose of these tests was to determine if the bond stress models were applicable when the bonded length did not extend to the surface of the concrete.
3. Three unconfined, partially bonded tests of anchors with diameters of 19 mm (¾ in.) embedded 178 mm (7 in.). The purposes of these tests were to determine if confinement affected the performance of partially bonded anchors.
4. Five unconfined, fully bonded tests of anchors with diameters of 19 mm (¾ in.) embedded 178 mm (7 in.) with two adhesive products (two tests with Product E1 and three tests with Product E2). The primary purpose of these tests was to verify the conclusions of Doerr et al. (*1*) that the contribution of the shallow concrete cone to the strength of the anchor is minimal and that the concrete cone is approximately 51 mm (2 in.) deep.

Test Equipment and Procedure

The confined tests were performed in accordance with ASTM E1512. Figure 4 shows the test apparatus used for the confined tension tests. The objective of the confined testing was to keep the reaction force close to the adhesive anchor. This was accomplished by the use of confining plates. Confining plates were steel plates 13 mm (½ in.) thick with a hole diameter 13 mm (½ in.) greater than the anchor diameter. They were placed over the anchor and onto the surface of the concrete.

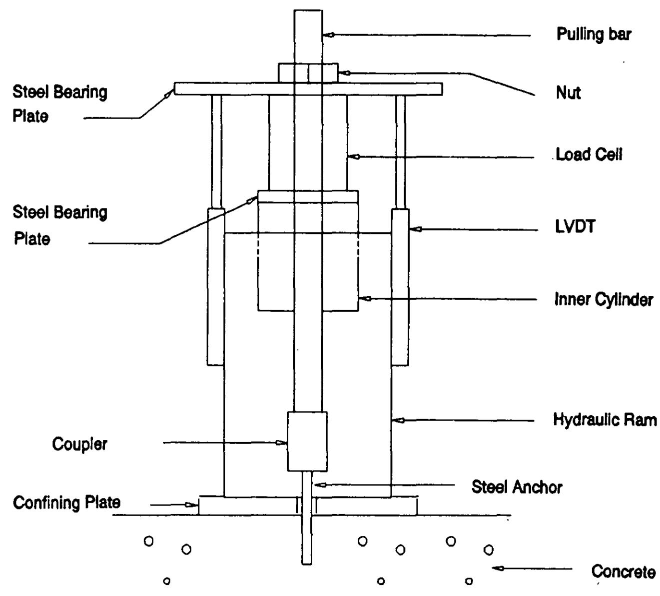

FIGURE 4 Schematic of loading apparatus of confined test.

A 890-kN (200-kip) centerhole hydraulic ram was then placed over the anchor and on top of the confining plate. A pulling rod extended through the center of the hydraulic ram and supplied the load to the adhesive anchors. This rod was of ASTM A193 Grade B7 steel and was connected to the adhesive anchors by means of high-strength steel couplers.

The hydraulic ram was connected by hydraulic hoses to a hand pump. Load was applied at a constant rate until the bond between the adhesive and the concrete was well beyond failure.

As shown in Figure 4, displacement was measured by two linear variable differential transformers (LVDTs) attached to the hydraulic ram. Measuring displacement at the top of the hydraulic ram necessitated a correction to the slope of the measured load-displacement diagrams to account for the stiffness of the pulling bar. This correction was accomplished by determining the stiffness of the pulling bar in a Tinius Olsen testing machine. Since the diameter of the pulling bar was large in comparison with the anchor diameter, the necessary correction was minimal.

The purpose of the unconfined tests was to keep the reaction force away from the adhesive anchor. This was accomplished by the use of an ASTM E488–type test frame. The same instrumentation and procedure used for the confined testing was used for the unconfined testing.

TEST RESULTS

Baseline Tests

A typical load-displacement diagram is shown in Figure 5. Figure 5 indicates a range of elastic behavior up to an elastic

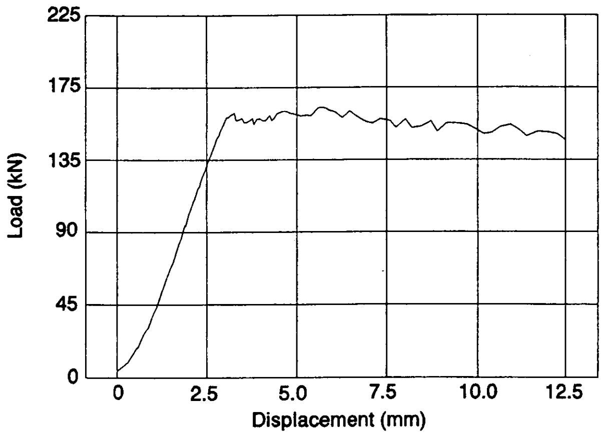

FIGURE 5 Typical load-displacement diagram: Product E5, 19-mm anchor diameter, 178-mm bonded length.

limit. After the elastic limit is reached, the graph shows additional increases and decreases in tensile strength. Some test results showed an overall strength increase after the elastic limit, and others showed an overall decrease. This appeared to be a random phenomenon and is mainly due to mechanical interlock of the adhesive anchor and the surrounding concrete after the initial bond is broken. This indicates that one should not rely on the strength of adhesive-bonded anchors past the elastic limit. The load-displacement diagrams for each repetition in a test series indicated a consistent behavior in the elastic range.

The load at the elastic limit was taken at the point where the slope of the graph begins to deviate from a straight line. The load at the elastic limit was averaged for each of the three repetitions of a test series. The resulting load was used in Equation 1 to determine a value of τ_0 for each test series. The values of τ_0 for each test series were approximately equal for a given adhesive. Therefore, a single value of τ_0 represents each adhesive.

The slope of the initial straight-line portion of the graph (the elastic range) represents the stiffness of the test system. It was calculated using the regression analysis feature of a computer spreadsheet. For each adhesive, an average stiffness k was calculated for each test series. The k-values were then substituted into Equation 6 to solve for λ'. For each adhesive, the values of λ' for each test series were approximately equal. Therefore, a single value of λ' represents each adhesive. Values of τ_{max} were determined for each test series from Equation 7 using the value of λ' for the adhesive and the average load at the elastic limit. The values of τ_{max} for each test series were approximately equal for a given adhesive. Therefore, a single value of τ_{max} represents each adhesive.

The values of τ_0, τ_{max}, and λ' for each of the 16 adhesives tested are given in Table 1. Table 1 indicates the following:

1. The bond properties of adhesives are dependent on the adhesive product.
2. The stiffness of the bonded anchor system decreases with decreasing bond strength.
3. The uniform bond stress τ_0 is nearly the same as the maximum bond stress τ_{max} determined from elastic theory.

TABLE 1 Summary of Bond Properties

Adhesive Number	Type of Adhesive	Bond Properties		
		τ_0 MPa	τ_{max} MPa	λ' $mm^{-0.5}$
E5	Epoxy (Mercaptan)	14.6	15.9	0.017
E11	Epoxy (Mercaptan)	13.6	14.9	0.017
E12	Epoxy (Amine)	13.1	14.5	0.018
E15	Epoxy (Amine)	12.4	13.7	0.019
E6	Epoxy (Amine)	12.1	13.1	0.017
E7	Vinylester (Capsule)	12.1	13.0	0.015
E2	Epoxy (Mercaptan)	10.0	10.7	0.014
E4	Polyester (Capsule)	9.4	10.0	0.014
E10	Epoxy (Amine)	9.2	9.8	0.014
E9	Polyester (Pouch)	8.9	9.6	0.015
E16	Epoxy (Amine)	8.9	9.5	0.015
E13	Vinylester	8.6	8.8	0.011
E1	Epoxy (Amine)	8.2	8.6	0.012
E14	Vinylester	7.9	8.1	0.009
E3	Epoxy (Amine)	6.4	6.7	0.013
E8	Polyester (Pump)	6.3	6.6	0.013

1 MPa = 145 psi 1 $mm^{-0.5}$ = 5.04 $in^{-0.5}$

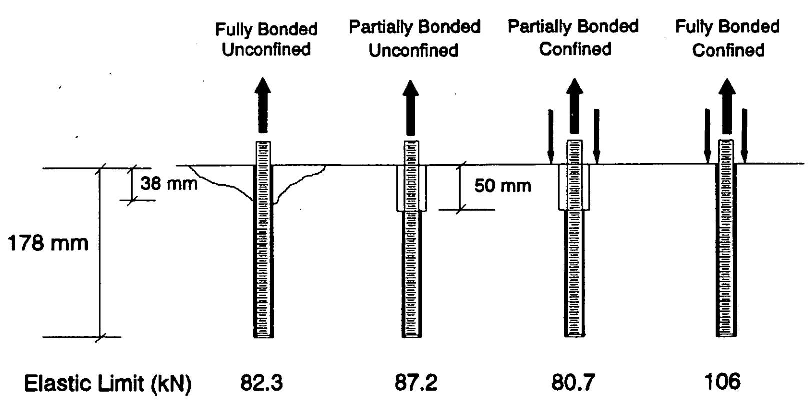

FIGURE 6 Fully and partially bonded, confined and unconfined tension tests.

Supplemental Tests

Load-displacement diagrams for the supplemental tests exhibited the same characteristics as those in the baseline test series. In the elastic range all repetitions of a particular test exhibited the same behavior.

Figure 6 shows the results for fully and partially bonded, confined and unconfined tension tests on 19 mm (¾ in.) diameter anchors embedded 178 mm (7 in.). The figure indicates that there was no appreciable difference in the strength of partially bonded anchors subjected to either confined or unconfined testing. As expected, Figure 6 also indicates that the strength of a fully bonded confined anchor is higher than that of a partially bonded anchor. This indicates that strength is directly related to the effective bonded length.

The results shown in Figure 6 for the fully bonded unconfined tests indicate an average cone depth of 38 mm (1.5 in.) and an anchor strength the same as for partially bonded anchors of the same embedded length. This agrees with the test results of Doerr et al. (*1*), which showed that the strength of a partially bonded anchor is essentially the same as a fully bonded anchor of the same embedment length. This indicates that the effective bonded length of an unconfined anchor may be taken as

$$\ell_{ef} = \ell - 50 \text{ mm}$$

$$\ell_{ef} = \ell - 2 \text{ in.} \tag{8}$$

where ℓ_{ef} is the effective bonded length of an adhesive anchor.

COMPARISON OF BOND STRESS MODELS TO TEST RESULTS

Table 2 gives a comparison of the uniform and elastic bond stress models to the baseline test results. Table 3 presents a comparison of the two bond stress models to the results of the 23 supplemental tests. The calculated values shown in Tables 2 and 3 were determined by using the results shown in Table 1 in Equation 1 for the uniform bond stress model and Equation 3 for the elastic bond stress model. In Table 3 the effective bonded length ℓ_{ef} given by Equation 8 was used for the partially bonded tests and the fully bonded unconfined tests.

Table 4 provides a statistical summary of the results. Table 4 indicates that both models provide a very good fit to both the baseline test data and the supplemental test data. As expected, the elastic bond stress model provides a slightly better fit to the test data than the uniform bond stress model; however, the difference is insignificant.

The reason both models fit the test data is that they are essentially the same for typical embedment lengths and anchor diameters. Figure 7 shows a comparison of the two models for a typical adhesive product; the anchor diameter is 16 mm, the hole diameter is 19 mm, $\tau_0 = 10.0$ MPa, $\tau_{max} = 10.7$ MPa, and $\lambda' = 0.015\ \text{mm}^{-0.5}$. As indicated by Figure 7, the elastic bond stress model (which is based on a rational analysis) matches the more easily applied uniform bond stress model up to a bonded length of about $40\sqrt{d_0}$ when d_0 is in millimeters or $8\sqrt{d_0}$ when d_0 is in inches. The actual deviation between the two models for any anchor diameter and adhesive bond properties can be shown to be less than 5 percent at this bonded length. Comparisons of results for the adhesives studied and various anchor diameters indicate that the deviation in behavior between uniform and elastic behavior is more closely related to the length as a function of $\sqrt{d_0}$ than it is to d_0.

TABLE 2 Experimental Versus Calculated Capacities for Baseline Tests

Adhesive Number	Anchor Diameter mm	Embedded Length mm	P_{exp}/P_{calc} Uniform	P_{exp}/P_{calc} Elastic
E1	13	127	0.91	0.92
	16	89	1.05	1.03
	19	178	1.03	1.05
E2	13	127	1.16	1.16
	16	89	0.99	0.95
	19	178	0.85	0.88
E3	13	127	0.88	0.88
	16	89	1.22	1.19
	19	178	0.89	0.91
E4	13	127	1.28	1.28
	16	89	0.84	0.81
	19	178	0.88	0.90
E5	13	127	0.88	0.88
	16	89	1.19	1.14
	19	178	0.94	0.98
E6	13	127	1.12	1.14
	16	89	1.12	1.07
	19	178	0.76	0.79
E7	13	127	0.97	0.98
	16	89	1.00	0.95
	19	178	0.93	1.11
E8	13	127	1.19	1.20
	16	89	1.07	1.04
	19	178	0.74	0.75
E9	13	127	0.91	0.92
	16	89	1.18	1.14
	19	178	0.92	0.94
E10	13	127	0.88	0.88
	16	89	1.14	1.10
	19	178	0.99	1.01
E11	13	127	0.89	0.91
	16	89	1.16	1.10
	19	178	0.94	0.98
E12	13	127	0.93	0.95
	16	89	1.20	1.14
	19	178	0.86	0.90
E13	13	127	0.98	0.98
	16	89	1.02	1.01
	19	178	1.00	1.01
E14	13	127	1.06	1.06
	16	89	1.01	1.00
	19	178	0.93	0.93
E15	13	127	0.93	0.94
	16	89	1.25	1.19
	19	178	0.82	0.86
E16	13	127	0.66	0.67
	16	89	1.27	1.22
	19	178	1.09	1.12

1 mm = 0.03937 in

TABLE 3 Experimental Versus Calculated Capacities for Supplemental Tests

Type of Test	Adhesive Number	Anchor Diameter mm	Embedded Length mm	Bonded Length mm	P_{exp}/P_{calc} Uniform	P_{exp}/P_{calc} Elastic
Confined Fully Bonded	E2	16	152	152	0.85	0.87
	E3	16	152	152	1.14	1.18
Confined Partially Bonded	E2	13	127	76	1.31	1.28
	E2	16	152	102	1.00	0.97
	E2	19	178	127	0.91	0.89
Unconfined Partially Bonded	E2	19	178	127	0.98	0.97
Unconfined Fully Bonded	E1	19	178	178	1.15	1.15
	E2	19	178	178	0.93	0.92

1 mm = 0.03937 in

TABLE 4 Comparison of Bond Stress Models

Test Series	Uniform Model $\frac{P_{exp}}{P_{calc}}$	Uniform Model Coefficient of Variation	Elastic Model $\frac{P_{exp}}{P_{calc}}$	Elastic Model Coefficient of Variation
Baseline (144 tests)	1.001	0.144	1.000	0.129
Supplemental (23 tests)	1.034	0.139	1.029	0.139

In summary, the elastic bond stress model, which is based on a rational analysis that considers compatibility of displacements for the bonded anchor system, best fits the test data. The elastic model should be used for effective bonded lengths greater than $40\sqrt{d_0}$ when d_0 is in millimeters or $8\sqrt{d_0}$ when d_0 is in inches. The more easily applied uniform bond stress model can be applied for shorter effective bonded lengths since it is the same as the elastic bond stress model in this range of bond length.

DESIGN RECOMMENDATIONS

In a typical application, adhesive-bonded anchors and dowels will not be fully confined. This means that the typical failure mode will be the combined cone-bond failure shown in Figure 1. The following design recommendations account for this failure mode and include an appropriate capacity reduction factor, ϕ.

Effective Embedment Length

The test results reported here and by Doerr et al. indicate that the contribution of the shallow concrete cone to the strength of the anchor is minimal and should be neglected. To account for formation of the shallow concrete cone, an effective bonded

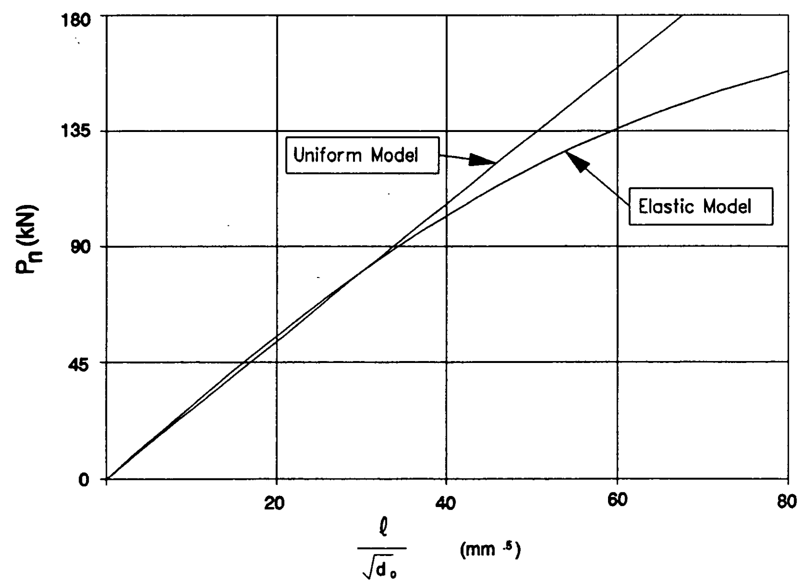

FIGURE 7 Comparison of bond stress models.

length ℓ_{ef} given by Equation 8 should be used in Equations 1 and 3 in place of ℓ.

Bond Stress Distribution

The transition between the uniform bond stress model and the elastic bond stress model is given by

$$\ell' = 50 + 40\sqrt{d_0} \text{ mm}$$

$$\ell' = 2 + 8\sqrt{d_0} \text{ in.} \quad (9)$$

where ℓ' is the transition length between uniform bond stress model and elastic bond stress model.

For anchor diameters of 13 to 25 mm (½ to 1 in.) this expression ranges from 16 to 10 anchor diameters, which represents fairly deep embedments for adhesive-bonded anchors. This indicates that the uniform bond stress model is appropriate for typical embedments.

For adhesive-bonded anchors embedded less than ℓ' the uniform bond stress model given by Equation 1 is appropriate. For embedment lengths longer than ℓ' the elastic bond stress model given by Equation 3 is appropriate.

Capacity Reduction Factors

For design purposes, the capacity reduction factor ϕ should be applied to Equations 1 and 3 to ensure that the calculated anchor capacity does not exceed the actual anchor capacity. Data from 144 baseline tests were used to investigate the appropriate ϕ-factors.

For $\phi = 0.80$, 93 percent of the experimental capacities exceed their respective calculated capacities for both the elastic and uniform solutions. This is the same as that recommended by the results of the tests reported by Doerr et al. and is recommended for design.

CONCLUSIONS

The results of this study indicate the following:

- The strength of adhesive-bonded anchors and reinforcing dowels can be determined on the basis of a rational design procedure. By establishing the basic bond properties (τ_0, τ_{max}, and λ') of an adhesive product from a standard test procedure (such as the baseline test series described in this paper), the capacity of any anchor diameter and embedment length can be determined. This procedure will eliminate job-by-job proof-load testing and reliance on manufacturers' information.
- Different adhesives have different strength and stiffness properties. The standard test procedure described in this paper should be used to establish the basic bond properties (τ_0, τ_{max}, and λ') for the product.
- The design recommendations presented are based on a rational analysis and agree with test results.
- A uniform bond stress model is acceptable for most typical anchor installations.
- An elastic bond stress model is appropriate for long embedments.

The purpose of this research project was to initiate a basic testing procedure for establishing bond characteristics of adhesive products. To verify the procedure, certain parameters were fixed. These parameters included testing at 24 hr, anchor installation in well-cleaned and dry holes, short-term tension tests, normal laboratory temperatures, and one type of concrete. It is expected that these bond characteristics will vary depending on actual in-service conditions. These conditions may include a longer curing period, installation in wet holes, installation in improperly cleaned holes, long-term sustained loading, elevated temperatures, and installation in other types of concrete.

Currently, a proposal for a research project to investigate the effects of these variables is under review. If the proposed project is implemented, tests will be performed to determine the influence of each of these variables on the bond characteristics. It is expected that this project will result in a series of multiplication factors to be applied to the bond characteristics established from the basic qualification tests. The design procedure will be similar to the ACI 318 procedure for development length where multiplication factors are applied to a basic development length.

ACKNOWLEDGMENTS

The research reported in this paper was conducted in the Structures Laboratory at the University of Florida and sponsored by the Florida Department of Transportation. The successful completion of this project would not have been possible without the contributions of materials, time, and technical expertise from the following manufacturers: Ackerman Johnson Fasteners; Covert Operations; Gunnebo (U.S.E. Diamond); HILTI, Inc.; ITW Ramset/Red Head; Molly; and Sika-Rawl.

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Publication of this paper sponsored by Committee on Adhesives, Bonding Agents, and Their Uses.