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# Behavior and Design of Single Adhesive Anchors under Tensile Load in Uncracked Concrete




by Ronald A.Cook, Jacob Kunz, Werner Fuchs, and Robert C. Konz

*A user-friendly model for the design of single adhesive anchors subjected to tension loading in uncracked concrete is presented. Descriptions of the various types of adhesive anchor systems is included as well as a summary of previously published design models. The development of the user-friendly design model includes a comparison of the model and previously published models to a database including 888 European and American tests. The comparison shows that the simple user-friendly model provides a better fit to the database than more complicated design models previously presented. Although the model is limited to anchors located away from free edges, it provides the basis for development of models which account for the effect of edges, anchor groups, and other design conditions.*

**Keywords:** adhesive anchors; adhesives; anchor bolts; anchors; bolts; bonded anchors; chemical anchors; concrete; connections; embedments; fastenings; retrofit.

## INTRODUCTION

The demand for more flexibility in the planning, design and strengthening of concrete structures has resulted in an increased use of fastening systems. Currently employed are cast-in-place anchors such as headed studs or headed bolts and fastening systems to be installed in hardened concrete, such as expansion anchors, undercut anchors, adhesive anchors, or grouted anchors. Figure 1 shows the typical types of anchors. The working principle of mechanical and cast-in-place headed anchors is to transfer the load into the concrete at the anchor head. Adhesive anchors, on the other hand, transfer the load from the steel through the adhesive layer into the concrete along the entire bonded surface. Adhesive anchors provide a viable, economical method for adding new concrete sections or steel members to existing concrete structures.

The relevant literature contains several approaches for the calculation of the tensile failure load of single adhesive anchors as related to the embedment of the anchor. These design approaches have either been developed for specific products or they are based on test series with limited variation of the relevant parameters. In order to establish a general design approach for the calculation of tension failure of adhesive anchors, relevant test data have been collected worldwide and compiled into a database. Current design concepts are compared to the worldwide database. The comparison of the current design concepts with the database indicates that a simple physical model based on uniform bond stress provides the best fit to the database. The design concepts considered address the calculation of the ultimate tensile load of single adhesive anchors set in clean, dry holes far from concrete edges in uncracked concrete for glass capsule, injection, and bulk systems of all known chemical compositions. The database used for the evaluation of the various design concepts is based on tests conducted at room temperature. Some reduction in anchor capacity may be appropriate for anchors loaded at elevated temperatures.

## BACKGROUND

An adhesive 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 prepackaged in glass capsules or in dual-cartridge injection systems, or as two-component systems requiring user proportioning. Figure 2 shows the typical types of adhesive anchor systems and types of adhesives.

A grouted anchor may be a headed bolt, threaded rod with a nut at the embedded end,or deformed reinforcing bar with or without end anchorage installed in a pre-formed or drilled hole with a portland cement and sand grout or a commercially available pre-mixed grout. Typically, the hole size for grouted anchors is about twice the diameter of the anchor. Grouted anchors are not covered in this paper.

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## Adhesive anchor systems

The most common version of the capsule anchor consists of a cylindrical glass capsule containing a polymer resin, an accelerator, and mineral aggregate. The capsule is inserted in a drilled hole; deeper embedments are typically achieved by stacking multiple capsules in the hole. Setting of the anchor is accomplished by direct boring through the capsule with a threaded anchor rod (usually equipped with a chiseled end) chucked directly into a rotary drill. Straight reinforcing bars may be installed in the same way. The drilling and hammering action of the drill mixes the contents of the capsule with the fractured fragments of the capsule to form a relatively fast-setting polymer/glass matrix (Fig. 3). As well as stiffening the polymer matrix and reducing shrinkage, the fractured glass and aggregate components serve to improve bond by scouring the sides of the hole during installation.

As an alternative to glass capsules, foil capsules have recently been developed. They are better suited for use on construction sites since they are more robust. Because of their flexibility they adapt themselves to the hole geometry and can easily be installed overhead.

In injection anchor systems, plastic cartridges containing pre-measured amounts of resin and hardener allow controlled mixing of polymer components. The components are typically mixed through a special mixing nozzle as they are dispensed, or are completely mixed within the cartridge immediately before injection. Typically, the catalyzed resin is injected into the hole first and the anchor rod (straight or deformed bar or threaded rod) is pushed into the hole and rotated slightly to promote complete contact between rod and adhesive (Fig. 4). Care must be taken to prevent the formation of air bubbles in the adhesive during insertion of the rod. Other systems utilize a plastic pouch to contain the polymer components, which are mixed by manual kneading of the pouch. Immediately after mixing a small incision is made in the pouch, and the resin is poured into the hole.

Polymer components may also be purchased in bulk and mixed either manually or with a power mixer in a bucket and used immediately, or they may be pumped through a mixer and then injected into the hole. Both epoxies and polyester resins are available in bulk packaging. Care must be taken to assure proper mix design and adequate mixing of the resin components on site, and to protect personnel from exposure to fumes and direct contact with the polymer materials.

## Adhesives

An epoxy adhesive is a synthetic compound consisting of an epoxy resin cross-linked with a curing agent. By national standard, the epoxy resin is designated as component "A" and the curing agent as "B." Epoxy adhesives are thermosetting polymers; that is, they require heat to cure. This heat is generated during the exothermic reaction between the epoxy resin and the curing agent. Epoxy adhesives are durable, have a long shelf life, and undergo almost no shrinkage during curing.[1,2]

A polyester adhesive is a thermosetting plastic consisting of a polyester resin and a catalyst, typically benzoil peroxide. Because of their chemical nature, polyester adhesives usually have faster exothermic reactions and curing times than do epoxy adhesives. However, limitations of polyester adhesives can include a short shelf life, a tendency to degrade under exposure to ultraviolet light, and a tendency to self-polymerize (without the addition of a catalyst) at high temperatures normally reached during summer months in hot climates.[1,2]

A vinylester adhesive is a thermosetting plastic consisting of a vinylester resin and a catalyst, typically benzoil peroxide. Vinylester adhesives usually have exothermic reactions and curing times which are faster than those of epoxy adhesives, but slower than those of polyester adhesives. With respect to shelf life, sensitivity to ultraviolet exposure, and tendency to self-polymerize, vinylester adhesives fall between epoxy adhesives and polyester adhesives.[1,2]

Hybrid systems consisting of organic and inorganic bonding agents have recently been developed. The polymerization reaction of the resin component ensures good bonding and a rapid curing injection system with good handling characteristics. The cementitious reaction improves stiffness and bonding, especially at higher temperatures. The combined action of the two components results in negligible material shrinkage.

## Installation and in-service conditions

A good bond between the adhesive and the concrete depends on the correct installation of the anchor and on the in-service conditions experienced by the anchor. Cook, et al.[3] have conducted a comprehensive investigation on these parameters based on over 1000 confined tension tests of twenty adhesive products. Cook, et al.[3] summarize the following main influences:

a) Bond strength: The bond strength ($\tau$) of adhesives is product dependent and cannot be generalized. For most products the bond stress is generally constant for all anchor sizes. For the twenty products tested in this study, a limited number of products exhibit higher bond stresses for 12 mm diameter anchors. Overall, test results indicate that the bond stress determined from tests on 16 mm ($^5/_8$ in.) anchors is appropriate for larger diameters and conservative for smaller diameters.

b) Concrete strength: The effect of concrete strength on the capacity of adhesive bonded anchors is negligible for

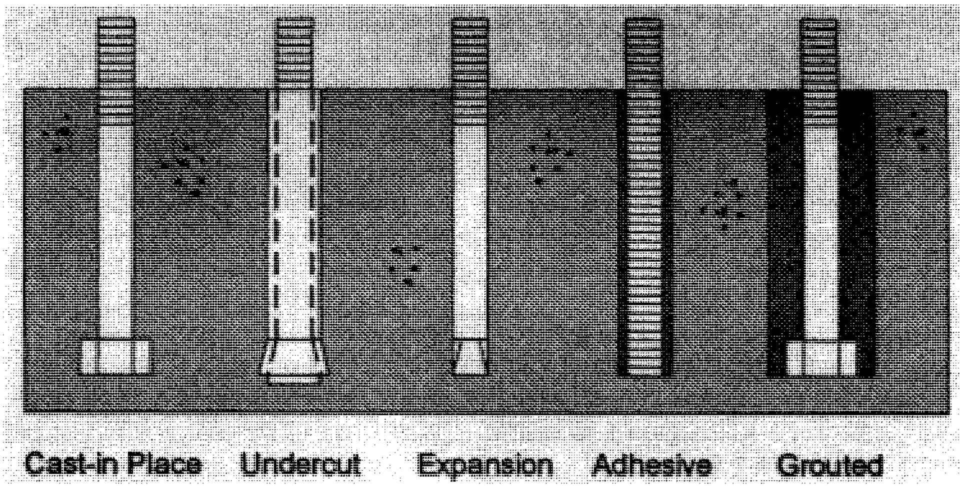


*Fig. 1—Types of anchors*

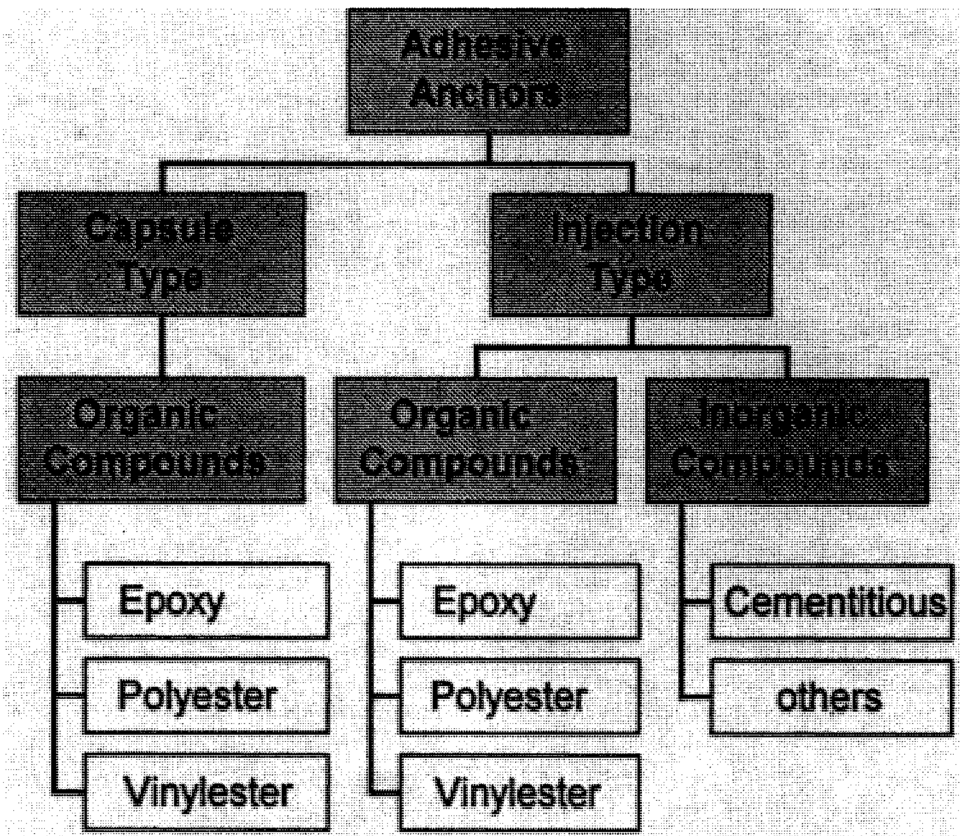


*Fig. 2—Types of adhesive anchor systems and adhesives*

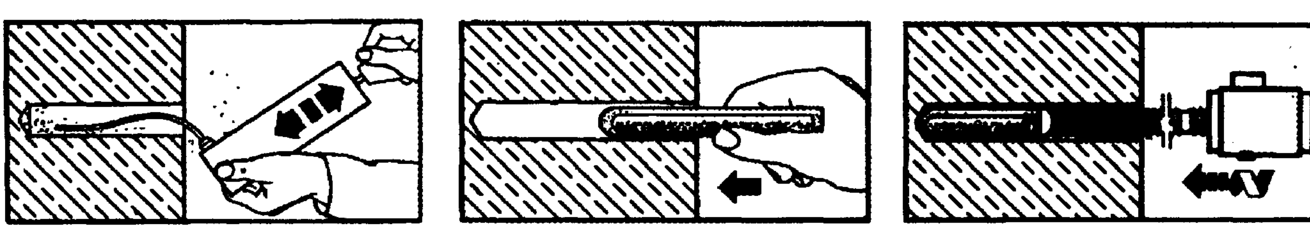


*Fig. 3—Typical capsule anchor system*

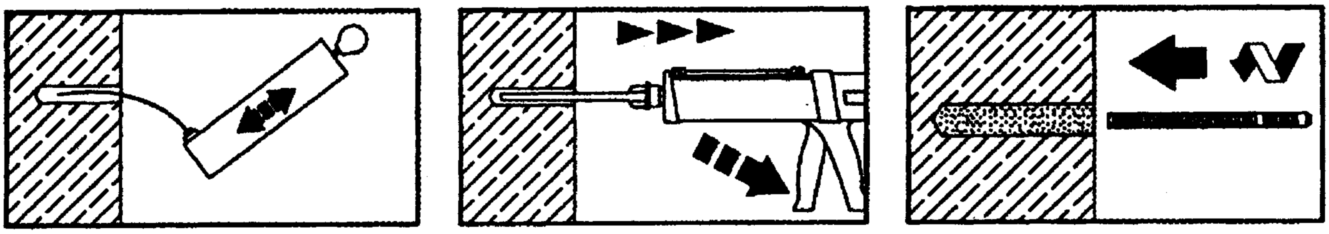


*Fig. 4—Typical injection anchor system*

most products. The majority of products exhibit slight increases in bond strength from $f_c$ = 20 MPa to about $f_c$ = 40 MPa but decrease slightly for strengths up to $f_c$ = 60 MPa. The bond strength established for $f_c$ = 20 MPa appears to be conservative for products up to a concrete strength of $f_c$ = 60 MPa.

c) Hole cleaning: The effect of holes not cleaned properly results in a significant decrease in capacity for most products while there is a negligible decrease in capacity for other products. For the twenty products tested, the uncleaned hole strength ranged from 20 percent to 100 percent of the clean hole strength with a mean of 66 percent. As with bond strength, the strength of anchors in uncleaned holes is product dependent and cannot be generalized. In general, it is recommended that all installations be inspected for proper hole cleaning prior to installation of the anchor.

d) Damp installations and submerged installations: Damp holes (i.e., holes blown free of standing water) result in some reduction in capacity for the majority of products. In general, the reduction is not significant particularly compared to the drastic reduction in capacity for anchors installed in submerged holes (i.e., underwater applications). In submerged applications capsule packaged products generally perform better than injection type products.

e) Elevated temperature and creep: Under elevated temperatures usually observed during the summer months in hot climates, the tensile load capacity of organic resins may decrease substantially while creep becomes much more important than under normal temperatures. Cementitious components are not practically sensitive to elevated temperatures. Figure 5 shows the reduction in bond strength with increasing temperature for three products. As indicated by Fig. 5, each product exhibits unique behavior under elevated temperature. Product acceptance criteria for adhesive anchors must include elevated temperature tests under sustained load. It should be noted that the results presented in this paper are based on room temperature short-term tensile tests and that some reduction in anchor strength may be necessary for elevated temperature applications and sustained loading.

f) Durability: Although not specifically addressed in the Cook, et al.[3] tests, the long-term durability of adhesive anchors is of concern and should be addressed in product acceptance criteria.

In general, adhesive anchor performance under differing installation and in-service conditions is product dependent. A product acceptance standard for adhesive anchors is currently being developed by ASTM Committee E06.13. The standard will include appropriate tests and acceptance criteria for the evaluation of bond stress and product performance under various installation and in-service conditions.

### Behavior under tensile loading

Figure 6 shows the typical failure modes observed for adhesive anchors. If the embedment depth of an adhesive anchor is very small, then usually a concrete cone is pulled out. If the embedment of the anchor is deeper, a combined failure is typically observed. The combined failure includes a shallow concrete cone with a bond failure below the cone. The bond failure can be at the adhesive/concrete interface, the steel/adhesive interface, or a mixed bond failure with failure at the adhesive/concrete interface in the upper portion of the anchor and a steel/adhesive failure in the lower portion of the anchor. If the embedment is very deep, the bond is so strong that the steel failure occurs in the anchor. The minimum depth for steel failure represents the basic development length of the anchor. The development length depends on the steel quality and the properties of the bonding agent.

### Design

Currently, most designers follow the adhesive manufacturers' 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 depth. Although there are several design methods for adhesive anchors in use around the world, no unified approach to the design of adhesive anchors exists at this time. The design of adhesive anchors is not specifically handled in most U.S. building standards, but the increasing use of adhesive anchors encountered today exemplifies the need for a standard specification and design procedure for these anchors. An initiative is currently underway to include design rules for adhesive anchors in Chapter 23 of the next edition of ACI 318. The design model presented in this paper is intended to assist with the standardization process for adhesive anchor design.

## RESEARCH SIGNIFICANCE

This paper provides a comparison of previously published design concepts for computing the tensile capacity of adhesive bonded anchors to a worldwide database. The results of these comparisons indicate that a simple user-friendly design model based on a uniform bond stress fits the database better than more complicated models previously presented. As a result, the simple user-friendly design model is presented for possible incorporation into the new ACI 318 Chapter 23 "Fastening to Concrete." While earlier design concepts were limited to specific products or standard embedment depths, the design concept presented in this paper is applicable to adhesive anchors in general and significant variation of the relevant parameters is possible, this allows an optimum design of the fastening and improves the prediction

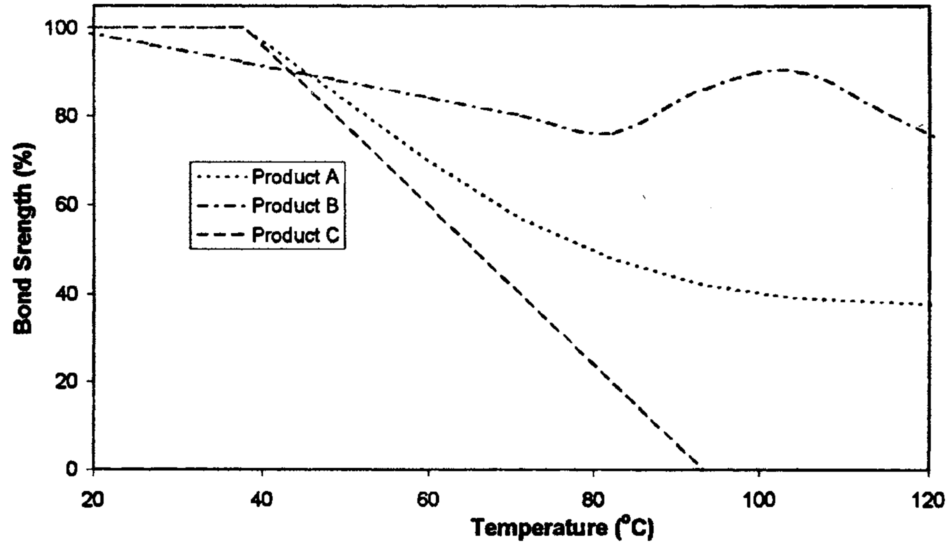



*Fig. 5—Change in bond strength with temperature for three products*

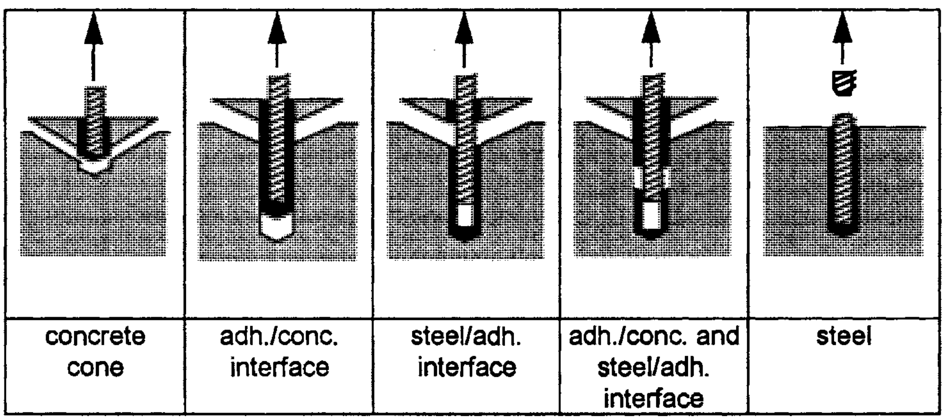



*Fig. 6—Observed failure modes*

quality of the tensile load capacity of adhesive anchor products. The calculation model is easy to handle and quickly understood by the practicing engineer.

## WORLDWIDE DATABASE

Test reports on the behavior of adhesive anchors have been collected in Europe, in the USA, and in Japan. From 38 reports, a database containing the results of 2929 tests has been established. The database contains tensile and shear load testing in uncracked and cracked concrete with single anchors, groups of two anchors, and groups of four anchors. It distinguishes between confined and unconfined tests as well as between tests far from the concrete edge, tests near the concrete edge, and tests with close anchor spacing. Figure 7 shows the types and number of tests contained in the database. Distinction is also made between the types of anchors tested. The database contains tests carried out with threaded rods, insert sleeves, and rebars. Finally, the database contains tests with epoxies, vinylesters, unsaturated polyesters, hybrid adhesives, and inorganic adhesives. The database can readily be expanded as additional test information becomes available. Currently, the adhesive anchor database is being maintained for ACI 355 by Ronald A. Cook, Department of Civil Engineering, University of Florida, Gainesville, Florida 32611.

For the purposes of this paper, the database was reduced to consider only unconfined tension tests of threaded rod and reinforcing bar anchors which were away from free edges (edge distance greater than or equal to embedment length) with clean, dry, and brushed holes. Tests which exhibited steel failure were excluded. This resulted in a total of 888 tests. These tests were divided into 8 data sets representing unique products. The important characteristics of the 888 tests and individual product data sets are shown in Table 1.

### Regression analysis of the database

With each data set of Table 1, a regression was performed using the following formula:

$$N_u = \alpha d^{\beta} h^{\gamma}_{eff} f^{\delta}_{c} \qquad (1)$$

Although the regression analysis represents an entirely empirical approach to the definition of a design model, it does provide insight to which physical model is most appropriate.

**Table 1—Main parameters of tests used for model development**

| Data set no. | Number of tests | $d$, mm | | | $h_{ef}$, mm | | | $d_o / d$ | | | $h_{ef} / d$ | | | $f_c$, MPa | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | min. | max. | avg. | min. | max. | avg. | min. | max. | avg. | min. | max. | avg. | min. | max. | avg. |
| 1 | 205 | 8.0 | 24.0 | 14.9 | 80 | 300 | 147 | 1.10 | 1.83 | 1.26 | 7.8 | 15.0 | 9.9 | 21.3 | 68.0 | 29.0 |
| 2 | 141 | 9.5 | 32.3 | 18.2 | 89 | 457 | 187 | 1.13 | 1.38 | 1.28 | 6.9 | 18.7 | 10.4 | 13.4 | 39.7 | 24.8 |
| 3 | 296 | 8.0 | 25.0 | 13.6 | 44 | 254 | 118 | 1.04 | 1.33 | 1.12 | 4.5 | 14.0 | 8.8 | 21.3 | 47.6 | 29.6 |
| 4 | 120 | 9.5 | 50.8 | 19.0 | 84 | 482 | 179 | 1.13 | 1.25 | 1.18 | 6.5 | 12.7 | 8.0 | 13.5 | 43.0 | 26.1 |
| 5 | 23 | 12.7 | 32.3 | 18.6 | 114 | 254 | 151 | 1.17 | 1.25 | 1.23 | 6.3 | 10.0 | 8.5 | 27.6 | 37.0 | 28.5 |
| 6 | 56 | 12.7 | 25.4 | 18.0 | 95 | 321 | 184 | 1.13 | 1.29 | 1.20 | 5.9 | 18.0 | 8.7 | 13.0 | 31.6 | 22.9 |
| 7 | 27 | 15.9 | 15.9 | 15.9 | 76 | 191 | 127 | 1.20 | 1.20 | 1.20 | 4.8 | 12.0 | 8.0 | 43.7 | 44.6 | 44.0 |
| 8 | 20 | 15.9 | 15.9 | 15.9 | 76 | 152 | 114 | 1.20 | 1.20 | 1.20 | 4.8 | 9.6 | 7.2 | 42.1 | 42.1 | 42.1 |
| All | 888 | 8.0 | 50.8 | 15.9 | 44 | 482 | 149 | 1.04 | 1.83 | 1.20 | 4.5 | 18.7 | 9.5 | 13.0 | 68.0 | 28.0 |

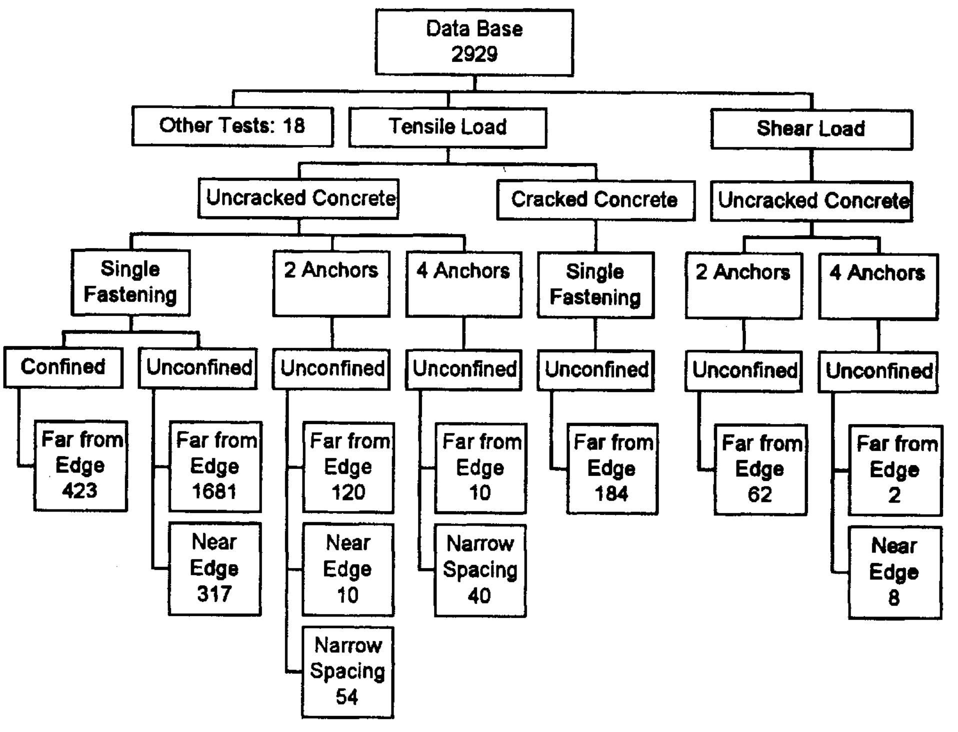



*Fig. 7—Types and number of tests in the worldwide database*

For the different data sets, the regression values for β, γ, and δ are shown in Table 2.

From the results of the regression analysis shown in Table 2, it appears that the influence of hole diameter (β) and embedment depth (γ) can be approximated with sufficient accuracy by influence exponents $\beta = \gamma = 1.0$. The influence of concrete strength, on the other hand, varies significantly between data sets (products). This indicates that for some products the strength of the adhesive anchor is related to the concrete strength while for other products there is an insignificant influence of concrete strength on the strength of the adhesive anchor. This reinforces the findings of the Cook, et. al[3] tests previously mentioned.

## CURRENT DESIGN CONCEPTS

Current design concepts are described in the following paragraphs. Although details of current design concepts vary they can be represented by the following categories, each of which is discussed below:

1. Concrete cone models (mechanical and headed anchor models): models that are dependent on the square root of the concrete compressive strength and the embedment length raised to a power (no influence of anchor diameter).

2. Bond models: models that are dependent on the bond strength of the product, the diameter, and the embedment length.

3. Bond models neglecting the shallow concrete cone: Similar to bond models except that the embedment length is reduced to account for the shallow concrete cone.

4. Cone models with bond models: Models that use concrete cone formulas for shallow embedments and bond stress formulas for deeper embedments.

5. Combined cone/bond model: Models that use concrete cone formulas for shallow embedments and combined cone/bond models for deeper embedments.

6. Two interface bond model: A bond model that is based on distinguishing between bond failure modes at the steel/adhesive interface and adhesive/concrete interface.

### Concrete cone models

This form of an adhesive anchor model was first proposed by Rehm, Eligehausen, and Mallée[4] and is given by Eq. (2). The model is derived from tests with a single adhesive and a constant ratio of embedment depth to anchor diameter of nine, but with different concrete strengths. In this model, the ultimate load depends only on the concrete strength and the embedment depth of the anchor. The formula does not take into account different failure modes, and, strictly speaking, is only valid for an $h_{ef}/d$ ratio of nine.

$$N_u = 0.92 h_{ef}^2 \sqrt{f_c} \quad (2)$$

Another possible cone model is given by Eq. (3) and is based on design models developed for cast-in-place headed anchors.[5]

$$N_u = 16.5 h_{ef}^{1.5} \sqrt{f_c} \quad (3)$$

### Bond models

Design models based on bond stress have been presented in several references.[6,7,8] Bond stress models include an elastic bond stress model and a uniform bond stress model. The elastic bond stress model is given by Eq. (4) and the uniform bond stress model is given by Eq. (5). Note that the bracketed term in Eq. (4) is replaced by $h_{ef}$ in Eq. (5). For most practical embedment lengths, the bracketed term in Eq. (4) is approximately the same as $h_{ef}$. For deeper embedments, the bracketed term is less than $h_{ef}$. This indicates that the anchor strength is not directly proportional to the embedment length for deep anchors. This is consistent with studies on bond stress distribution in reinforcing bars such as those by Nilson.[9]

$$N_u = \tau\pi d_o \left[\frac{\tanh(\lambda h_{ef})}{\lambda}\right] \quad (4)$$

$$N_u = \tau\pi d h_{ef} \quad (5)$$

Based on studies by McVay, Cook, and Krishnamurthy,[10] the elastic model appears to be appropriate for low loads while the uniform bond stress model is more appropriate for strength design methods. This is shown in Fig. 8. Figure 8, which is based on non-linear finite element studies, shows that the bond stress corresponds to the elastic distribution represented by Eq. (4) at low loads but approximates a uniform bond stress distribution at failure [Eq. (5)]. Based on Figure 8, the uniform bond stress model appears to be appropriate for shallow embedments (i.e., cone failure) as well as deeper embedments that exhibit the combined cone/bond failure mode. This is reinforced by Table 3 which shows the relationship between the failure loads and cone depths predicted by the finite element model and the actual failure loads and concrete cone depths measured in tests. As shown in Table 3, the predicted failure loads and cone depth match experimental results. Figure 8 and Table 3 indicate that a uniform bond stress model is appropriate for adhesive anchors exhibiting full concrete cone failure as well as the more commonly observed shallow concrete cone with bond failure mode.

**Table 2—Results of regression analysis**

| Data set no. | β | γ | δ |
|---|---|---|---|
| 1 | 0.80 | 0.80 | 0.08 |
| 2 | 0.95 | 0.81 | 0.35 |
| 3 | 0.59 | 1.34 | 0.30 |
| 4 | 0.57 | 1.07 | 0.11 |
| 5 | 1.12 | 0.77 | — |
| 6 | 0.81 | 0.90 | 0.19 |
| 7 | — | 1.37 | — |
| 8 | — | 0.94 | — |
| Average | 0.81 | 1.00 | 0.21 |
| *COV* | 0.26 | 0.24 | 0.58 |

**Table 3—Comparison of finite element results with test results (McVay, Cook, and Krishnamurthy[10])**

| $h_{ef}/d_o$ | $N_{test}/N_{pred}$ | $h_{c,test}/h_{c,pred}$ | $h_{c,test}/h_{ef}$ | $h_{c,pred}/h_{ef}$ |
|---|---|---|---|---|
| 4.00 | 0.96 | 1.00 | 1.00 | 1.00 |
| 5.33 | 1.13 | 1.19 | 0.55 | 0.46 |
| 6.67 | 1.02 | 0.92 | 0.37 | 0.40 |
| 8.00 | 1.01 | 0.91 | 0.38 | 0.42 |
| Average | 1.03 | 1.01 | — | — |

Additional work by Krishnamurthy[11] has shown that there is an upper limit to the $h_{ef}/d$ ratio where full redistribution of bond stress can be assumed to occur. As shown in Fig. 9, full redistribution occurs at an $h_{ef}/d$ ratio of 22.4 but does not occur at an $h_{ef}/d$ ratio of 32.0. Krishnamurthy[11] indicates that the upper limit for full redistribution of bond stress be taken at an $h_{ef}/d$ ratio of 25.0. Note that from a practical viewpoint this is a reasonable limit since drill bits for installing adhesive anchors are typically limited to $h_{ef}/d$ ratios less than 25.0.

The use of the uniform bond stress model requires the evaluation of whether the anchor diameter ($d$) or the hole diameter ($d_0$) is most appropriate in Eq. (5). The coefficients of variation of the uniform bond stress model with the entire database are 0.218 when anchor diameter ($d$) is used and 0.220 when hole diameter ($d_0$) is used. Figure 10 shows the differences in the coefficients of variation for each data set in the database. As shown in Fig. 10, there is a slight trend favoring anchor diameter but the results are not conclusive. Figure 11 shows the two methods compared to the ratio of hole diameter to anchor diameter. Figure 11 clearly shows that the calculation of bond stress based on anchor diameter is most appropriate. The use of the anchor diameter ($d$) is much more convenient for design purposes since the designer does not need to consider specific manufacturers' recommendations on hole diameter.

Figure 12 shows the comparison of the cone model [Eq. (3)] with the uniform bond stress model [Eq. (5)] for data sets 7 and 8. Figure 13 shows the measured loads for all data sets plotted as a function of bond area $A_b$. Since each individual data set has its own unique bond stress ($\tau_{data\ set}$), the failure loads shown in Fig. 13 were normalized to $\tau$ = 10 MPa by multiplying them with the factor $10/\tau_{data\ set}$.

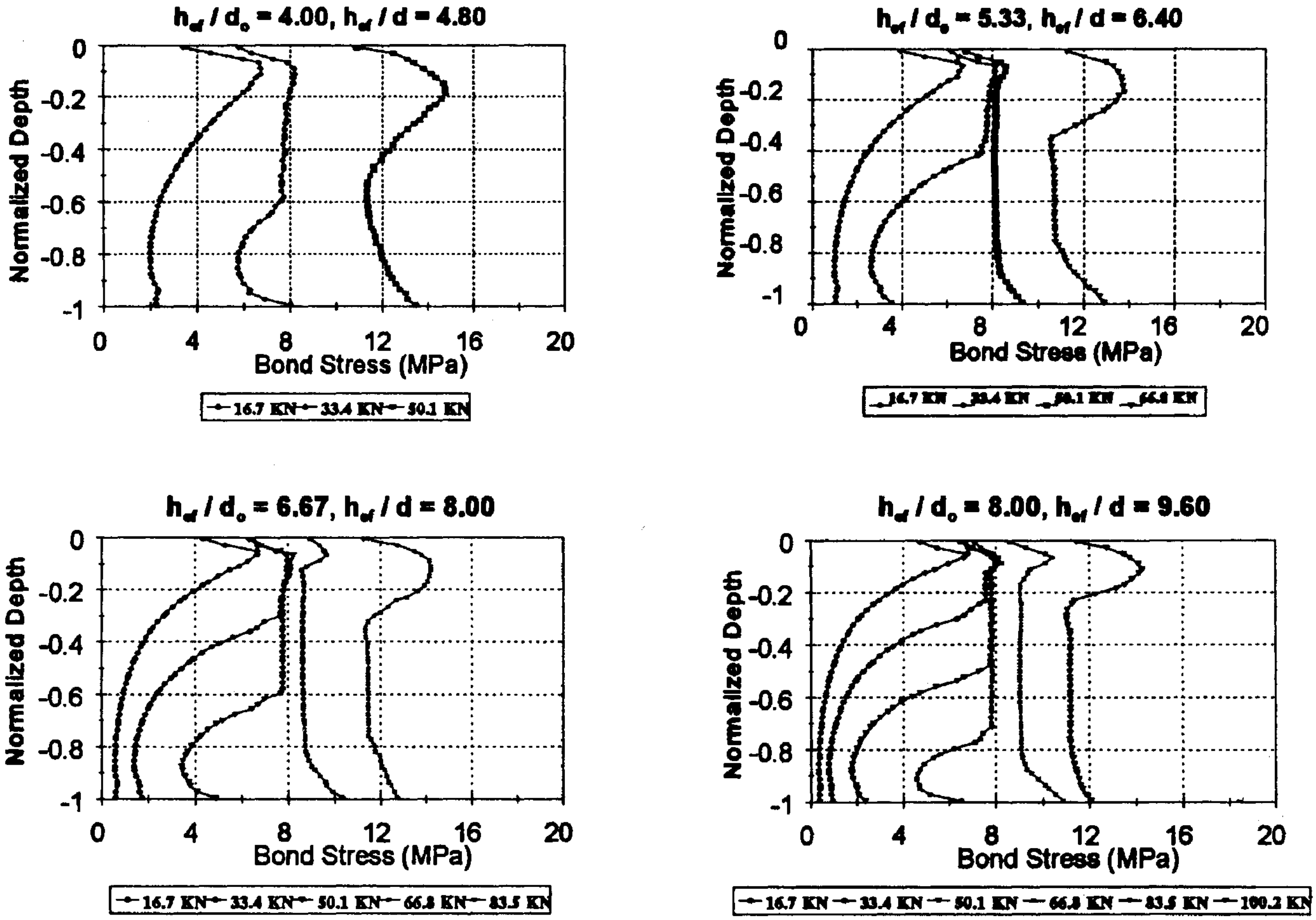



*Fig. 8—Bond stress distribution with increasing load for various* $h_{ef} / d_0$ *ratios (McVay, Cook, Krishnamurthy*[10]*)*

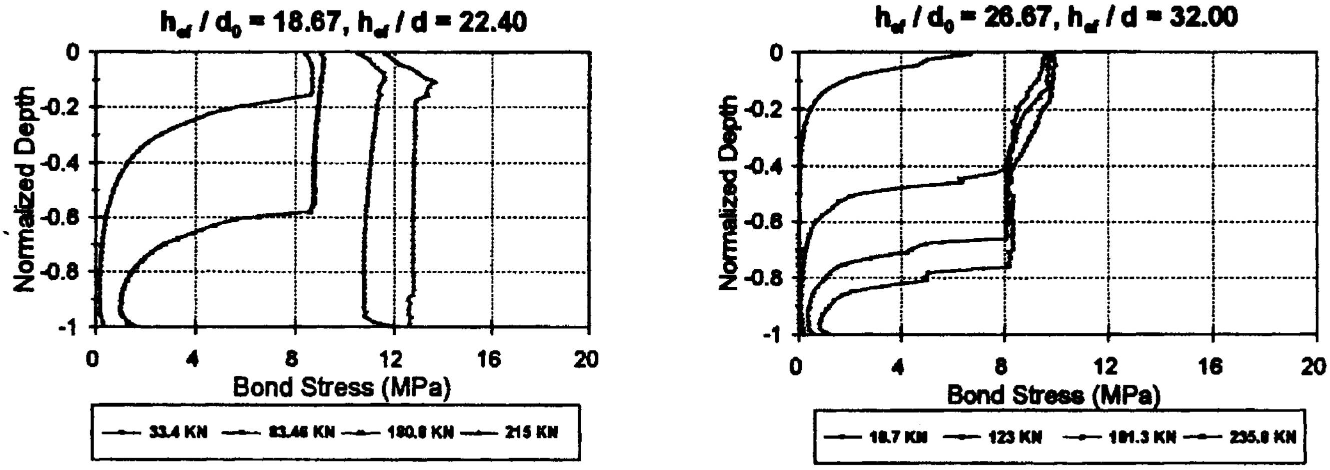



*Fig. 9—Bond stress distribution with increasing load for large* $h_{ef} / d_0$ *ratios (Krishnamurthy*[11]*)*

Figure 13 shows the actual data points as well as the mean and a possible design value for the uniform bond stress model using the anchor diameter. The design value is based on recommendations given in the draft Chapter 23 of ACI 318 which prescribe a design value based on a lower 5 percent fractile with a 75 percent confidence. The design value shown in Fig. 13 is based on a coefficient of variation of 20 percent. Using the draft Chapter 23 provisions, the design value is equal to $^2/_3$ of the mean value [mean value $x$ (1 - 1.67 *COV*)].

Analysis of the data used to construct the design value line of Fig. 13 indicates that there are 42 data points out of 888 which fall below the design value line (4.7 percent below the design value). This corresponds very well with the 5 percent fractile proposed in the draft Chapter 23 of ACI 318 for mechanical and cast-in-place anchors. The design uniform bond

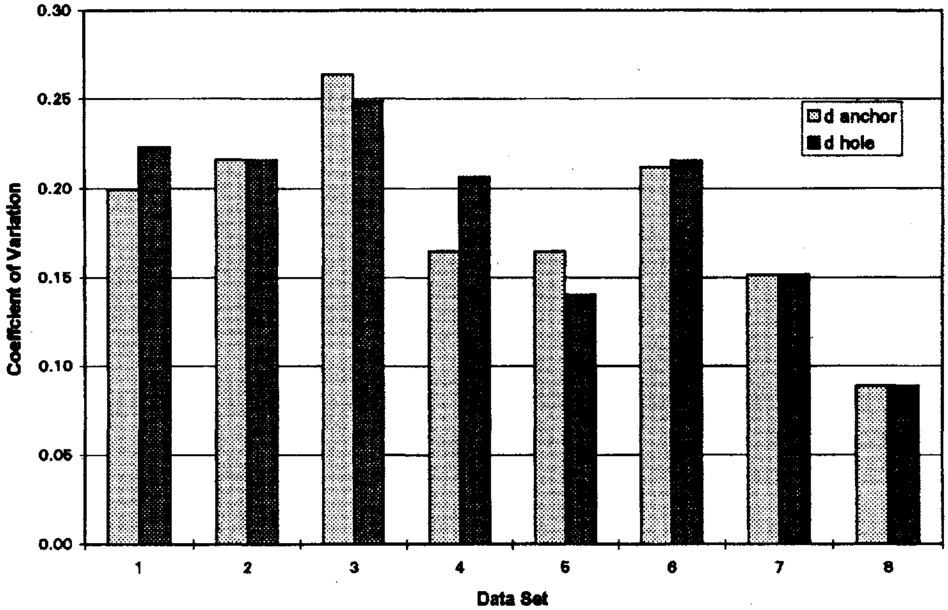



*Fig. 10—Coefficients of variation for uniform bond model using anchor diameter and hole diameter*

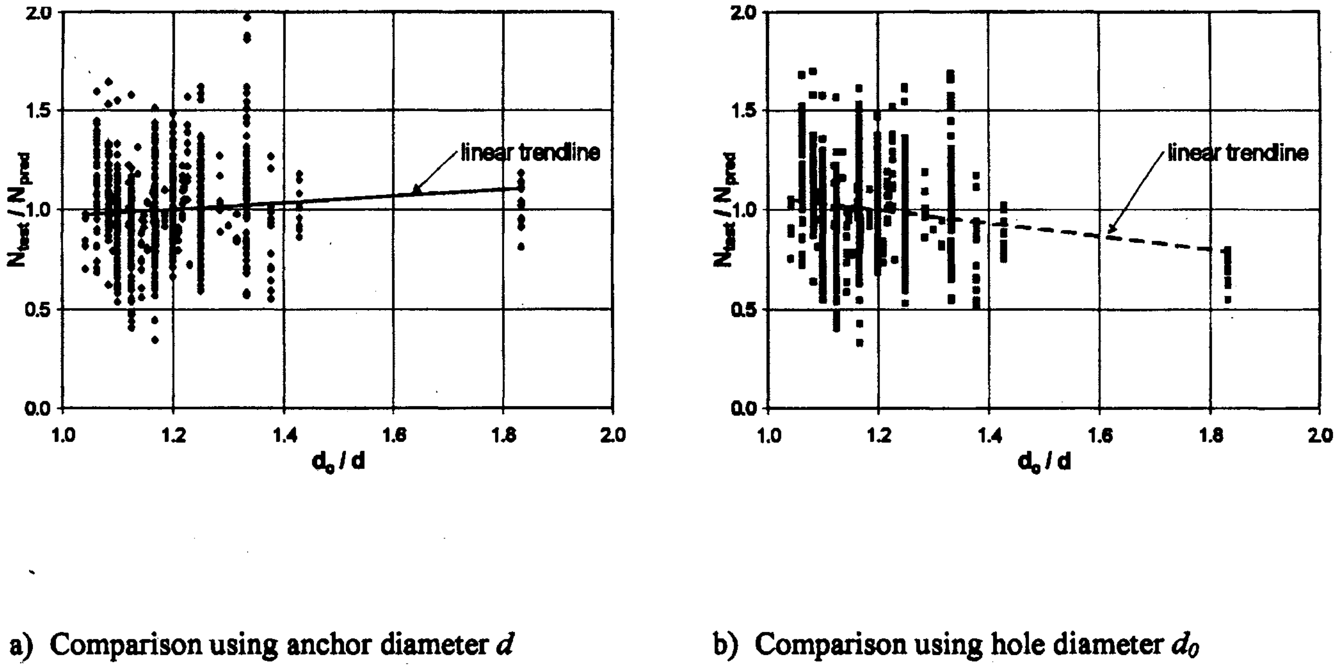



*Fig. 11—Comparison of uniform bond model using anchor diameter and hole diameter to database*

stress model for adhesive anchors shown in Fig. 13 does not include any influence of concrete strength.

Note that the three data points with bond areas of approximately 47,000 mm$^2$ that fall below the design curve are the results of deep embedment tests using stacked glass capsules. The manufacturer involved with performing these tests has indicated that complete mixing of the components may not have occurred due to the particular installation procedure utilized.

### Bond models neglecting the shallow concrete cone

Models presented by Cook, et al.[6,7] assume an effective embedment length equal to the actual embedment length less 50 mm ($\cong 3d$) to account for the shallow concrete cone [Eq. (6)]. Figure 8 indicates that a significant portion of the load is transferred by bond in the portion of the anchor where the concrete cone failure occurs. The results of the finite element analysis shown in Fig. 8 tend to discount using a reduced bond length to account for the shallow cone.

$$N_u = \tau\pi d(h_{ef} - 3d) \qquad (6)$$

### Cone models with bond models

These models are based on using a concrete cone formula for shallow embedments and a bond stress model for deeper embedments. The state-of-the art report of the Japanese Concrete Institute (JCI)[8] quotes two design concepts that follow this procedure. For shallow embedments, they assume a con-

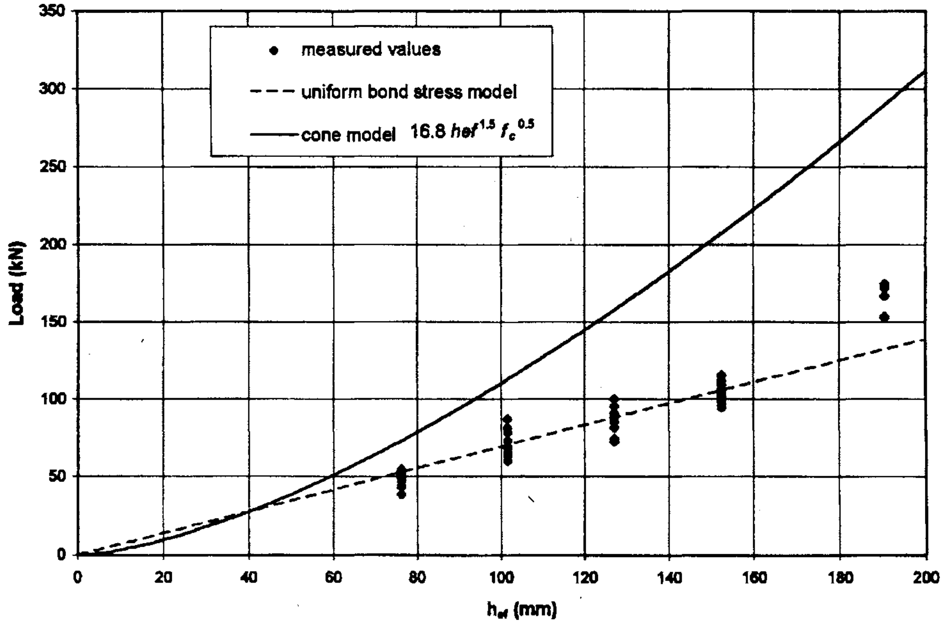



*Fig. 12—Comparison of cone model Eq. (3) with uniform bond model Eq. (5) for data sets 7 and 8*

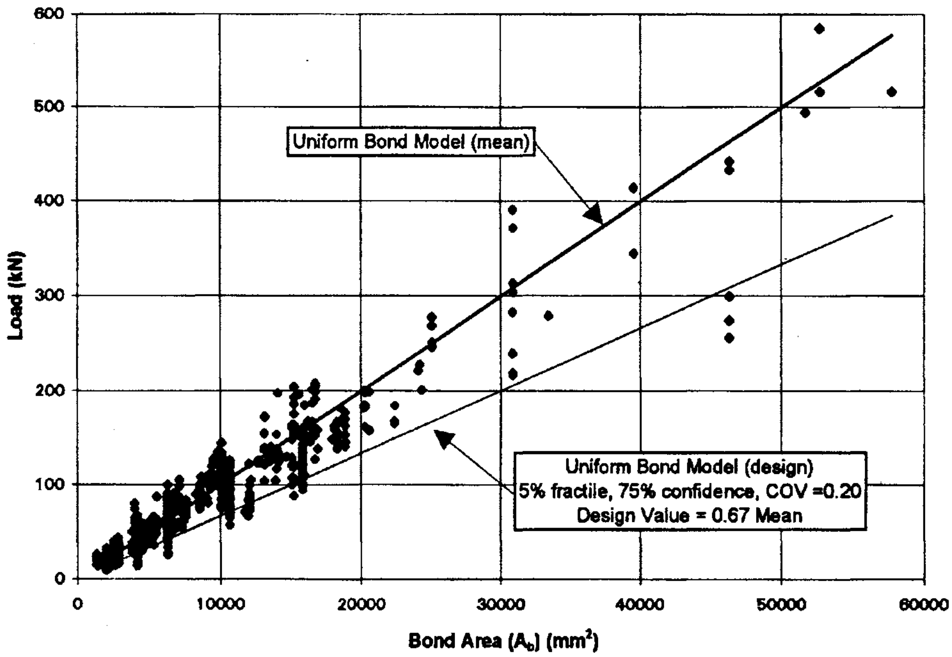



*Fig. 13—Comparison of measured loads in all data sets with the uniform bond model*

crete cone failure according to ACI 349.[12] The ACI 349 formula for cone failure is approximately the same as Eq. (2) with a different constant. For deeper embedments, the formula for bond failure is in accordance with the uniform bond stress model of Eq. (5). Both approaches do not suggest any dependence on the concrete strength for bond failure.

Cone models [Eq. (2) and Eq. (3)] for shallow embedments and bond models [Eq. (5) using either $d$ and $d_0$] for deeper embedments were compared to the database by calculating the embedment depth where the concrete cone equation gave the same predicted capacity as the bond stress equation. The data points with embedment lengths less than this value were then compared to both the appropriate concrete cone equation and the appropriate bond stress equation. The results of this comparison are shown in Fig. 14. Notice in Fig. 14 that the results of using Eq. (3) for the cone model and Eq. (5) with anchor diameter for the uniform bond stress equation yielded no data points in the region supposedly controlled by the cone model. In addition to the cone and bond models compared in Fig. 14, "best fit" constants for Eq. (2) and Eq. (3) for the entire database were also determined and the resulting cone equations compared in the same manner. In all cases, the bond stress equation provided a better fit to the data points in the region where the cone equation is assumed to control than the cone equation. This indicates that the concrete cone models are not appropriate for use with even shallow adhesive anchors.

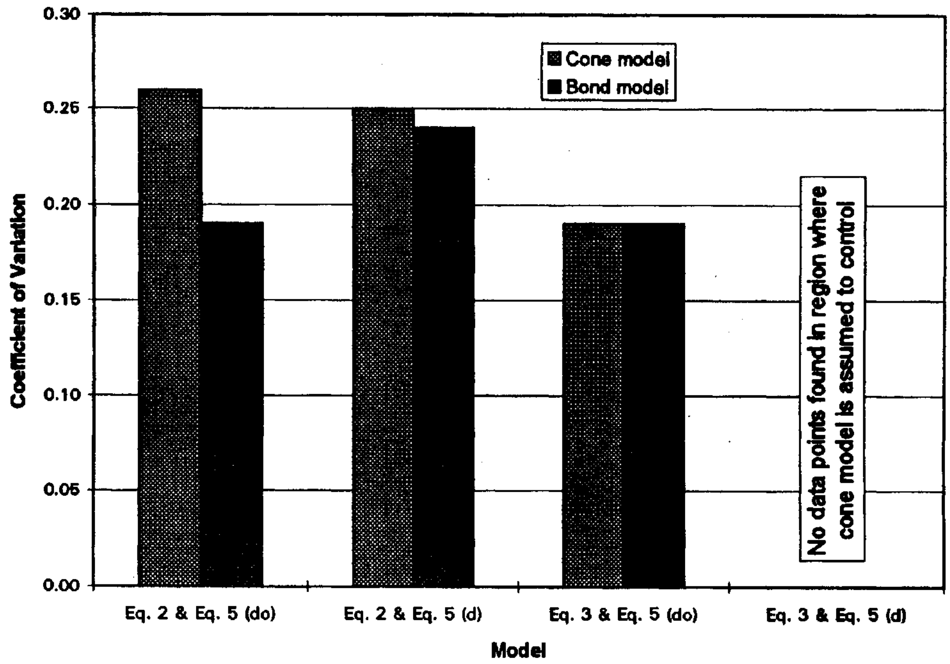



*Fig. 14—Coefficients of variation for cone models and bond models in region where cone model is assumed to control*

## Combined cone/bond models

Combined concrete cone and bond stress models have been proposed by the Japan Concrete Institute[8] for reinforcing bar and Cook[13] for adhesive anchors in general. These models assume a concrete cone formula for very shallow embedment lengths. For deeper embedments, these models use a two term equation to combine the strength of the shallow cone with the bond strength. In the model proposed by Cook[12] the cone depth is calculated by Eq. (7). Equation (7) is based on combining Eq. (2) and Eq. (5) and minimizing the load required to produce failure. If $h_{ef}$ is less than or equal to $h_c$, Eq. (2) is used. If $h_{ef}$ is greater than $h_c$, Eq. (8) is used to calculate the combined cone/bond failure.

$$h_c = \frac{\tau\pi d}{1.84\sqrt{f_c}} \tag{7}$$

$$N_u = 0.92h^2{}_c\sqrt{f_c} + \pi\tau d(h_{ef} - h_c) \tag{8}$$

More sophisticated combined cone/bond models based on Eq. (4) are presented by Cook;[13] however these models are generally too complex for practical use. Although the combined cone/bond failure model may represent a more exact theoretical formulation of the behavior of adhesive anchors the model is not conducive to a simplified design model.

## Two interface bond model

This design model is based on distinguishing between failure at the adhesive/concrete interface and failure at the steel/adhesive interface. This concept has been established for rebar applications with one specific adhesive.[14] A generalized form of this design concept based on the physical bond stress model is given by Eqs. (9) and (10). In the case of steel/adhesive failure [Eq. (9)], the ultimate load depends on the bond stress evaluated at the steel/adhesive interface, the embedment depth, and anchor diameter. If the failure mode is adhesive/concrete [Eq. (10)], the ultimate load depends on the bond stress evaluated at the concrete/adhesive interface at a low concrete strength, the diameter of the hole, the embedment length, and the ratio of the square root of the concrete strength being considered to the square root of the low strength concrete used to establish $\tau_0$.

$$N_u = \tau\pi d h_{ef} \tag{9}$$

$$N_u = \tau_0\pi d_0 h_{ef}\sqrt{\frac{f_c}{f_{c,\,low}}} \tag{10}$$

The difficulty with this model is that the database does not adequately distinguish between failure at the steel/adhesive interface and failure at the adhesive/concrete interface. In fact, many of the failure modes recorded in the database indicate a combined steel/adhesive and adhesive/concrete failure mode (Fig. 8). This is reinforced by the results of tension tests by Cook et al.[3] on twenty different adhesive products. For typical adhesive anchors, it is not possible to clearly distinguish trends between failure modes at the adhesive/concrete, steel/adhesive, or combined adhesive/concrete-steel/adhesive failure modes. Additionally, studies by Krishnamurthy[11] indicate that the thickness of the adhesive layer does not have a significant influence on the strength of the anchor.

Figure 15 shows the variation in bond stress with concrete strength for the various data sets using both anchor diameter ($d$) and hole diameter ($d_0$). As shown in Fig. 15, certain data sets indicate that the bond stress is affected by either the cube root or fifth root of the compressive strength but not by the square root of compressive strength. The implication of this

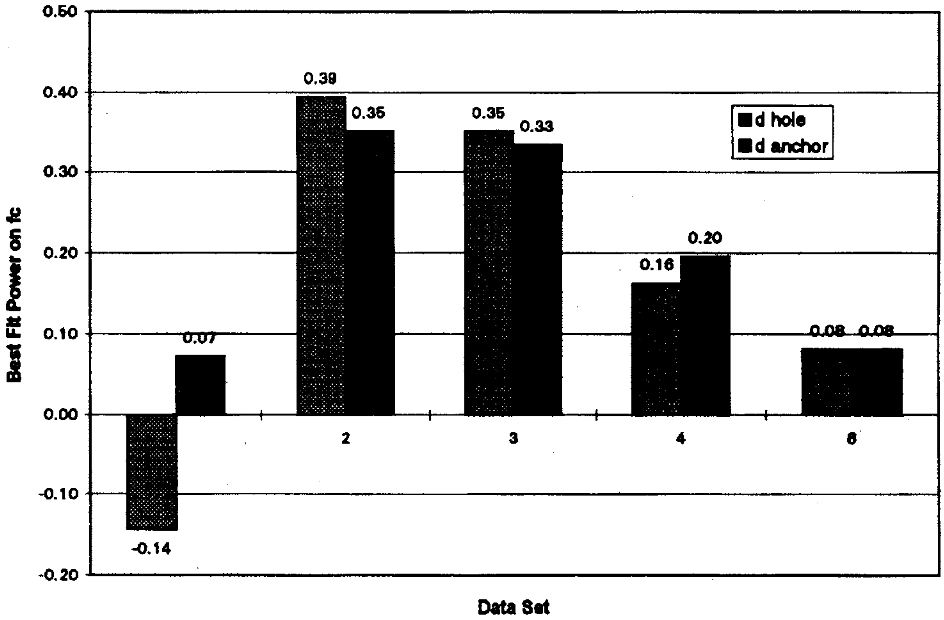



*Fig. 15—Best fit power on concrete strength for data sets with significant variation in concrete strength*

model is that the effect of concrete compressive strength on bond strength is important for some products. This effect is addressed in the recommended design model presented below.

## Summary of design concepts

Figure 16 shows the averages and coefficients of variation for the various design concepts presented above. Notice that the average and coefficient of variation for the cone with bond model using Eq. (3) (cone dependent on $h_{ef}^{1.5}$) and Eq. (5) (uniform bond stress based on $d$) is identical to the average and coefficient of variation for Eq. (5). The reason for this is that there are no data points in the area assumed to be controlled by the concrete cone for this model. The last two bars on each of the graphs in Fig. 16 show the averages and coefficients of variation for the uniform bond stress model [Eq. (5)] adjusted for factors related to concrete strength and bond area. These adjustment factors are discussed in the next section. The following summarizes the various current design concepts:

1. *Concrete cone models (mechanical and headed anchor models)*: These models provide the worst fit to the database of any of the models. This indicates that there is an inherent difference between the behavior of mechanical/headed anchors and bonded anchors.

2. *Bond models*: Uniform bond stress models provide a good fit to the database and are based on a simple physical model. The use of anchor diameter ($d$) rather than hole diameter ($d_0$) in the uniform bond stress model [Eq. (5)] provides a better fit to the database and is user friendly in that it does not require the designer to know each manufacturers' recommended hole diameter.

3. *Bond models neglecting the shallow concrete cone*: As with other design models, these models compared favorably to the test results from which they were developed. When the results of the finite element analysis and the comparison to the worldwide database are considered, it is readily apparent that these models do not provide as viable a model as those based on the simple uniform bond stress model.

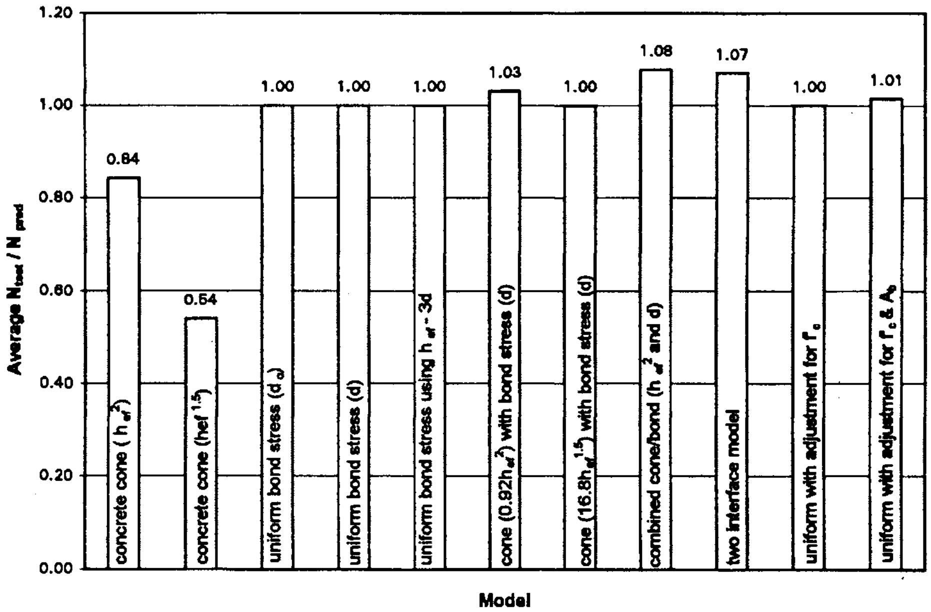
4. *Cone models with bond models*: The results show that in the region assumed to be controlled by the cone model the bond model actually provides a better fit to the data. These results serve to exemplify the basic physical difference between mechanical/headed anchors and adhesive anchors and the need for unique equations for adhesive anchors.

5. *Combined cone/bond model*: Although this model provides a theoretical method for predicting the combined cone/bond failure mode exhibited by adhesive anchors, it is not user friendly. For single anchors, the simple uniform bond stress model provides a better fit and is much easier to implement. The basic theoretical concept of this model should be considered in developing relationships for anchor groups.

6. *Two interface bond model*: Of all the design concepts previously proposed, this concept appears to provide the best fit to the database. Based on Fig. 15, the design concept of increased anchor tensile strength with increased concrete strength is appropriate for consideration in the development of the recommended design model since some products show an increase in bond stress with concrete compressive strength. Although none of the data sets exhibit a direct correlation of bond stress to the square root of concrete compressive strength, some products do exhibit a lesser increase in strength with concrete compressive strength.

## DEVELOPMENT OF BOND MODEL

In this section, a procedure for the evaluation of the ultimate tension load of adhesive anchors based on bond failure is presented. The model is derived from the tests contained in the database and the evaluation of the design concepts presented above. The bond model is based on Eq. (5) with modification factors to account for concrete strength and bond area.



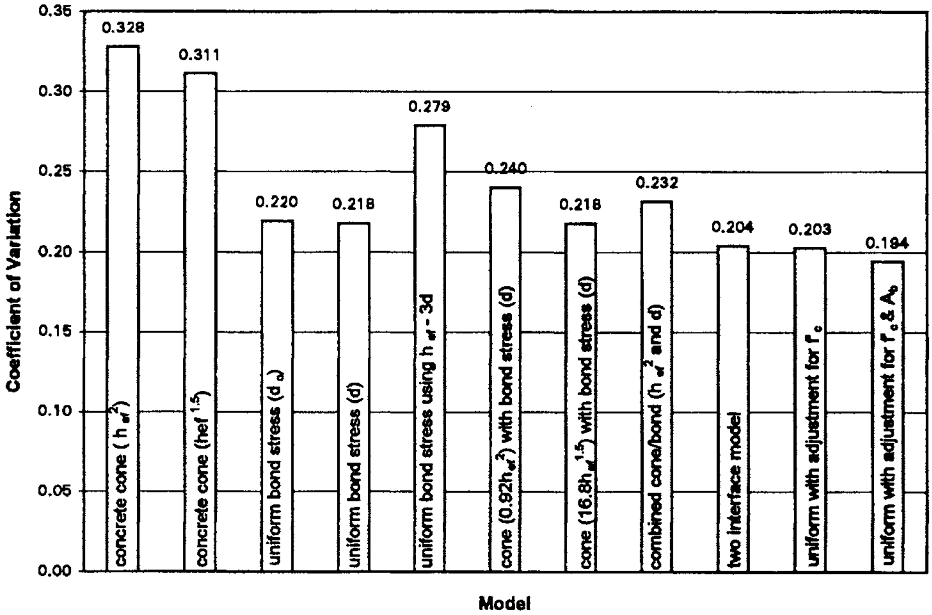




*Fig. 16—Summary of averages and coefficients of variation for all design concepts*

As previously noted, for many adhesive products, the influence of the concrete strength may be neglected. If the strength of a particular adhesive product is significantly affected by concrete strength the appropriate modification factor can be determined by testing in various strengths of concrete. The uniform bond stress model including a modification factor for concrete strength ($\Psi_c$) is given by Eq. (11). For data sets 1, 5, 6, 7, and 8, which show little if any variation in strength with concrete compressive strength, $\Psi_c$ is taken as 1.0. In accordance with Fig. 15, the modification factor $\Psi_c$ is determined using $n = 3$ for data sets 2 and 3 and $n = 5$ for data set 4. Incorporating the concrete modification factor in the uniform bond stress model reduces the overall coefficient of variation from 0.218 to 0.203 (Fig. 16).

$$N_u = \tau\pi d h_{ef}\Psi_c \qquad (11)$$

where:

$\Psi_c = 1.0$ for products with little or no influence of concrete strength

$= \sqrt[n]{\dfrac{f_c}{f_{c,low}}}$ for products influenced by concrete strength

Figure 17 shows the relationship between the ratio of the actual measured load and the predicted load using Eq. (11) ($N_{test}/N_{pred}$) plotted against $f_c$, $h_{ef}/d$, $h_{ef}$, $d$, and the bond area ($A_b$) for the entire database. Figure 17 also shows power curve "best fit" grenadines for all graphs. As shown in Fig. 17, the graphs with $f_c$ and $h_{ef}/d$ as the independent variable indicate no appreciable influence of $f_c$ or $h_{ef}/d$ over the full range. Figure 17 does show a tendency to slightly underestimate anchor strength for anchors with small values of $h_{ef}$, $d$, and bond area ($A_b$) and overestimate strength for anchors with large values of $h_{ef}$, $d$, and bond area ($A_b$). This indicates that the bond area is a possible variable to be included in the overall uniform bond stress model. As shown in Fig. 16, the coefficient of variation for the entire database is 0.203 when $\Psi_c$ is included in the model.

Although the effect of the bond area is relatively small, it can be explained by the previous discussions on bond strength and the elastic bond model. As noted in the previous discussion on bond strength, i.e., adhesive anchors with diameters smaller than 16 mm (small bond areas) tend to exhibit higher bond strength than 16 mm and larger anchors. Additionally, Eq. (4) and studies by Nilson[9] and others indicate that anchor strength is not directly proportional to embedment length (large bond areas). The bond area effect can be represented by an additional modification factor ($\Psi_b$) as shown by Eq. (12). Although the $\Psi_b$ used in Eq. (12) is empirically derived from the database, it is based on rational concepts.

$$N_u = \tau \pi d h_{ef} \Psi_c \Psi_b \quad (12)$$

where:

$$\Psi_b = \frac{5}{3} A_b^{-0.06}$$

Figure 18 shows the relationship between the ratio of the actual measured load and the predicted load using Eq. (12) ($N_{test}/N_{pred}$) plotted against $f_c$, $h_{ef}/d$, $h_{ef}$, $d$, and the bond area ($A_b$) for the entire database. As shown by Fig. 18, incorporating the bond area modification factor results in horizontal trendlines with mean values of 1.0. As shown in Fig. 16, the coefficient of variation for the entire database is 0.194 when both $\Psi_c$ and $\Psi_b$ are included in the model.

Figure 19 shows the coefficients of variation for all of the data sets with both $\Psi_c$ [Eq. (11)] and $\Psi_c$ and $\Psi_b$ [Eq. (12)] included. Note that for all data sets the coefficients of variation are reasonable without the inclusion of $\Psi_b$. Figure 19 does not show the ratio of the actual measured load and the predicted load ($N_{test}/N_{pred}$) since it is always equal to 1.0 when the average uniform bond stress for each individual data set is used to evaluate the data set. Figure 20 shows the uniform bond stress value for all data sets calculated using the anchor diameter.

## RECOMMENDED DESIGN MODEL

In this section, a procedure for the evaluation of the design value ($\phi N_n$) for the tension load of adhesive anchors is presented. The model is derived from the tests contained in the database and the evaluation of the design concepts presented above. The general form of the design model is in accordance with the provisions of draft Chapter 23 of ACI 318.

### Steel failure

The design value for steel failure ($\phi_s N_{n,steel}$) is calculated by:

$$\phi_s N_{n,\,steel} = \phi_s A_e f_y \quad (13)$$

### Bond failure

A very simple formula corresponding to the uniform bond stress model and incorporating an optional modification factor for concrete strength ($\Psi_c$) is proposed. The modification factor for bond area ($\Psi_b$) discussed above is not included in the recommended design model since it offers marginal improvement to the predicted capacity while adding increased difficulty to the design calculations.

$$\phi_b N_{n,\,bond} = \phi_b \tau' A_b \Psi_c \quad (14)$$

where:

$$A_b = \pi d h_{ef} \quad (15)$$

$$\tau' = \tau_{f_c = 20MPa}(1 - kCOV) \quad (16)$$

$\Psi_c = 1.0$ for testing in only $f_c = 20$ MPa strength concrete (17)

$= \sqrt[n]{\frac{f_c}{20}}$ for testing in higher strength concrete (optional)

### Predicted design load

The predicted design load is based on determining the minimum controlling design load in accordance with Eq. (13) and Eq. (14):

$$N_u = \min(\phi_s N_{u,steel}, \phi_b N_{u,bond}) \quad (18)$$

## CONCLUSIONS

In this study, various design models for single adhesive anchors located away from concrete edges are compared to a worldwide database. The results of the comparisons indicate that a model based on uniform bond stress provides the best fit to the data and agrees with non-linear analytical studies of the adhesive anchor system. The uniform bond model is user-friendly since it is based on an easily visualized physical model that is very simple to implement.

Implementation of the model necessarily includes the development of a product acceptance standard which will include a series of simple tension tests to determine the appropriate bond strength of a product and the susceptibility of the product to commonly occurring installation and in-service conditions. Currently, a detailed product acceptance standard for adhesive anchors is being developed by ASTM Committee E06.13. The standard will include appropriate tests and acceptance criteria for the evaluation of bond stress and product performance under various installation and in-service conditions.

The conclusions developed in this paper are technically only valid for the limits of the database as shown in Table 1. The following should be considered as limitations to the uniform bond stress model unless additional testing is performed:

| | | |
|---|---|---|
| $h_{ef}/d$ | = | 4.5 to 25.0 |
| $f_c$ | = | 13.0 to 68.0 (MPa) |
| $A_b$ | = | 1250 to 60,000 (mm$^2$) |

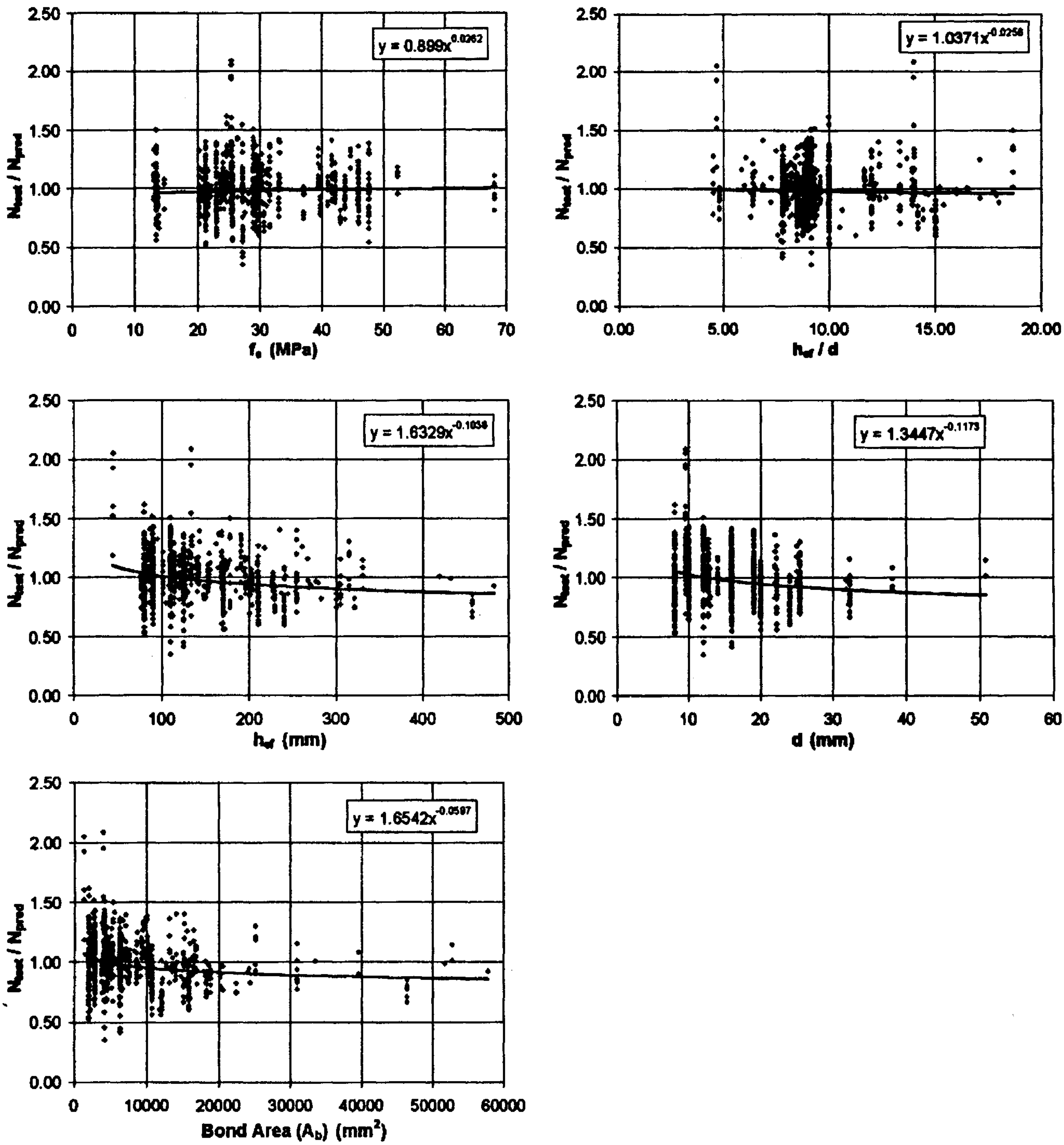



*Fig. 17—Measured test results compared to predicted results plotted against* $f_c$, $h_{ef}$ / d, $h_{ef}$, d, *and* $A_b$ *with* $\Psi_c$ *included*

These limitations are not overly restrictive since they include the range of practical applications.

The design model must be extended for groups of anchors, and include the influence of edge distance. The aim is to arrive at a model for adhesive anchors which is comparable to the CCD method for mechanical and undercut anchors.[5] The influences of environmental conditions like hole cleaning, humidity, temperature, etc., may be included in this concept by appropriate modification factors for each product as determined from product acceptance tests. As an alternative, product acceptance criteria may include minimum environmental performance thresholds (for example, the strength of a product in a damp hole must meet or exceed 80 percent of the strength in a clean, dry hole). Whichever procedure is implemented (product specific modification factors or minimum acceptance thresholds), it is essential that product acceptance criteria be developed before the design model can be fully implemented by building codes.

## NOTATION

| | | |
|---|---|---|
| $A_b$ | = | (bonded area of anchor calculated at the anchor diameter) |
| $A_e$ | = | effective tensile stress area of anchor |
| $d$ | = | outside diameter of anchor (mm) |
| $d_0$ | = | hole diameter (mm) |
| $f_c$ | = | concrete strength, measured on 150 by 300 mm cylinders (MPa) |
| $h_c$ | = | depth of shallow concrete cone |
| $h_{ef}$ | = | embedment depth (mm) |

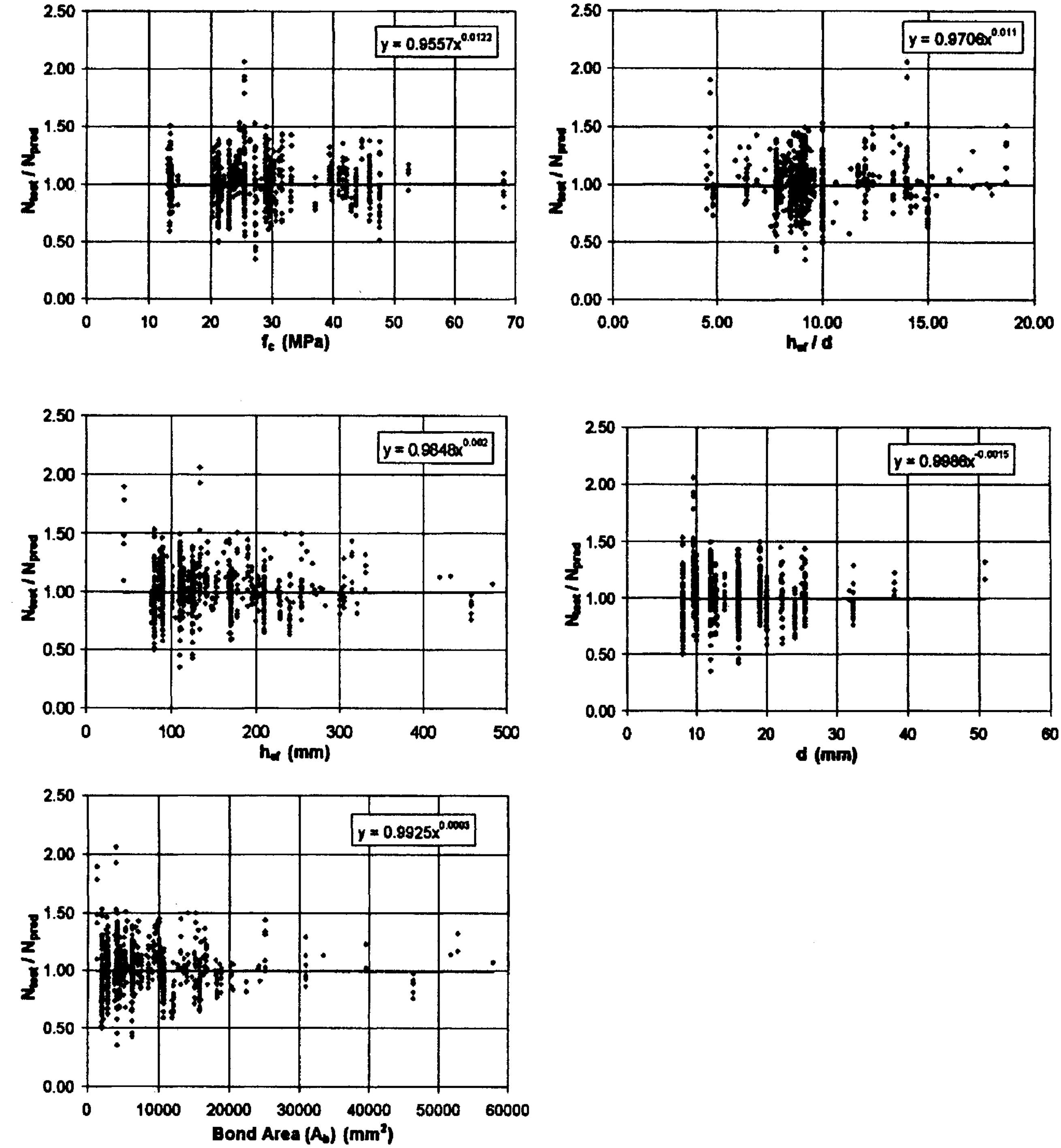



*Fig. 18—Measured test results compared to predicted results plotted against* $f_c$, $h_{ef}$ / d, $h_{ef}$, d, *and* $A_b$ *with* $\Psi_c$ *and* $\Psi_b$ *included*

$k$ = a statistically determined coefficient based on the 5 percent fractile, number of tests, and confidence to be used for design (Note: This value is 1.65 for several tests).

$n$ = power to be applied in determining $\Psi_c$. The value for n is product dependent and is determined from tests of individual adhesive products in various concrete strengths.

$N_{n,steel}$ = nominal strength of the anchor as controlled by steel strength

$N_{n,bond}$ = nominal strength of the anchor as controlled by bond strength

$N_u$ = ultimate predicted strength of the anchor

$COV$ = coefficient of variation

$\alpha,\beta,\gamma,\delta$ = variables used in regression analysis of database

$\lambda$ = stiffness characteristic of the adhesive anchor system ($mm^{-1}$)

$\phi_b$ = capacity reduction factor for bond failure (0.85 is recommended)

$\phi_s$ = capacity reduction factor for steel failure (0.90 is recommended)

$\tau$ = bond stress (MPa)

$\tau_{data\ set}$ = average uniform bond stress (MPa) evaluated for each of the 8 data sets

$\tau_{f_c'=20\ MPa}$ = mean value for uniform bond stress (MPa) at the anchor/adhesive interface determined from tensile tests in $f_c$ = 20 MPa concrete (minimum recommended anchor size: 16 mm diameter x 100 mm embedment)

$\tau'$ = design value for uniform bond stress (MPa) at the anchor/adhesive interface

$\tau_0$ = bond stress evaluated at hole diameter [Eq. (10)] (MPa)

$\Psi_b$ = modification factor for concrete strength

$\Psi_{=c}$ = modification factor for bond area

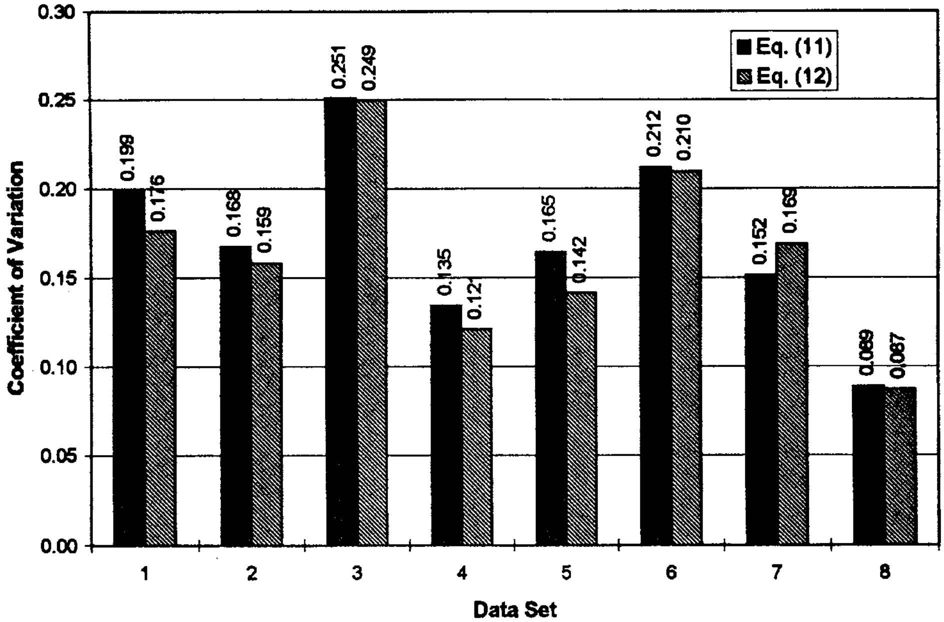



*Fig. 19—Coefficients of variation for each data set*

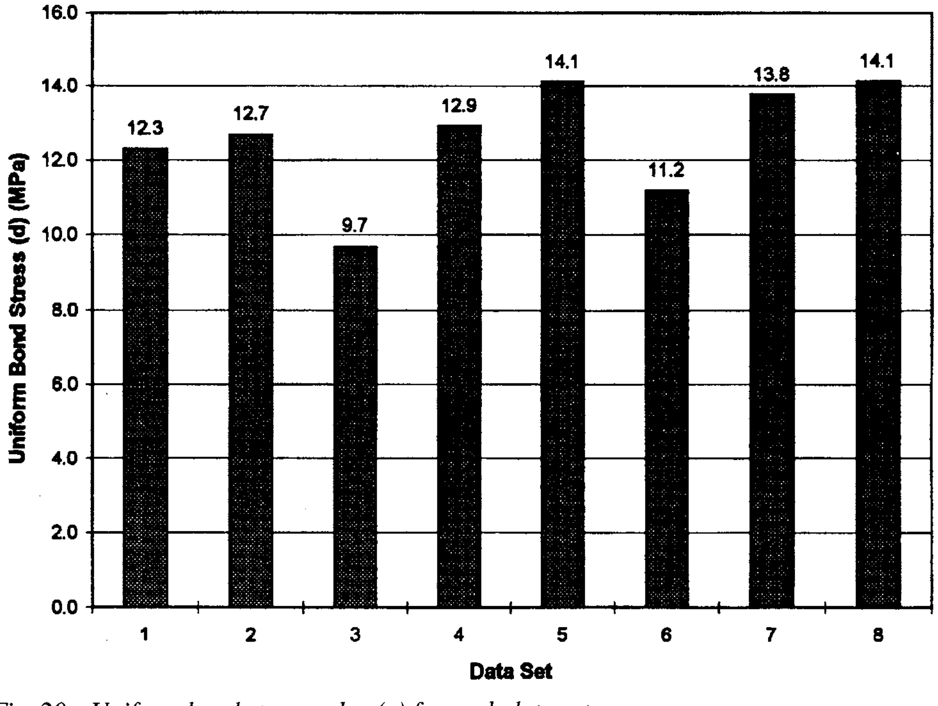



*Fig. 20—Uniform bond stress value (τ) for each data set*

## ACKNOWLEDGMENTS

The authors wish to express special thanks to Mr. Yohei Akiyama for the seemingly endless hours that were needed to compile the worldwide database. As mentioned there are 2929 total tests in the database; what was not mentioned was that each test contains seventy possible column entries. This was an incredible task. Special thanks are also accorded to the manufacturers who allowed the results of their testing programs to be incorporated into the database.

## REFERENCES

1. Doerr, G. T.; Cook, R. A.; and Klingner, R. E., "Adhesive Anchors: Behavior and Spacing Requirements," *Research Report* No. 1126-2, Center for Transportation Research, University of Texas at Austin, 1989, 68 pp.

2. Doyle, E. N., *The Development and Use of Polyester Products*, McGraw Hill, New York, 1969, 365 pp.

3. Cook, R. A., et al., "Adhesive Bonded Anchors: Bond Properties and Effects of In-Service and Installation Conditions," *Structures and Materials Research Report* No. 94-2, Engineering and Industrial Experiment Station, University of Florida, Gainesville, 1994, 164 pp.

4. Eligehausen, R.; Mallée, R.; and Rehm, G., "Befestigungen mit Verbundankern (Fastenings with bonded anchors)," *Betonwerk + Fertigteil-Technik*, No. 10, pp. 682-692, No. 11, 781-785, No. 12, 825-829, Berlin, 1984 (in German).

5. Fuchs, W.; Eligehausen, R.; and Breen, J. E., "Concrete Capacity Design (CCD) Approach for Fastening to Concrete," *ACI Structural Journal*, V. 92, No. 1, January-February 1995, pp. 73-94.

6. Cook, R. A.; Doerr, G. T.; and Klingner, R. E., "Bond Stress Model for Design of Adhesive Anchors," *ACI Structural Journal*, V. 90, No. 5, September-October 1993, pp. 514-524.

7. Cook, R. A.; Fagundo, F. E.; and Biller, M. H., "Tensile Behavior and Design of Adhesive-Bonded Anchors and Dowels," *Transportation Research Record* 1392, Transportation Research Board, 1993, pp. 126-133.

8. Post Installed Anchors, State of the Art Report, Japan Concrete Institute, 1994 (in Japanese).

9. Nilson, A. H., "Internal Measurement of Bond Slip," ACI JOURNAL, V. 69, No. 7, July 1972, pp. 439-441.

10. McVay, M.; Cook, R. A.; and Krishnamurthy, K., "Behavior of Chemically Bonded Anchors," *Journal of Structural Engineering*, American Society of Civil Engineers, V. 119, No. 9, September, 1993, pp. 2744-2762.

11. Krishnamurthy, K., "Development of a Viscoplastic Consistent-Tangent FEM Model with Applications to Adhesive-Bonded Anchors," PhD Thesis, University of Florida, Gainesville, 1996.

12. ACI Committee 349, *Code Requirements for Nuclear Safety Related Concrete Structures (ACI 349-85)*, American Concrete Institute, Detroit, 1985.

13. Cook, R. A., "Behavior of Chemically Bonded Anchors," *Journal of Structural Engineering*, American Society of Civil Engineers, V. 119, No. 9, September, 1993, pp. 2744-2762.

14. Marti P., "Anchoring of Concrete Reinforcement Using HIT-HY 150," *Report* No. 93.327-1, Hilti Development Corporation, Kaufering, Germany, 1993.