Shear Strength of Adhesive Anchors

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While there are several procedures for calculating the capacity of headed studs and other mechanical fasteners anchored in concrete, comparable information is not readily available for adhesive anchors. This paper examines the validity of applying the two most commonly used procedures for headed stud anchors to predict the shear capacity of adhesive anchors. These are the PCI Design Handbook (Fifth Edition) method and the Concrete Capacity Design (CCD) method. An analysis is first carried out which compares the use of these methods with headed studs and adhesive anchors. The application of these methods for adhesive anchors is then examined in more detail, and appropriate adjustments are proposed. It is concluded that, for single adhesive anchors, the PCI Design Handbook method and the CCD method, with proper adjustments, can be used for predicting the shear capacity of adhesive anchors with similar accuracy.

Adhesive anchors have come to play an increasingly important role in the precast concrete industry in the past decade. Initially, they were used primarily for field correcting fabrication errors, and for repair and retrofit situations. However, with the demand for more flexibility in the planning and design of concrete structures, they are also now commonly used in new construction.

An adhesive anchor is a threaded rod or a reinforcing bar that is inserted into a hole drilled into hardened concrete. The hole diameter is typically 10 to 25 percent larger than the inserted anchor or bar diameter. The hole is filled with an adhesive that bonds the steel anchor to the concrete. For a more complete discussion of adhesive anchors and adhesive anchor systems, see Reference 1.

Partly because of the numerous and varied products available, the design of adhesive anchors has generally not been addressed in building codes. Thus, designers must rely on the manufacturer's recommendations to predict the tensile and shear strengths of such anchors. These recommendations are typically based on laboratory tests specific to the manufacturer's product and type of application. In many cases, on-site proof testing is required

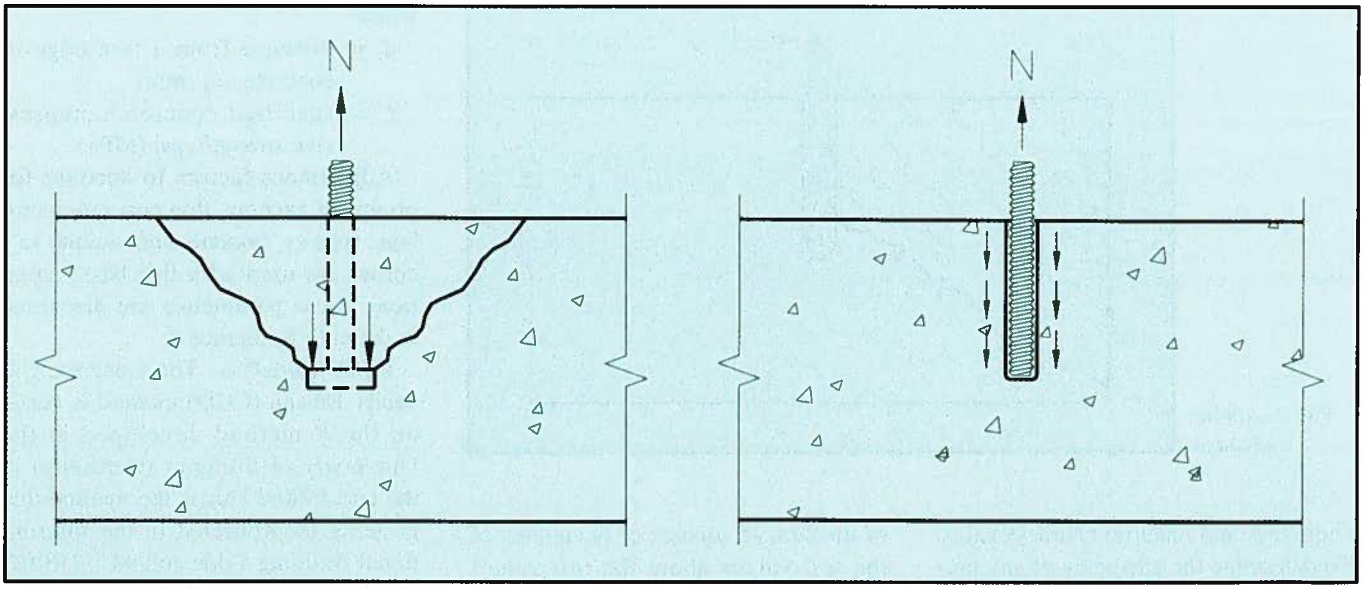

Fig. 1. Headed studs and adhesive anchors.

for each diameter, embedment length, and concrete substrate condition specific to a project.

Several methods exist for calculating the shear capacity of headed studs embedded in concrete. The objective of this paper is to examine the validity of applying two of the most commonly used procedures to predict the shear capacity of adhesive anchors. With that intent, as appropriate, only minor modifications to these procedures will be suggested.

The authors believe this is a reasonable research focus because the concrete failure mechanism for a single adhesive anchor loaded in shear should be similar to any other type of concrete anchor (as opposed to distinct differences for various anchors in tension). This task was also considered important because of the lack of a model based on the latest data to predict adhesive anchor shear capacity.

By using the same capacity calculation method for both headed studs and adhesive anchors, some basic differences between the two anchor types can be highlighted, along with some of their similarities. Because of the limited amount of test data available on adhesive anchors, only single anchors located away from corners and exhibiting concrete failure in unreinforced specimens were examined.

Based on correlation with experimental results shown in the data available to the authors, the accuracy of applying these methods to adhesive anchors is assessed. Where appropriate, modifications are proposed for using the two methods with adhesive anchors.

INVESTIGATION

This section furnishes the experimental data sources used in this study, describes the behavior of fasteners under load, provides analytical models for predicting shear capacity, and describes the predictive models used.

Experimental Data Sources

Two bodies of experimental data were used for this study. For headed studs, data were obtained from the work of Dr. Richard E. Klingner and the Concrete Capacity Design (CCD) database made available to the Precast/Prestressed Concrete Institute. These data were used in research work done previously at the University of Wisconsin-Milwaukee.[2] From these data, 122 tests were applicable to this study, namely, single anchor shear tests near one edge exhibiting plain concrete failure.

For adhesive anchors, data were obtained from a worldwide database made available to the authors by Dr. Ronald Cook at the University of Florida.[3] As of early 2000, the database had nearly 3000 tests with varying parameters covering the range of practical applications. A total of 89 tests were selected as applicable to this study.

Behavior of Fasteners Under Load

Adhesive anchors in tension have a distinctly different concrete failure mechanism from that of headed studs in tension. In headed studs, the resistance is concentrated at the base of the head, which results in a shear cone failure. The resistance of adhesive anchors is distributed along the embedment depth of the anchor, as illustrated in Fig. 1. Because of this behavioral difference, models used to predict the tensile strength of headed studs are not appropriate for determining the tensile strength of adhesive anchors.[1]

This clear distinction, however, does not exist between headed studs and adhesive anchors loaded in shear. When loaded in shear, the headed stud shank or an adhesive anchor's adhesive layer bears on the concrete. With enough force, each of these will cause the edge of the concrete to break out as in Fig. 2, or if the edge distances are larger, the anchor will yield.

Assessing Predictive Models

If a perfect procedure were available for predicting shear capacity, then for any particular anchor, that procedure would give results in exact agreement with experimental results. This would also be true for all combinations of an-

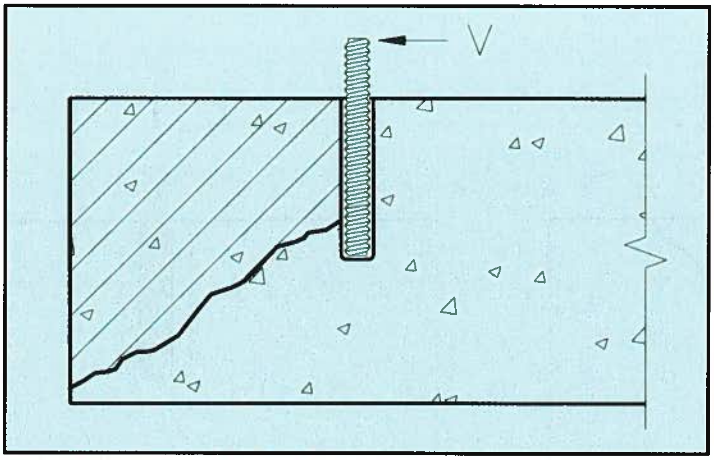

Fig. 2. Anchor in shear.

chor sizes and material characteristics. To determine the adequacy of any predictive model, it is necessary to compare the results of the analytical model with experimental results.

A typical comparison method examines the actual tested anchor capacity with the capacity predicted by the model. An analysis can be performed on this ratio (actual to predicted capacity) for a body of data. The mean of this ratio indicates how conservative the model may be; a mean greater than one suggests, on the average, the actual anchor capacity will be greater than that predicted by the model.

Typically, the model is probabilistically calibrated to a fractile level, which for a large body of data is essentially a percentile. The ACI 318 Building Code uses a 5 percent fractile in the anchorage design model based on the CCD method. The 5 percent fractile level indicates that for 95 percent of tests performed, the actual anchor capacity would be greater than that predicted by the model.

One way of assessing the adequacy of the model is to examine the coefficient of variation (COV). The COV gives the standard deviation as a percentage of the mean. The standard deviation indicates how far the ratios of actual to predicted strength are spread from the mean. While this provides some measure of the model's validity, it is limited in that it deals with the variation in ratios, rather than dealing with variation in the actual test data.

Another statistical tool used in assessing the adequacy of a model is the coefficient of determination, or *R*-squared. The term R^2 is the proportion of the sum of squares of deviations of the test values about the test values mean attributed to a linear relation between the test and predicted values.

For example, an R^2 of 0.9 indicates that the model explains 90 percent of the variation in the test data, and the other 10 percent may be explained by parameters other than those in the model, or is simply due to random error. The term R^2 provides a more accurate assessment of a model than the COV because it relates the model to the test data as a whole, rather than individual ratios.

Summary of Predictive Models Used

This section provides a brief summary of the two analytical models used in this study. Only the parts of the models pertaining to the scope of this study are presented here; that is, the parts of the models that predict anchor shear capacity based on concrete strength for a single anchor near one edge. The models in their entirety can be examined in their respective reference sources.

PCI Design Handbook (Fifth Edition) Model[4] — The shear strength (in lb or N) limited by concrete for a single anchor is:

U. S. customary units:

$$V_c' = 12.5 d_e^{1.5}\sqrt{f_c'} \qquad (1a)$$

SI units:

$$V_c' = 5.2 d_e^{1.5}\sqrt{f_c'} \qquad (1b)$$

where

d_e = distance from a free edge of concrete, in. (mm)

f_c' = specified concrete compressive strength, psi (MPa)

Adjustment factors to account for groups of anchors, thin concrete members, type of concrete, and vicinity to a corner are used with this basic equation. These parameters are discussed in detail in Reference 4.

CCD Model[5] — The Concrete Capacity Design (CCD) method is based on the *K*-method developed at the University of Stuttgart (Germany) in the late 1980s. This is the method that is being incorporated in the International Building Code and ACI 318-02. The basic equation of the concrete capacity (in lb or N) of an individual anchor in a thick, uncracked structural member under shear loading toward the free edge is:

U.S. customary units:

$$V_{no} = 13\left(\frac{h_{ef}}{d_b}\right)^{0.2}\sqrt{d_b}\sqrt{f_c'}\left(c_1^{1.5}\right)$$

SI units:

$$V_{no} = 1.1\left(\frac{h_{ef}}{d_b}\right)^{0.2}\sqrt{d_b}\sqrt{f_c'}\left(c_1^{1.5}\right) \qquad (2)$$

where

h_{ef} = embedment depth of the anchor, in. (mm)

d_b = diameter of the anchor, in. (mm)

c_1 = distance from a free edge of concrete, in. (mm)

f_c' = specified concrete compressive strength, psi (MPa)

Several adjustment factors are used to account for the presence of a corner, multiple anchors, thin concrete members, cracked concrete, and other parameters affecting the concrete capacity. These are discussed in detail in Reference 5.

PRELIMINARY ANALYSIS

PCI Method — The model as described in the previous section was used to predict the strength of anchors with the same parameters as those tested. These results were then com-

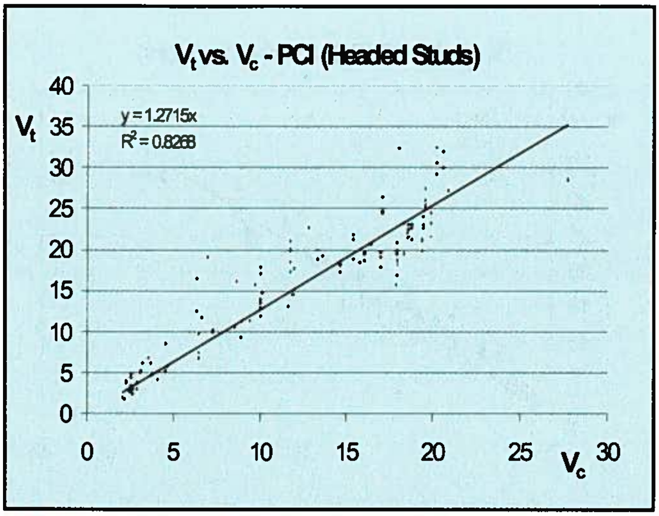

Fig. 3. PCI method for headed studs in shear.

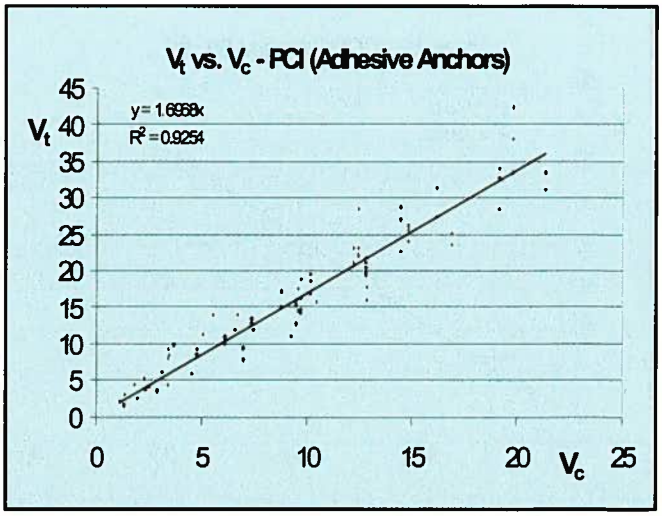

Fig. 4. PCI method for adhesive anchors in shear.

pared to the test results. The results for headed studs are shown in Fig. 3 and Table 1, and the results for adhesive anchors are shown in Fig. 4 and Table 2. In the two plots, V_t is the predicted capacity and V_c is the test load.

For headed studs, the PCI method is generally conservative with a mean of test-to-predicted values of 1.36. The COV of 0.235 shows a reasonably small deviation of the test-to-predicted capacity ratios from the mean. The best-fit line in Fig. 3 shows an R^2 of 0.83, indicating the PCI method accounts for 83 percent of the variation in the test data.

Table 2 shows that the PCI method is even more conservative for adhesive anchors than for headed studs, with a mean of 1.73 for the ratio of actual strength-to-predicted strength. The best-fit line in Fig. 4 also shows a slightly better correlation for adhesive anchors. The R^2 of 0.93 indicates the PCI model accounts for about 10 percent more of the variation in the adhesive anchor data than for the headed stud data.

CCD Method — The same analysis performed in the previous section with the PCI method was also performed with the CCD method. The results for headed studs are shown in Fig. 5 and Table 3, and the results for adhesive anchors are shown in Fig. 6 and Table 4.

For headed studs, the CCD method is generally conservative with a mean of test-to-predicted values of 1.11. The COV of 0.189 shows a small deviation of the test-to-predicted capacity ratios from the mean. The best-fit line in Fig. 5 shows an R^2 of 0.89 indicating that the CCD method accounts for 89 percent of the variation in the test data.

Table 4 shows that the CCD method is also more conservative for adhesive anchors than for headed studs, with a mean of 1.33 for the ratio of actual strength-to-predicted strength. The best-fit line in Fig. 6 also shows a slightly better correlation for adhesive anchors. The R^2 of 0.93 indicates that the CCD model accounts for 5 percent more of the variation in the adhesive anchor data than for the headed stud data.

Based on this preliminary analysis, a general observation is that these models are more conservative for adhesive anchors than for headed studs. That is, capacity is under-predicted in relation to the test data. Also, the data for test-to-predicted ratios are generally grouped more tightly about the mean for adhesive anchors than for headed studs.

When comparing both prediction models on the basis of R^2, that is, how well the models account for variations in test data, the models are better predictors for adhesive anchors than for headed studs. Some discussion on a physical explanation for this is included in the next section.

MODELING FOR ADHESIVE ANCHORS

While the PCI and CCD models were developed for headed studs, it can be seen from the previous section that they actually fit the adhesive anchors data better than the headed stud data. The models are also more conservative for adhesive anchors, implying that adhesive anchors may have more shear capacity than headed studs.

Table 1. Statistical summary – PCI method for headed studs.

Mean	1.36
Standard deviation	0.318
Coefficient of variation (COV)	0.235
Fractile percent	6.6
Coefficient of determination squared (R^2)	0.827

Table 2. Statistical summary – PCI method for adhesive anchors.

Mean	1.73
Standard deviation	0.356
Coefficient of variation (COV)	0.206
Fractile percent	0
Coefficient of determination squared (R^2)	0.925

In this section, a more detailed analysis is performed on the PCI and CCD models for adhesive anchors. Each of the behavioral model parameters is discussed as well as the amount of influence that they have on the given model. Also, a regression analysis is performed to determine the exponents of the various parameters for a best fit to the data. Changes are recommended for each model to provide a better fit to the data. With all of this, an attempt is made to provide a qualitative physi-

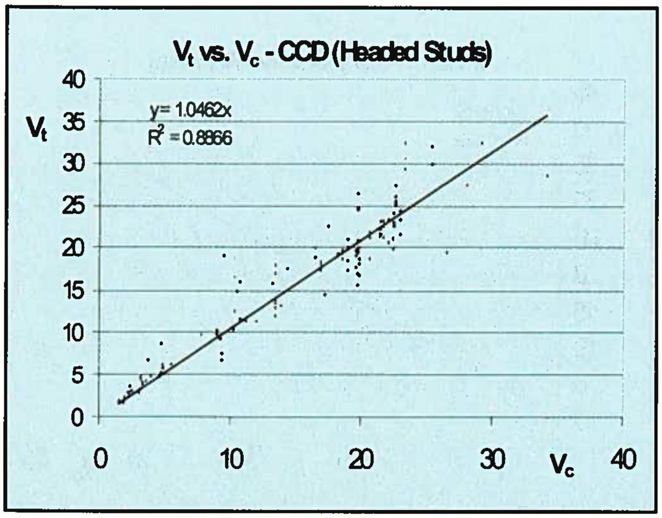

Fig. 5. CCD method for headed studs in shear.

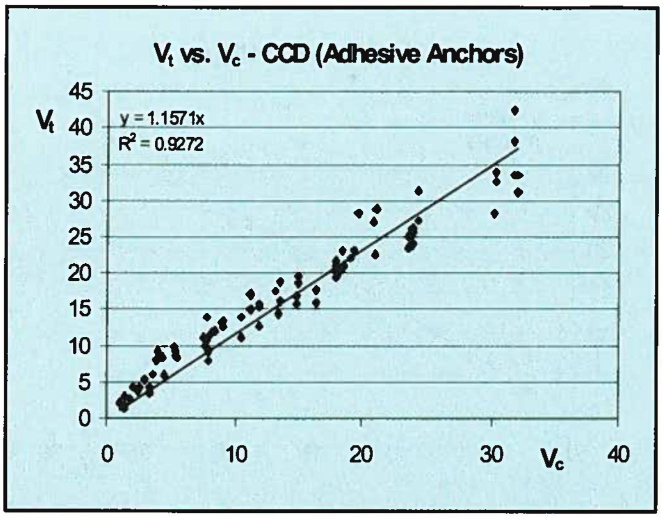

Fig. 6. CCD method for adhesive anchors in shear.

Table 3. Statistical summary – CCD method for headed studs.

Mean	1.11
Standard deviation	0.210
Coefficient of variation (COV)	0.189
Fractile percent	27.1
Coefficient of determination squared (R^2)	0.887

Table 4. Statistical summary – CCD method for adhesive anchors.

Mean	1.33
Standard deviation	0.319
Coefficient of variation (COV)	0.24
Fractile percent	5.6
Coefficient of determination squared (R^2)	0.927

cal explanation of the differences in headed stud and adhesive anchor behavior, which would partially explain the different fits of the models to the data.

PCI Method

Model Parameters — All data examined in this study were for single anchors near the edge exhibiting concrete failure. This mode of failure is caused by a limiting tensile stress in the concrete. Therefore, any model predicting a failure load must attempt to relate that load to a tensile stress required to fail concrete multiplied by an area of the failure surface. The PCI model deals with this concept very directly. The general equation of the model is reproduced here for convenience:

$$V_c' = 12.5 d_e^{1.5} \sqrt{f_c'} \qquad (1)$$

The area of the failure surface is a function of the edge distance (d_e) and $\sqrt{f_c'}$ is the failure stress parameter. The constant of 12.5 in the model is the calibration constant. Fig. 7 shows the relationship between the ratio of actual measured failure loads and predicted loads using the PCI model plotted against the two parameters of the model: f_c' and d_e. The best-fit power curves are shown for these graphs.

As shown in Fig. 7, the graph with edge distance as the independent variable indicates no appreciable influence of d_e over the full range. The graph with f_c' as the independent variable does, however, show a variability in the influence of concrete strength on the model. This will be addressed by a multiple regression analysis.

Multiple Regression — For the given test data, a multiple regression analysis was performed using the basic form of the PCI model:

$$V = \alpha f_c'^{\beta} d_e^{\gamma} \qquad (3)$$

The regression values obtained for the exponents were $\beta = 0.344$ and $\gamma = 1.522$. While these values provide the best fit, they are not very user friendly. These values were rounded off to make them more practical, yielding the following adjustment to the PCI model. (Note that α was chosen to correspond to the 5 percent fractile level.)

$$V = 58\left(\sqrt[3]{f_c'}\right) d_e^{1.5} \qquad (4)$$

As can be seen in Fig. 8, rounding the exponents to more convenient values has very little impact on correlation. By modifying the PCI model in this way, correlation with the test data is slightly improved. The COV of test/calculated ratios becomes 0.197, which is slightly lower than 0.206 for the original PCI model. Fig. 8 shows the test values plotted against the values calculated by this equation. The R^2 for this model is 0.936, which is also a slight improvement over the 0.925 of the original PCI model.

Model Modifications — For single anchors, the PCI model is quite straightforward, such that it is difficult to improve upon it without making it more complex. The change shown in Eq. (4) is to reduce the influence of concrete strength by using the cube root rather than the square root. However, since the square root of concrete compressive strength is commonly recognized as describing concrete tensile strength, it is the opinion of the authors that the slight improvement in correlation by using the cube root does not warrant making this modification.

Because of the traditional and recognizable use of $\sqrt{f_c'}$, a second analysis was performed with the following equation:

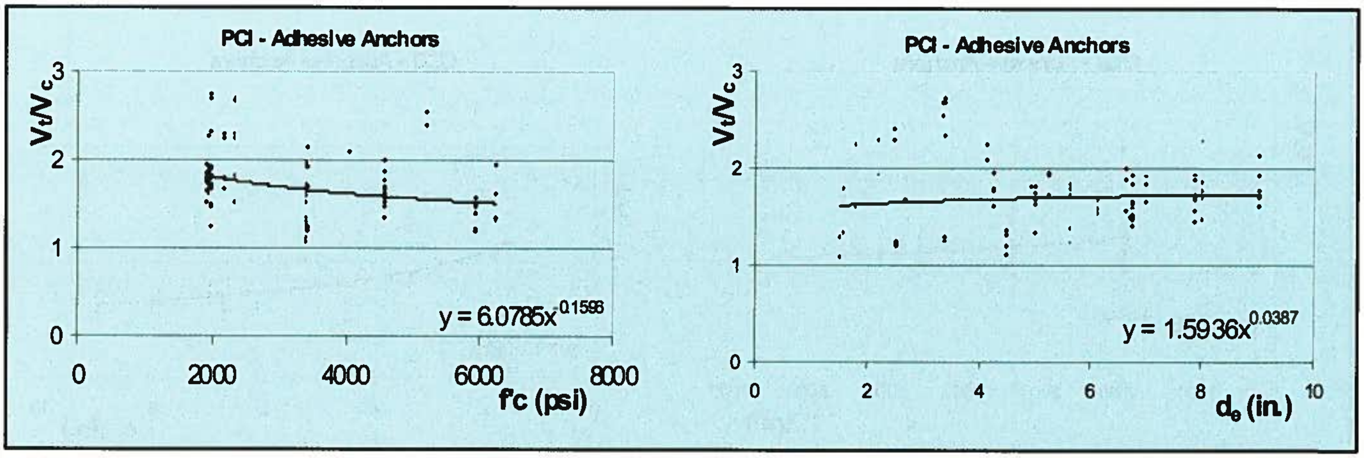

Fig. 7. PCI model – Test/calculated ratios versus f_c' and d_e.

$$V = 15\sqrt{f_c'}\, d_e^{1.5} \quad (5)$$

Since only the constant has changed from Eq. (1), the correlation is the same with a COV of 0.206 and an R^2 of 0.925. The constant was chosen to correspond to a fractile level less than 5 percent.

Therefore, for single adhesive anchors, the PCI model can be used in a similar manner to headed studs. However, the model is more conservative for adhesive anchors than for headed studs. For adhesive anchors, a constant of 15 can be substituted for the headed stud constant of 12.5, as shown in Eq. (5), and achieve a fractile level consistent with the model used for headed studs. This simple change is consistent with the authors' intent to apply a commonly used, existing procedure to adhesive anchors.

CCD Method

Model Parameters — As discussed in the previous section, the prediction of a load at which concrete will fail must account for tensile stress acting on a failure surface. The PCI model determines the stress in terms of f_c' and the failure surface only in terms of edge distance (designated as c_1 in the CCD method). The general equation for single anchors for the CCD model is also provided below.

$$V_{no} = 13\left(\frac{h_{ef}}{d_b}\right)^{0.2}\sqrt{d_b}\sqrt{f_c'}\left(c_1^{1.5}\right) \quad (2)$$

As in the PCI model, the CCD model estimates tensile stress in terms of f_c', but uses more parameters to estimate the failure surface other than edge distance. The effect of anchor diameter is considered, as well as the effect of the "activated length," which is the embedment depth divided by the anchor diameter (h_{ef}/d_b).

Fig. 9 shows the relationship between the ratio of actual measured failure loads and predicted loads using the CCD model plotted against the four variables of the model: f_c', (h_{ef}/d_b), d_b, and c_1. The best-fit power curves are shown for these graphs.

As seen in Fig. 9, the graph with f_c' as the independent variable shows a decreasing influence of concrete strength on the model, similar to the PCI model. The graphs with edge distance and anchor diameter as independent variables both show that as they get larger, the model overestimates anchor strength. However, as the h_{ef}/d_b values get larger, the model underestimates anchor strength. This will be addressed by a multiple regression analysis.

Multiple Regression — For the adhesive anchor test data, a multiple regression analysis was performed using the basic form of the CCD model:

$$V = \alpha\left(\frac{h_{ef}}{d_b}\right)^{\beta} d_b^{\delta} f_c'^{\varepsilon} c^{\gamma} \quad (6)$$

The regression values obtained for the exponents were $\beta = 0.625$, $\delta = 0.657$, $\varepsilon = 0.306$, and $\gamma = 1.169$. Because β and δ are so similar, the effect of anchor diameter effectively cancels out, leaving only embedment, concrete strength, and edge distance as the basic model parameters.

A few interesting observations can be made from the regression analysis. First, the data set for adhesive anchors

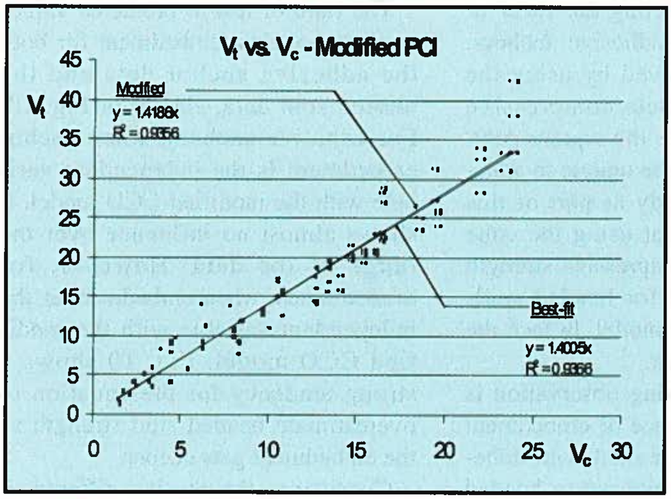

Fig. 8. Test versus calculated – modified PCI method.

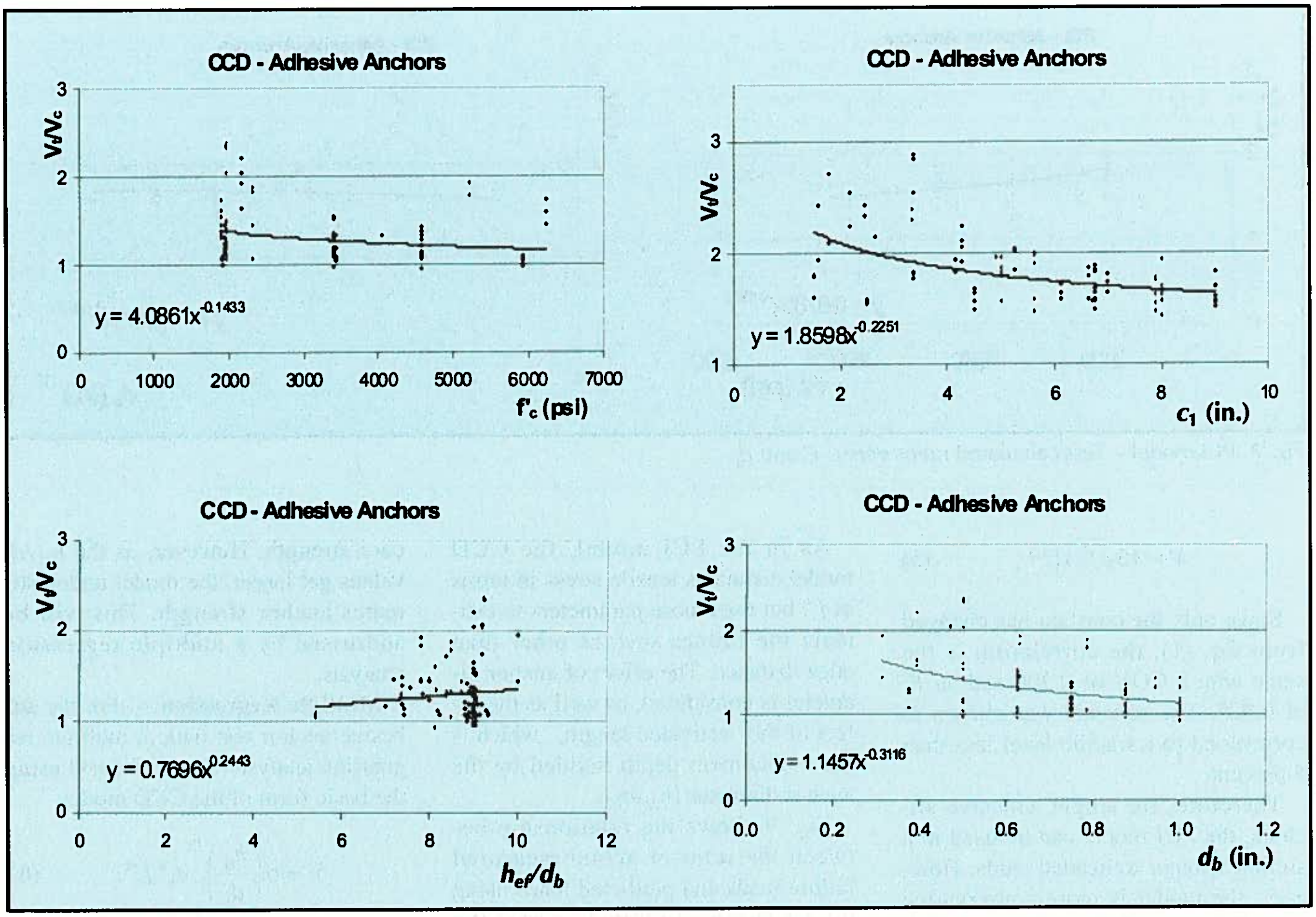

Fig. 9. Test/calculated ratios versus f'_c, c_1, h_{ef}/d_b, and d_b.

does not exhibit a direct correlation of shear failure load with the square root of concrete compressive strength. Rather, the data exhibits a lesser increase in strength with concrete compressive strength; the cube root is more appropriate as determined from the regression analysis. Interestingly, Cook et al.[1] have made the same observation in their study on the tensile strength of adhesive anchors.

Thus, when predicting the shear or tension strength of adhesive anchors, the model is improved by using the cube root of concrete compressive strength rather than the square root. This trend seems to be unique to adhesive anchors. A study as part of this research showed that using the cube root of concrete compressive strength in the CCD model for headed studs did not improve the model. In fact, the correlation was lower.

A second interesting observation is the increased influence of embedment depth for the CCD model with adhesive anchors, as compared to headed studs. When the coefficients obtained from the regression analysis are used with the CCD model, the following equation is obtained (exponents have been rounded to convenient values and α was chosen to correspond to the 5 percent fractile level):

$$V = 33h_{ef}^{0.65}\left(\sqrt[3]{f'_c}\right)c_1^{1.2} \tag{7}$$

The ratio of test-to-predicted values is plotted against embedment for both the adhesive anchor data and the headed stud data, shown in Fig. 10. For adhesive anchors, when anchor embedment is the independent variable with the modified CCD model, it shows almost no influence over the range of the data. However, for headed studs, when embedment is the independent variable with the modified CCD model, Fig. 10 shows a strong tendency for the equation to overestimate headed stud strength as the embedment gets deeper.

Considering the physical differences between headed studs and adhesive anchors, this is not surprising. When a headed stud is loaded in shear, its shank bears directly on the concrete over a small area near the surface and transfers the shear load to concrete over that area.[6] Therefore, if a model, such as the modified CCD model in Eq. (7), predicts increasing failure loads with increasing embedment, it will prove unconservative for headed studs. Stud strength is, thus, less affected by embedment depth.

The embedment depth influence of adhesive anchors can be explained by examining the load transfer mechanism. If an adhesive anchor is loaded in shear, the anchor bolt bears on the layer of adhesive. This layer is typically $^1/_{16}$ in. (1.6 mm) for anchors less than 1 in. (25.4 mm) in diameter, and $^1/_8$ in. (3.2 mm) for anchors greater than 1 in. (25.4 mm) in diameter.

Adhesives have a compressive modulus of elasticity in the range of 10 to 40 percent of the typical values of concrete's modulus of elasticity, making

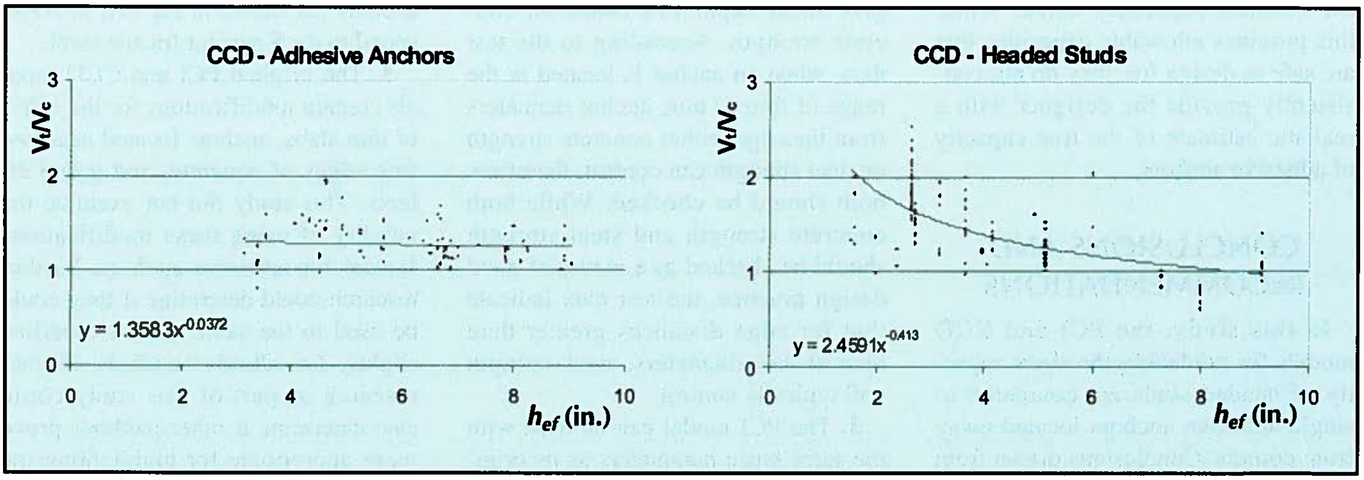

Fig. 10. V_t/V_c versus h_{ef} for adhesive anchors and headed studs.

them more compressible than concrete. As they compress, this allows the adhesives to distribute stresses more uniformly over a much larger portion of the anchor length. In effect, the adhesive layer acts as a "bearing pad."

Model Modifications — While the regression analysis provided some interesting insight into the physical differences between headed studs and adhesive anchors, it produces a model significantly different from the original form of the CCD model. The stated purpose of this study was to examine the validity of using the existing model for determining the shear capacity of adhesive anchors. Thus, it is the intention of the authors, if appropriate, to make only minor modifications to the original model.

As seen in the preliminary analysis, the original CCD model provides a stronger correlation to the adhesive anchor data than the headed stud data. Therefore, no changes to the basic model parameters are necessary in order to use it effectively for adhesive anchors. The only change suggested is to the present calibration constant of 13. For the headed stud data available to the authors, this constant corresponds to the 27 percent fractile level. To correspond to the 5 percent fractile level for the headed stud data, this constant would have to be 10.8.

To make a direct comparison to the original CCD model, a constant of 14.2 for adhesive anchors corresponds to the 27 percent fractile level. However, the constant 13 corresponds to the 5 percent fractile level for the adhesive anchor data. Therefore, the model could be used in its present form and provide good results with an even higher level of safety than when used for headed studs.

Table 5. Comparison of model and manufacturer's recommendations.

Anchor parameters (in.)			Predicted strength (kips)		Reported strength (kips)	
Diameter	Edge distance	Embedment	PCI Eq. (5)	CCD Eq. (2)	Manufacturer X	Manufacturer Y
⅜	3	3½	4.9	4.1	4.6	4.9
½	4	4¼	7.6	7.1	8.9	9.0
⅝	5	5	10.6	11.0	11.8	13.2
¾	6	6⅝	14.0	16.2	17.6	21.9
⅞	6½	7½	15.8	19.6	22.3	25.8
1	7½	8¼	19.5	25.8	28.3	38.3

Note: 1 in. = 25.4 mm; 1 kip = 4.45 kN.

COMPARISON WITH MANUFACTURER'S RECOMMENDATIONS

It was stated earlier in this paper that designers are currently dependent on the manufacturer's recommendations for adhesive anchor design. It is interesting to compare these models to recommendations presented in two manufacturer's product catalogs for various situations. Table 5 shows this comparison. Failure capacities are given (in kips) for adhesive anchors in 4000 psi (27.6 MPa) concrete. The diameter, edge distance, and embedment are specified for each anchor.

In the lower range of anchor diameter, edge distance, and embedment, both models and the manufacturer's recommended capacities compare reasonably well. As embedment increases, the PCI model and the CCD model begin to differ. One reason for this is that the PCI model does not take anchor embedment into account. In fact, the PCI Design Handbook suggests that this model should not be used for anchors embedded over 8 in. (203 mm).

Although slightly over-predicting strength, Manufacturer X compares reasonably well with the CCD model. However, the ultimate capacities recommended by Manufacturer Y are unconservative at the larger diameters when compared to CCD. The capacities listed by these manufacturers are assumed to be based on the actual testing of anchors with varying parameters.

What is unknown is the fractile levels these capacities were determined at in the manufacturer's testing data. As stated previously, the models reviewed in this study were based on the 5 percent fractile level. Different probabilistic analysis could partly explain the discrepancies between the model's capacities and the manufacturer's recommendations.

Both manufacturers recommend a factor of safety of 4 to be used with the ultimate capacities listed. While this provides allowable capacities that are safe to design for, they do not consistently provide the designer with a realistic estimate of the true capacity of adhesive anchors.

CONCLUSIONS AND RECOMMENDATIONS

In this study, the PCI and CCD models for predicting the shear capacity of headed studs are compared to single adhesive anchors located away from corners. Conclusions drawn from this study and recommendations are as follows:

1. The shear failure mechanism for adhesive anchors is essentially the same as that for headed studs and other mechanical anchors. This is in contrast to the marked differences in the tensile failure mechanisms for adhesive anchors and headed studs.

2. The results of this study indicate that the PCI and CCD models can be effectively used to predict the shear strength of adhesive anchors, and generally are more conservative for adhesive anchors than for headed studs. It should be also noted that these models give shear capacities based on concrete strength. According to the test data, when an anchor is located in the range of four to nine anchor diameters from the edge, either concrete strength or steel strength can control; therefore, both should be checked. While both concrete strength and steel strength should be checked as a matter of good design practice, the test data indicate that for edge distances greater than nine anchor diameters, steel strength will typically control.

3. The PCI model can be used with the same basic parameters as its original form to predict the shear strength of adhesive anchors. The calibration constant of 12.5 used for headed studs can be changed to 15 for adhesive anchors, as shown in Eq. (5). This results in a fractile level below 5 percent for adhesive anchors.

4. The CCD model can be used with the same basic parameters as its original form to predict the shear strength of adhesive anchors. The calibration constant of 13 for headed studs corresponds to the 27 percent fractile level for the headed stud test data available to the authors. The same calibration constant of 13 can be used for adhesive anchors [as shown in Eq. (2)] to correspond to the 5 percent fractile level.

5. The original PCI and CCD models contain modifications for the effect of thin slabs, anchors located near two free edges of concrete, and group effects. This study did not examine the validity of using these modifications factors for adhesive anchors. Further research could determine if they could be used in the same way or modified slightly for adhesive anchors. Further research as part of this study could also determine if other methods prove more appropriate for highlighting the physical differences between adhesive anchors and headed studs.

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REFERENCES

1. Cook, R. A., Kunz, J., Fuchs, W., and Konz, R. C., "Behavior and Design of Single Adhesive Anchors Under Tensile Load in Uncracked Concrete," *ACI Structural Journal*, V. 95, No. 1, January-February 1998, pp. 9-26.
2. Sunsaneeyachevin, K., "Assessment of Procedures for Prediction of Shear Capacity of Headed Stud Anchors," MS Thesis, University of Wisconsin-Milwaukee, WI, 1997.
3. Adhesive Anchor Database (made available by Prof. Ronald A. Cook, University of Florida, Gainesville).
4. *PCI Design Handbook – Precast and Prestressed Concrete*, Fifth Edition, Precast/Prestressed Concrete Institute, Chicago, IL, 1998.
5. Fuchs, W., Elighausen, R., and Breen, J., "Concrete Capacity Design (CCD) Approach for Fastening to Concrete," *ACI Structural Journal*, V. 92, No. 1, January-February 1995, pp. 73-94.
6. Shaikh, A. F., and Yi, W., "In-Place Strength of Welded Headed Studs," PCI JOURNAL, Precast/Prestressed Concrete Institute, V. 30, No. 2, March-April 1985, pp. 56-81.

APPENDIX A — NOTATION

c_1, d_e = distance, measured perpendicular to direction of load, from free edge of concrete to centerline of anchor (in.)

COV = coefficient of variation

d_b = stud diameter

f'_c = 28-day compressive strength of concrete

h_{ef} = embedment depth of stud

N = tensile load on anchor

R^2 = coefficient of determination

V = shear load on anchor

V'_c = predicted shear strength of a single stud based on concrete strength (PCI method)

V_{no} = predicted shear strength of a single stud based on concrete strength (CCD method)

V_t = test shear strength

APPENDIX B — EXAMPLE PROBLEM

Check the adequacy of the adhesive anchors used to suspend the pipe shown in Fig. B1 from an existing concrete beam.

Adhesive Anchor Parameters:
Anchor diameter: $^1/_2$ in. (13 mm)
Embedment depth: $5^1/_2$ in. (140 mm)
Edge distance: 2 in. (51 mm)

Pipe Loads:
Dead Load: 20 lbs per ft (292 N/m)
Live Load: 30 lbs per ft (438 N/m)

$$\begin{aligned} V_u &= (\text{Tributary length})[1.4(DL) + 1.7(LL)] \\ &= (12)[1.4(20) + 1.7(30)] \\ &= 0.95 \text{ kips } (4.2 \text{ kN}) \end{aligned}$$

Anchor Capacity:

PCI Handbook (Fifth Edition) Method

$$\begin{aligned} \phi V_c &= \phi 15(d_e)^{1.5}\sqrt{f'_c} \\ &= 0.85(15)(2)^{1.5}\sqrt{4000}/1000 \\ &= 2.27 \text{ kips } (10.1 \text{ kN}) \quad \text{OK} \end{aligned}$$

CCD Method

$$\begin{aligned} \phi V_c &= \phi 13\left(h_{ef}/d_b\right)^{0.2}\sqrt{d_b}\sqrt{f'_c}(c_1)^{1.5} \\ &= 0.85(13)\left(5.5/0.5\right)^{0.2}\sqrt{0.5}\sqrt{4000}(2)^{1.5}/1000 \\ &= 2.25 \text{ kips } (10.0 \text{ kN}) \quad \text{OK} \end{aligned}$$

Additional Checks:

Although not part of the study itself, additional checks should be made for both the bolt shear and plate tensile capacity, which are furnished below. These calculations are based on the AISC Manual of Steel Construction (Third Edition LRFD).

Bolt Shear: (A36 Threaded Rod with threads included in shear plane)

$$\begin{aligned} V_u &= (12)[1.2(20) + 1.6(30)] \\ &= 0.86 \text{ kips } (3.8 \text{ kN}) \end{aligned}$$

$$\begin{aligned} \phi R_n &= 0.75(0.4 \times 58)(0.20) \\ &= 3.48 \text{ kips } (15.5 \text{ kN}) \quad \text{OK} \end{aligned}$$

Edge distance = $1^1/_4$ in. > $^3/_4$ in. (min.) OK

Plate Tensile Capacity: (PL $^3/_8$ in. × $2^1/_2$ in. – A36)
$P_u = 0.86$ kips (3.8 kN)

Tensile Strength:

$$\begin{aligned} \text{Yield: } \phi P_n &= 0.9(36)(0.375 \times 2.5) \\ &= 30.38 \text{ kips } (135.1 \text{ kN}) \end{aligned}$$

$$\begin{aligned} \text{Fracture: } \phi P_n &= 0.75(58)(0.375)(2.5 - 0.625) \\ &= 30.59 \text{ kips } (136.1 \text{ kN}) \end{aligned}$$

Shear Rupture Strength:

$$\begin{aligned} \phi P_n &= 0.75(0.6 \times 58)[2 \times 0.375 \times (1.25 - 0.3125)] \\ &= 18.35 \text{ kips } (81.6 \text{ kN}) \end{aligned}$$

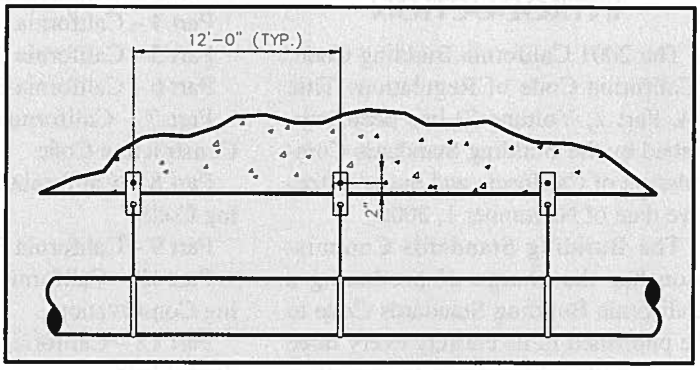

Fig. B1. Pipe suspended from existing concrete beam.