Slip-Pullout Strength of Hooked Anchors

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May 1, 1996

Abstract

This report examines design equations for slip-pullout strength of hooked anchors ("L" bolts). Both existing models and a newly developed one are investigated and strength predictions compared to available data. A cursory statistical comparison is carried out, and a design equation is proposed. Inadequacy of available test information is noted and recommendations for future research are given.

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1 Background

1.1 General

Hooked anchors ("J" and "L" bolts) are used extensively for connections in concrete and masonry construction. The anchors typically consist of either smooth or deformed bars bent 90 or 180 degrees and embedded into concrete (fig. 1). The anchors can then be subjected to tension, shear, or a combination of loads.

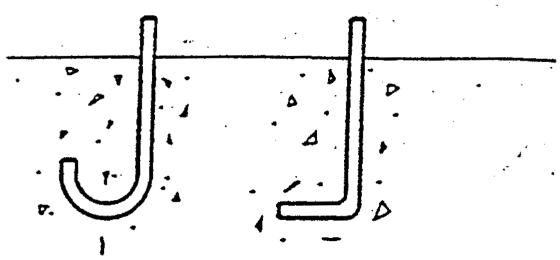


Figure 1: Hooked Anchor Bolts

1.2 Failure Modes

Hooked anchors have three potential modes of failure:

- Steel failure
- Concrete cone breakout
- Anchor Slip-pullout

1.2.1 Steel Failure

The steel failure mode is precipitated by yielding of the anchor material. The bolt then begins to neck and carries additional load until the ultimate load for the anchor is reached. Steel failure is generally ductile, and therefore, the desirable mode of failure. The generally used design equation for steel tensile failure is:

$$\phi_s P_s = \phi_s A_s f_y$$

Notation for all terms is provided in Appendix A.

1.2.2 Concrete Cone Breakout

If the embedment depth is not long enough to develop the full tensile strength of the anchor, a cone-shaped plug of concrete may break out of the concrete member. This mode of failure is typically brittle unless sufficient reinforcement is provided in the vicinity of the anchor. The design equation used for cone breakout is also readily available:

$$\phi_{c/b} P_{c/b} = \phi_{c/b}\, 4\sqrt{f_c^{\prime}}\ (\pi l_e^2)$$

Here, the $4\sqrt{f'_c}$ is the estimated nominal tensile strength of concrete, and ${}_e\pi l^{2}$ is the projected area of a 45 degree failure cone on the concrete member surface. Thus the equation simply becomes a stress multiplied by and area--producing the available breakout resistance.

1.2.3 Anchor Slip-Pullout

A second possibility if the full tensile strength of the anchor is not achieved is that a slip-pullout failure occurs when the tension force applied causes the hooked bolt to straighten and pull out of the member. Design equations for the slip-pullout failure mode are not as readily available as for the other two failure modes. Models of slip-pullout have been proposed based on testing at both Clemson University (Whitlock and Brown, 1983) and Wiss Janney Elstner Associates (Osborn and Krueger, 1993). Both equations predict well the slip strength of the bolts when compared to their own background data. However, when the equations are applied to others' data, the reliability falters to varying degrees. Thus, it is necessary to develop a slip-pullout strength equation that reasonably predicts failure loads for all available data and for various parameters (bolt diameter, embedment depth, concrete vs masonry embedment, etc.)

2 Scope

The scope if this project was to identify and evaluate existing equations for slip-pullout of hooked anchor bolts. If an adequate model could not be found, a new model was to be developed with existing data as well as from additional testing. The stages of the project were as follows:

Stage 1: Laboratory Testing: Pullout tests of "L" bolts were performed. Eight bolts of the same diameter were embedded in plain concrete at various depths. Direct tension load was applied, and the failure load and character recorded. This data, along with any existing data, was used to compare different design models.

Stage 2: Existing Models: Two relevant models were examined: the aforementioned Clemson University (CU) and Wiss Janney Elstner Associates (WJE) models. A parametric study of the design equations was performed, and test results from all sources checked with both equations.

Stage 3: Equation Development: Not finding a model with both a broad accuracy and physical significance, a new model was developed, and data from all testing applied to it. Recommendations for a design equation and future testing were developed.

3 Laboratory Testing

Eight tension pull-out tests of "L" bolts were run. Each bolt had a diameter of 9/16 inch, a length of 12.5 inches, and a leg extension of 1.938 inches (See Appendix A for definition of terms). The bolts were embedded in concrete to differing depths; two each at two inches, four inches, six inches, and eight inches. Direct tension was applied with a 100 kip jack, and the failure loads and failure types were recorded (Table 1). The two inch embedment tests both resulted in concrete cone failure, while the four inch bolts gave steel yield. The six and eight inch embedments all produced a hybrid failure. The bolts began to straighten and lift out of the concrete (up to 1.5 inches), but then locked in place in the concrete block (increasing moment at the bend of the bolt), and the steel ruptured at the bolt bend. This hybrid failure had the effect of raising the failure load above what would be expected for a pure slip pull-out; thus, the slip strength equations appear more conservative compared to this test data.

Table 1: UWM Test Data

L-Bolt Pullout Test Results

Diameter: 9/16 inch
Length: 12.5 inches
Leg Extension: 2.5 inches

Embedment (in)	Load (kips)	f'c (psi)	Comments
2	5	6560	Concrete cone failure.
2	8.3	6560	Concrete cone failure
4	16.8	6560	Steel yield.
4	17.2	6560	Steel yield
6	14.6	3290	Hybrid failure. Bolt rose 1.25 inches before steel failed. Fracture on bolt at 6" below original concrete surface level.
6	15.2	3290	Hybrid failure. Bolt rose 1.50 inches before steel failed. Fracture on bolt at 6.5" below original concrete surface level.
8	13.4	3290	Hybrid failure. Bolt rose 1.00 inches before steel failed. Fracture on bolt at 8" below original concrete surface level.
8	15	3290	Hybrid failure. Bolt rose 1.00 inches before steel failed. Fracture on bolt at 8" below original concrete surface level.

4 Existing Models

4.1 Clemson University

$$P_{slp} = \frac{f_y d^2}{1.85}$$

The Clemson University (CU) equation (Whitlock and Brown, 1983, p. 95) was developed following pullout tests of hooked anchors in masonry. The CU model assumes a statically determinate model of the anchor bolt. After applying the basic statics equations and setting the moment at the bend of the anchor equal to the plastic moment of the steel, one can derive an expression for slip strength in terms of steel yield strength, bolt diameter, and the static coefficient of friction between bolt steel and concrete (μ). Assuming μ to be 0.4 produces the above equation. The complete development of the CU model is provided in Appendix B.

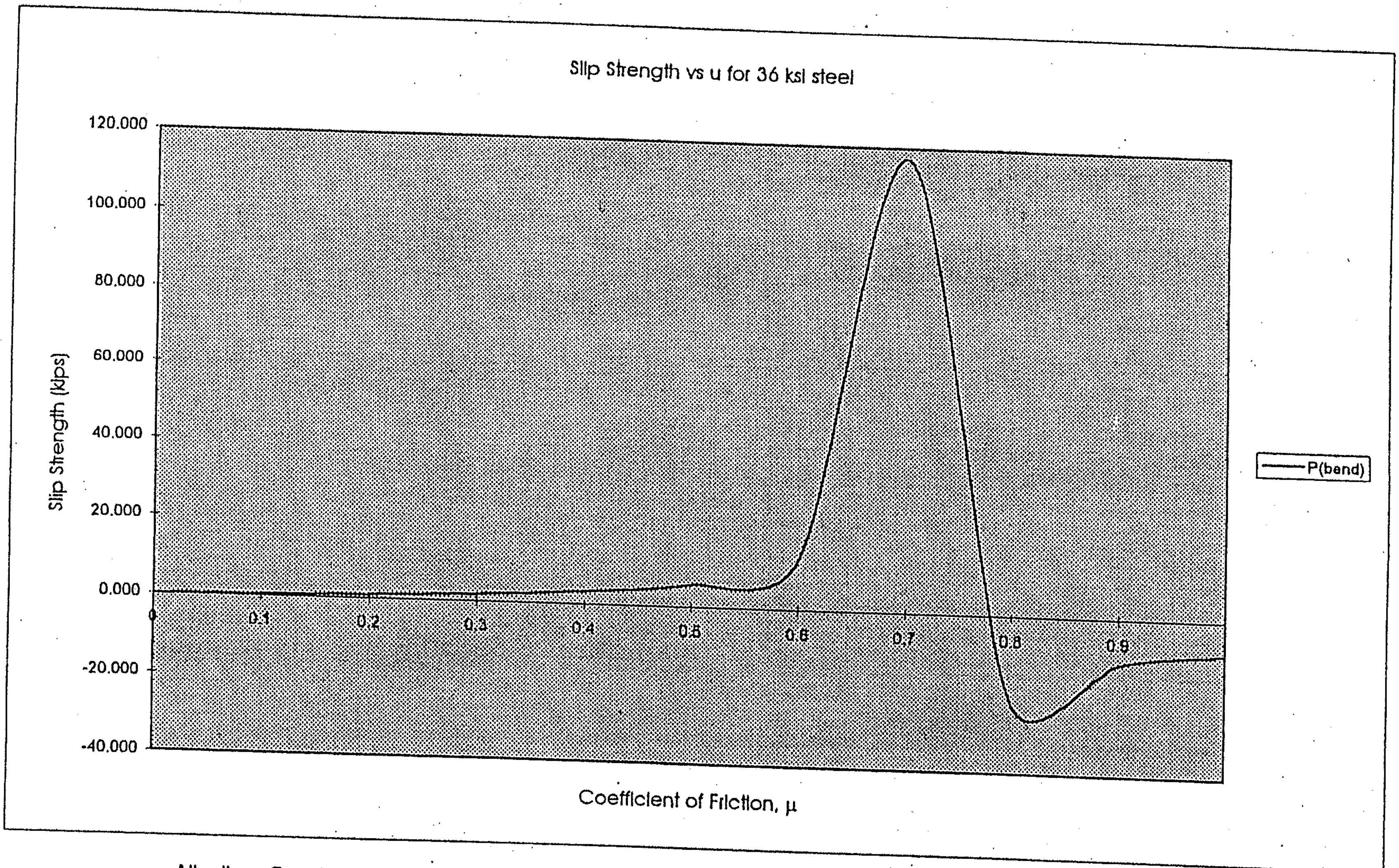
There appear to be several concerns with the CU model. In developing the equation, the moment summation (Appendix B, Eqn B.3) contains a sign error. The $1.5\mu B$ term should be negative. Also, in Equation B.5 (Appendix B), the moment about point "o" should be equal to $Ad(1-\mu/2)$; again the sign is reversed. A parametric study of the CU model shows these discrepancies to be significant when μ is low (0.0 - 0.2), but of little significance for the assumed μ value of 0.4. For this value, the corrected equation is:

$$P_{slp} = \frac{f_y d^2}{1.82}$$

This is almost indistinguishable from the given CU equation.

A second anomaly of the model was highlighted by the parametric study. For μ in the range 0.3 - 0.5, the CU model appears to be reasonable. However, for higher levels of μ, the predicted strength peaks dramatically, then dives below zero (see Fig. 2). This behavior appears physically implausible.

Slip Strength for 3/8" Diameter Bolts as a Function of the Coefficient of Friction



All other Grade Steel P(bend) values are linearly related to 36 ksi by the ratio of their yield strengths

Fig. 2

There is also a conceptual concern with this model. Tests have shown that the slip strength varies with embedment depth and leg extension length (Osborn and Krueger, 1993, p. 1), yet the CU model assumes the strength to be a function of solely the bolt diameter.

The above notwithstanding, the CU equation compares well to the CU test data, giving a mean for $P_{test} / P_{predicted}$ of 1.02 with a standard deviation of 0.25. However, when comparing it to the data from the WJE study, it produces a $P_{test} / P_{predicted}$ mean of 2.04 with a standard deviation of 0.38, and when compared to the data from this study, a mean of 3.16 with a standard deviation of 1.32 is obtained. Lumping all test data together, the CU model gives a overall $P_{test} / P_{predicted}$ mean of 1.33 with a standard deviation of .56. See appendix C test result data comparison. Thus, it is concluded that the CU equation is many cases overconservative and produces too much variation for general use.

4.2 Wiss Janney Elstner Associates

$$P_{slip} = P_b + P_f$$

where:

$$P_b = 28\sqrt{f'_c}(e-d)^2 \; > 9600d^2$$

$$P_f = 1800 f_t (l_e + e - d) d$$

An evaluation of the development of the Wiss Janney Elstner Associates (WJE) equation was not possible because background information is not provided in the available WJE source document (Osborn and Krueger, 1993). What is known is that the P_b term represents the bearing strength of the bolt leg extension and the P_f term is an expression for friction. However, it is difficult to apply a physical significance to the various terms: (1) the bearing strength of concrete is generally taken as a function of f'_c, not its square root; (2) one bolt diameter is subtracted from the leg extension for the leg bearing, and then that length is squared, again without apparent physical basis and (3) the friction coefficient of 1800 is much larger than the generally used 200 to 400 (even when dividing the 1800 by π, assuming the friction to be a function of the bolt's surface area).

Despite a lack of physical significance of the terms, the WJE equation does very well when compared to its test data ($P_{test} / P_{predicted}$ mean of 0.98 with a standard deviation of 0.11). When compared to the CU data the standard deviation remains low (0.19); however, the mean becomes non-conservative at 0.82 (and remains non-conservative for almost one entire standard deviation). Combining the CU and WJE data gives a $P_{test} / P_{predicted}$ mean of 0.87 with a standard deviation of 0.19. Comparing the WJE model to this study's data, the mean rises to 1.27 with a deviation of 0.15 (See Appendix C). Overall, while the WJE equation provides acceptable deviation, it is generally non-conservative. Thus, it is concluded that the WJE model is not well suited for general use.

5 Proposed Equation Development

For reasons stated above, it was decided that a new model for slip-pullout strength should be investigated. The basis of the model is similar to that of the WJE equation--the slip strength is the sum of two components: a bearing force and a friction force.

$$\phi_{slp}P_{slp}=\phi_{slp}\left[k_b f_c' e d + k_f f_l \pi (l_e + e + d) d\right]$$

Where:

k_b = Bearing calibration factor = 1.5
k_f = Friction calibration factor = 300

The first expression is for bearing of the bolt leg extension on concrete. The bearing strength is the product of the projected surface area in the direction of force (e*d) multiplied by the compressive strength of concrete (with k_b as a calibration factor). The second term, friction, is expressed as the surface area of the bolt $\pi(L+e+d)d$ multiplied by an estimated bond strength of concrete, 300 psi, and k_f, the friction index. The friction index (described in Appendix A) provides a reduction in bond force when the anchor is greased or wrapped.

Comparing this model to the combined CU and WJE test data gives a $P_{test} / P_{predicted}$ mean of 1.03 with a standard deviation of 0.24 (against CU and WJE separately, means are 1.00 and 1.09 with standard deviations of 0.24 and 0.20, respectively). Compared to the test data from this study, a $P_{test} / P_{predicted}$ mean of 1.40 with a standard deviation of 0.12 results. (Again, the failure of the bolts for this study was a hybrid failure--steel ultimately controlled. Thus, a higher load was reached than would be expected for pure slip pull-out, making the equations look more conservative.) The above noted mean and standard deviation values are given in Table 2 and Figures 3 and 4 compare the predicted nominal strengths with the test data; the calculations are contained in Appendix D. As seen, this model predicts the mean of a series of tests more accurately than the other models, and has a more plausible physical basis.

	CU Equation		WJE Equation		Proposed Equation	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
All Data	1.33	0.56	0.87	0.19	1.03	0.24
CU	1.03	0.25	0.82	0.19	1.00	0.24
WJE	2.04	0.38	0.98	0.11	1.09	0.20
UWM	3.16	1.32	1.27	0.15	1.40	0.12

Table 2: $P_{test} / P_{predicted}$ Mean and Standard Deviation.

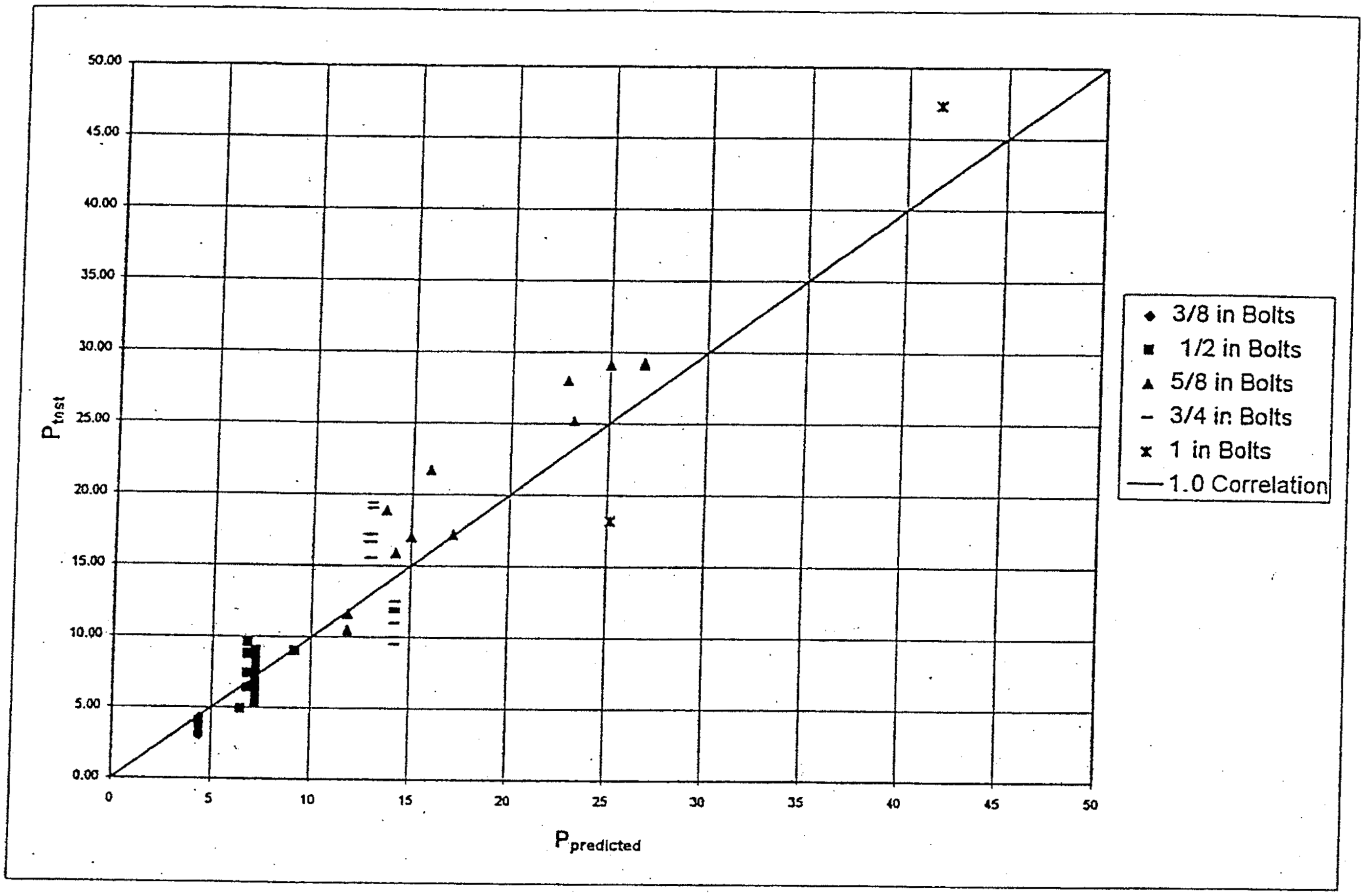


Fig. 3: $P_{predicted}$ vs P_{test} (Nominal Strength Equation)

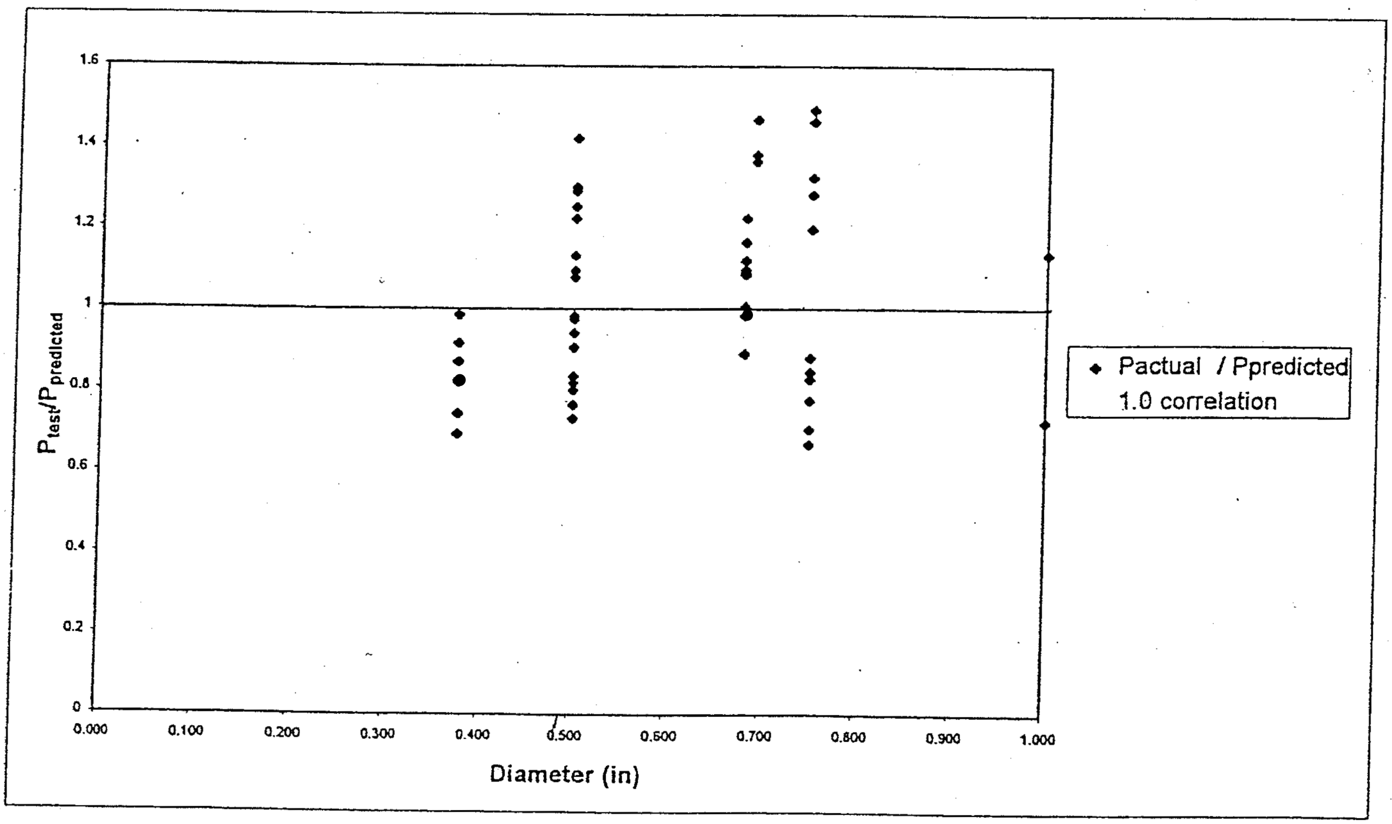


Fig. 4: $P_{test}/P_{predicted}$ vs Bolt Diameter (Nominal Strength Equation)

6 Recommendations

6.1 Proposed Design Equation

It is recommended that the equation developed in this study be used for slip pull-out strength of hooked anchors. This model more accurately predicts the average slip strength of the bolts over a wider range of embedment conditions.

For design, a strength reduction factor, $\phi_{s/p}$, equal to 0.65 is suggested (The resulting correlation with test data is then seen in Figures 5 and 6, and Appendix E). The proposed design equation for the anchor slip-pullout as well as the concrete cone breakout ~~and the steel~~ failure are given below:

Anchor Slip-Pullout Failure:

$$\phi_{s/p} P_{s/p} = \phi_{s/p}\left[k_b f'_c e d + k_f f_l \pi (l_e + e + d) d\right] \qquad (6.1.1)$$

where: $\phi_{s/p} = 0.65$
k_b = bearing calibration factor = 1.5
k_f = friction calibration factor = 300

Concrete Cone Breakout Failure:

$$\phi_{c/b} P_{c/b} = \phi_{c/b} 4\sqrt{f'_c}(\pi l_e^2) \qquad (6.1.2)$$

where: $\phi_{c/b}$=0.85

Steel Failure:

$$\phi_s P_s = \phi_s A_s f_y \qquad (6.1.3)$$

where: $\phi_s = 0.9$

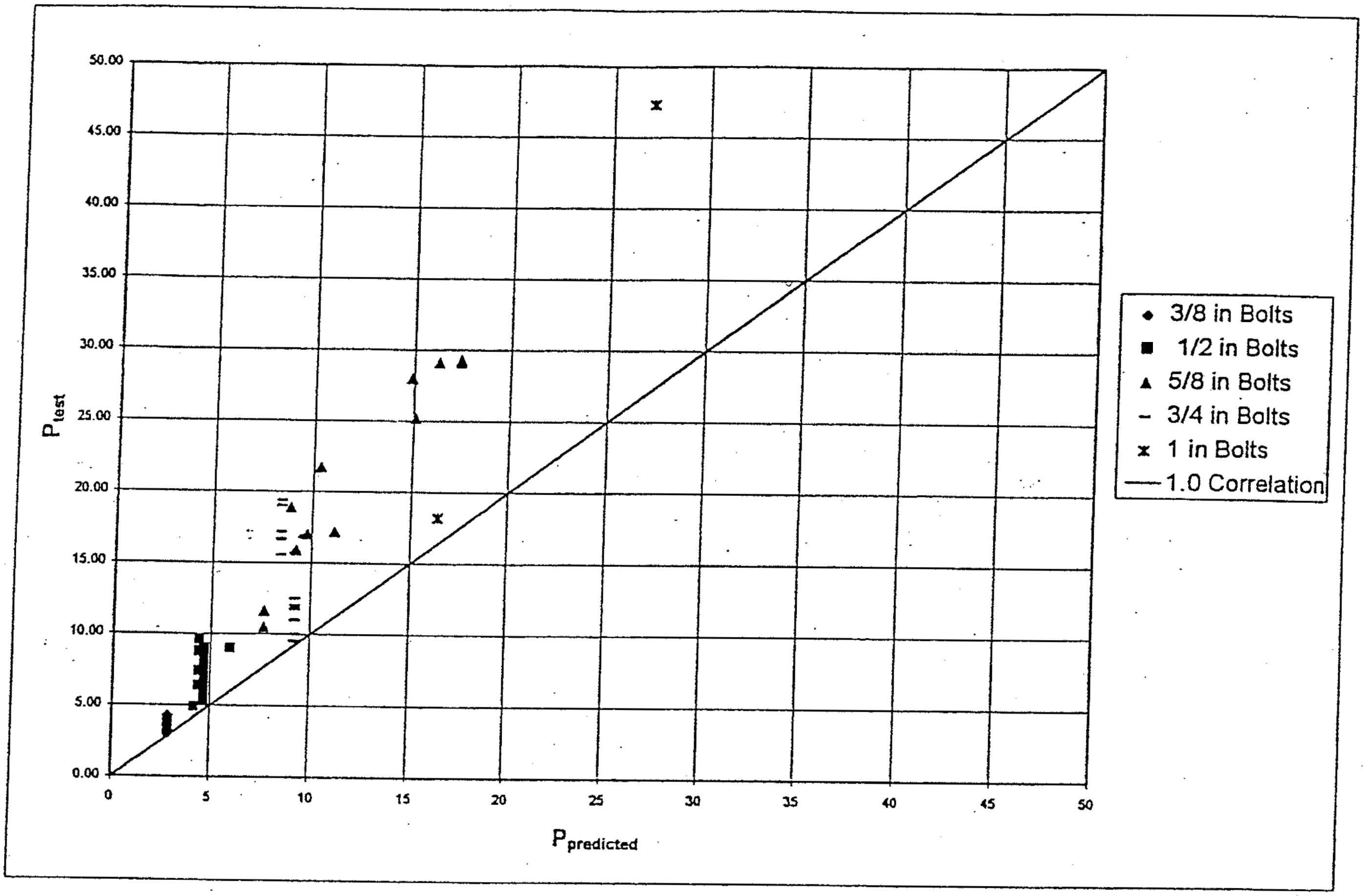


Fig. 5: $P_{predicted}$ vs P_{test} (Proposed Design Equation)

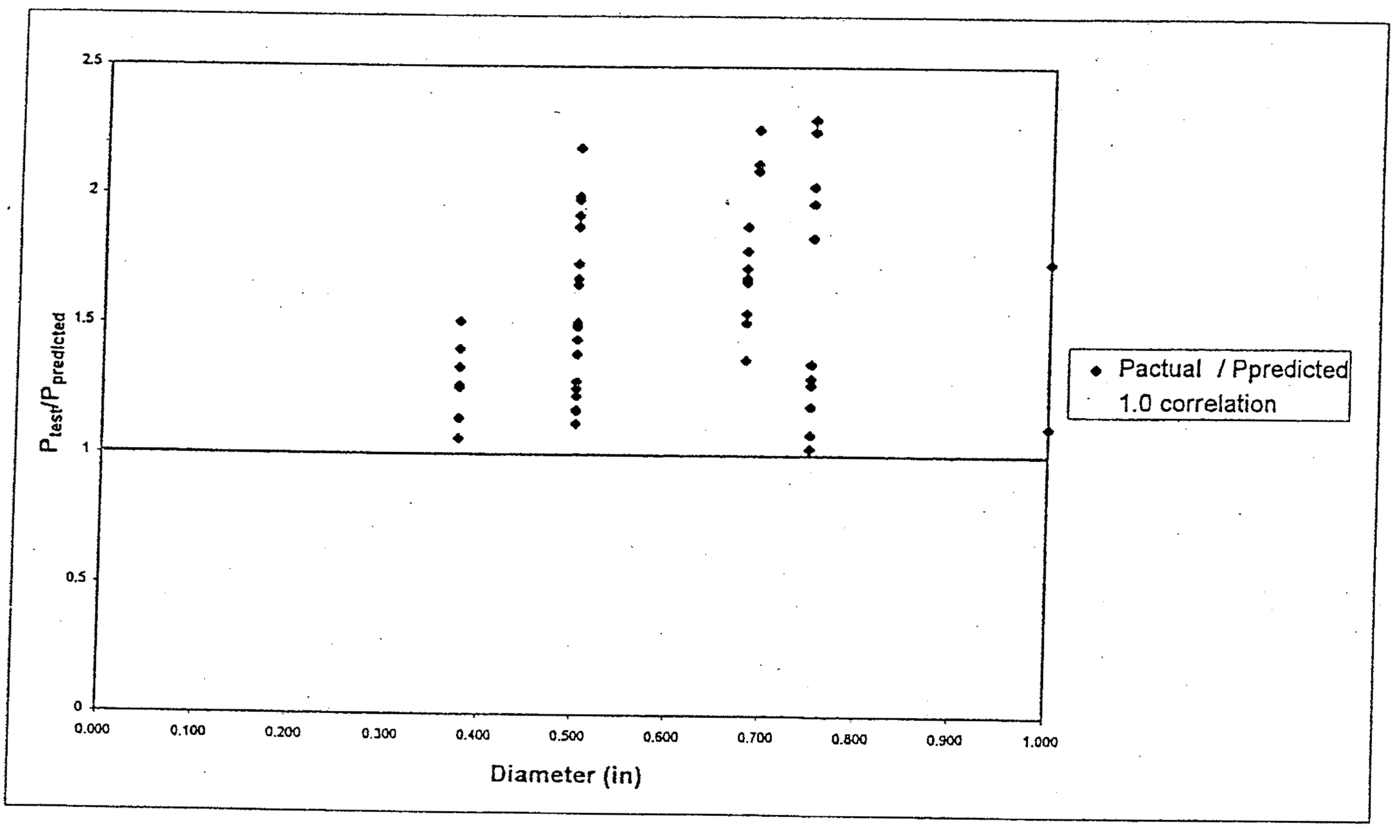


Fig. 6: $P_{test}/P_{predicted}$ vs Bolt Diameter (Proposed Design Equation)

6.2 Future Research

It is recommended that further research be conducted, mainly along two directions. The first is to test more hooked bolt specimens in both concrete and masonry. There is significant scatter among the test results, and more data points would allow a better statistical evaluation. Second, a more comprehensive stress analysis of a bolt in a slip pull-out mode is needed--for example, embedding the anchor in a photo-elastic material and also a finite element type analysis.

Works Cited

ACI Committee 355, State-of-the-Art Report on Anchorage to Concrete, American Concrete Institute, Detroit, Michigan, 1991.

Osborn, Andrew E.N., and Krueger, Mark R., Pull Out Tests on L Shaped Anchor Bolts - Summary Report, Wiss Janney Elstner Associates, 1993.

Whitlock, A. Rhett, and Brown, Russell H., Strength of Anchor Bolts in Masonry, NSF Award No. PRF-7806095, Clemson University, 1983.

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ACI Committee 318, Building Code Requirements for Structural Concrete and Commentary, American Concrete Institute, Detroit, Michigan, 1995.

Precast/Prestressed Concrete Institute, PCI Design Handbook, Fourth Edition, PCI, Chicago, Illinois, 1992.

Precast/Prestressed Concrete Institute, Design and Typical Details of Connections for Precast and Prestressed Concrete, PCI, Chicago, Illinois, 1988.

Appendix A:
Notation

A_s	Cross-sectional area of anchor bolt, in^2.
d	Diameter of anchor, in.
e	Horizontal leg extension of hooked anchor, measured from inside edge of anchor at bend to farthest point of anchor on horizontal plane, in.
f'_c	Compressive strength of concrete, psi.
f_i	Friction index, [(1 - fraction representing portion of the bar greased or wrapped)].
f_y	Yield strength of steel, psi.
k_b	Calibration factor for bearing, 1.5
k_f	Calibration factor for friction (bond), 300
l_e	Embedment depth, in.
$P_{c/b}$	Nominal strength based on concrete breakout, lbs.
$P_{predicted}$	Predicted failure load, lbs.
P_s	Nominal tension strength of steel, lbs.
$P_{s/p}$	Nominal anchor slip-pullout strength, lbs.
P_{test}	Test failure load, lbs.
$\phi_{c/b}$	Strength reduction factor for concrete breakout. $= 0.85$
ϕ_s	Strength reduction factor for steel. $= 0.9$
$\phi_{s/p}$	Strength reduction factor for anchor slip pull-out. $= 0.65$

Appendix B:
Development of Clemson University Equation

Appendix B

Approximate Slip Pullout Model for "J" Bolts

As an approximation for the slip load for bent bolt anchors, the model shown in Fig. B-1 was used. The model neglects bond strength between the steel and the masonry, but does include friction. The moment at point o was determined and set equal to the fully plastic moment for the bolt. From $\Sigma F_x=0$, $\Sigma F_y=0$, and $\Sigma M=0$, the following equations were derived:

$$-\mu A - 0.707(1 + \mu)B + C = -P \qquad (B.1)$$

$$-A + 0.707(1 - \mu)B - \mu C = 0 \qquad (B.2)$$

$$(1 - 2.5\mu)A + 1.5\mu B - (1 + 2.5\mu)C = -2P \qquad (B.3)$$

By solving the above equations for A, the following equation is obtained:

$$A = (de - fb)/(ad - bc) \qquad (B.4)$$

NEGATIVE

where

A = reaction,

$a = 1 + \mu^2$,

$b = .707(1 - 2\mu - \mu^2)$,

$c = 1 - 3.5\mu - 2.5\mu^2$,

$d = .707(-1 - 5.62\mu - 2.5\mu^2)$,

$e = -P\mu$,

$f = -P(3 + 2.5\mu)$,

μ = coefficient of friction.

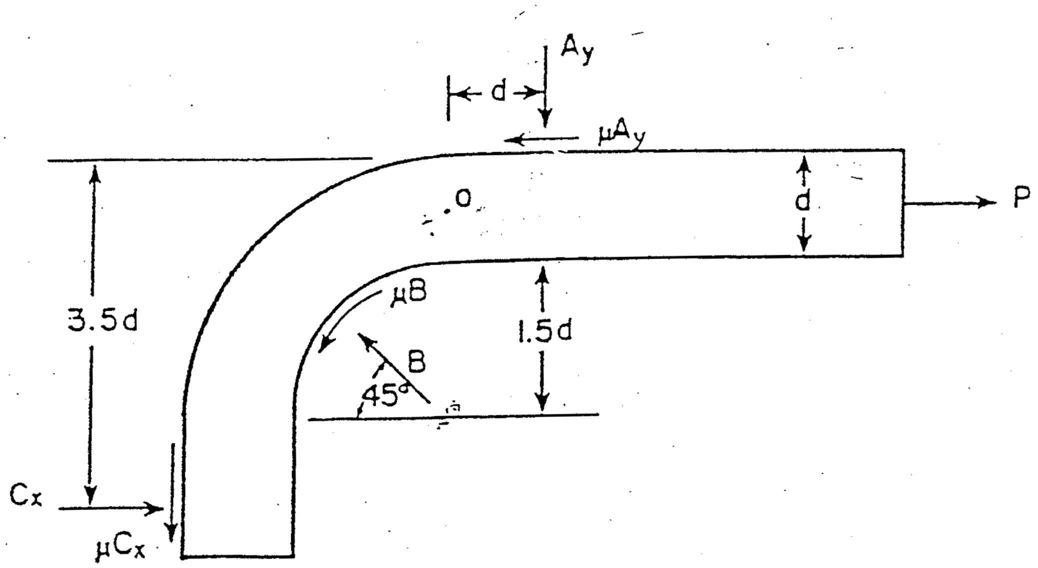

Figure B-1. Model for Slip Pullout of "J" Bolts

Note: The CU model assumes that reaction A_y of Figure B-1 acts in a direction opposite of that shown in ACI 530-92 (Fig. 5.14-5, p. CC-15). The impact of that change on the CU slip-pullout equation has not been assessed.

From the freebody diagram of point o in Fig. B-1, the moment equation is

diam. of bolt :. Not the same "d" as on p. 163

$$M = Ad(\mu/2 - 1) \qquad \text{(B.5)}$$

where $M = Ad(1 - \mu/2)$

M = moment at point o,

A = reaction given by equation E.1,

d = diameter of bolt.

The fully platic moment for a bolt is given by

$$M_{fp} = F_y Z \qquad \text{(B.5)}$$

where

M_{fp} = fully plasic moment,

F_y = yield stress of bolt,

Z = plastic section modulus for a circular cross section,
= $d^3/6$.

By equating equations B.3, B.4 and B.5 for a given bolt diameter, yield stress and coefficient of friction, the force required to cause slip can be estimated.

Appendix C:

Test Data and Predicted Load Comparison for Clemson University and Wiss Janney Elstner Associates Equations

Slip Pull-Out Strength

Comparison of Test Loads to Calculated Loads

Method 1: Brown, R. H., and Whitlock, A.R., **Engineering Report: Strength of Anchor Bolts in Masonry, A Final Report,** Department of Civil Engineering, Clemson University, August 1983

CU: $P_{slip} = f_y{*}d^2/1.82$

Method 2: Krueger, M. R., and Osborn, A. E. N., **Pull Out Tests on L Shaped Anchor Bolts--Summary Report,** Wiss Janney Elstner Associates, April 19, 1993

WJE: $P_{slip} = 28{*}f'_c{}^{1/2}{*}(e - d)^2 + 1800{*}f_i{*}(L + e - d){*}d$

Bearing Term ($>9600d^2$) Friction Term

where:
- f_y = Yield strength of steel
- d = Diameter of bolt
- f'_c = Compressive strength of imbedding material (Concrete)
- e = Leg extension --see figure
- L = Embedment length -- see figure

Test Number			Bolt Diameter (in)	Embedment (inches)	Leg Extension (in)	Concrete (or Grout) Comp. Strength (psi)	Steel Tensile Strength (ksi)	Friction Index	Predicted Failure Load (kips)		Actual Failure Load (kips)	$P_{actual} / P_{predicted}$	
	CU	WJE							CU	WJE		CU	WJE
	Table 8.3												
1	1		0.375	6.375	1.125	2513	63.4	1	4.90	6.16	3.58	0.73	0.58
2	2		0.375	6.375	1.125	2513	63.4	1	4.90	6.16	4.30	0.88	0.70
3	3		0.375	6.375	1.125	2513	63.4	1	4.90	6.16	3.24	0.66	0.53
4	4		0.375	6.375	1.125	2513	63.4	1	4.90	6.16	3.02	0.62	0.49
5	5		0.375	6.375	1.125	2513	63.4	1	4.90	6.16	3.80	0.78	0.62
6	6		0.375	6.375	1.125	2513	63.4	1	4.90	6.16	4.00	0.82	0.65
7	7		0.375	6.375	1.125	2513	63.4	1	4.90	6.16	3.60	0.73	0.58
8	8		0.500	6.375	1.500	2513	46.3	1	6.36	9.04	9.62	1.51	1.06
9	9		0.500	6.375	1.500	2513	46.3	1	6.36	9.04	8.74	1.37	0.97
10	10		0.500	6.375	1.500	2513	46.3	1	6.36	9.04	6.37	1.00	0.70
11	11		0.500	6.375	1.500	2513	46.3	1	6.36	9.04	8.80	1.38	0.97
12	12		0.500	6.375	1.500	2513	46.3	1	6.36	9.04	7.40	1.16	0.82
13	13		0.750	6.375	2.250	2513	45.3	1	14.00	16.03	19.38	1.38	1.21
14	14		0.750	6.375	2.250	2513	45.3	1	14.00	16.03	16.65	1.19	1.04
15	15		0.750	6.375	2.250	2513	45.3	1	14.00	16.03	15.54	1.11	0.97
16	16		0.750	6.375	2.250	2513	45.3	1	14.00	16.03	17.20	1.23	1.07
17	17		0.750	6.375	2.250	2513	45.3	1	14.00	16.03	19.00	1.36	1.19
18	18		0.750	6.375	2.250	2513	45.3	1	14.00	16.03	17.20	1.23	1.07
	Table 8.4												
19	1		0.500	5.625	1.500	3202	46.3	1	6.38	8.38	8.13	1.28	0.97

Test Number			Bolt Diameter (in)	Embedment (inches)	Leg Extension (in)	Concrete (or Grout) Comp. Strength (psi)	Steel Tensile Strength (ksi)	Friction Index	Predicted Failure Load (kips)		Actual Failure Load (kips)	$P_{actual} / P_{predicted}$	
	CU	WJE							CU	WJE		CU	WJE
20	2		0.500	5.625	1.500	3202	46.3	1	6.36	8.36	5.88	0.92	0.70
21	3		0.500	5.625	1.500	3202	46.3	1	6.36	8.36	6.50	1.02	0.78
22	4		0.500	5.625	1.500	3202	46.3	1	6.36	8.36	5.50	0.86	0.66
23	5		0.500	5.625	1.500	3202	46.3	1	6.36	8.36	5.25	0.83	0.63
24	6		0.500	5.625	1.500	3202	46.3	1	6.36	8.36	7.75	1.22	0.93
	Table 8.5												
25	1		0.500	5.625	1.500	3202	46.3	1	6.36	8.36	5.75	0.90	0.69
26	2		0.500	5.625	1.500	3202	46.3	1	6.36	8.36	7.00	1.10	0.84
27	3		0.500	5.625	1.500	3202	46.3	1	6.36	8.36	6.00	0.94	0.72
28	4		0.500	5.625	1.500	3202	46.3	1	6.36	8.36	6.50	0.96	0.68
29	5		0.500	5.625	1.500	3202	46.3	1	6.36	8.36	9.00	1.42	1.08
30	6		0.500	5.625	1.500	3202	46.3	1	6.36	8.36	8.80	1.38	1.05
31	7		0.750	5.625	2.250	3202	45.3	1	14.00	15.02	12.50	0.89	0.83
32	8		0.750	5.625	2.250	3202	45.3	1	14.00	15.02	10.00	0.71	0.67
33	9		0.750	5.625	2.250	3202	45.3	1	14.00	15.02	11.75	0.84	0.78
34	10		0.750	5.625	2.250	3202	45.3	1	14.00	15.02	9.50	0.68	0.63
35	11		0.750	5.625	2.250	3202	45.3	1	14.00	15.02	12.00	0.86	0.80
36	12		0.750	5.625	2.250	3202	45.3	1	14.00	15.02	11.00	0.79	0.73
37		2-1	0.690	7.500	3.100	1980	45.8	1	11.98	18.54	18.90	1.58	0.97
38		2-2	0.690	9.500	3.100	1980	45.8	1	11.98	22.03	22.00	1.84	1.00
39		2-3	0.690	10.900	3.100	1980	45.8	1	11.98	23.77	21.70	1.81	0.91
40		3-3	1.000	12.000	4.500	3730	44.2	1	24.29	48.86	47.30	1.95	0.97
41		3-19	0.680	13.500	3.100	3730	45.6	1	11.59	29.50	28.00	2.42	0.95
42		4-3	0.680	8.300	3.100	5460	45.8	1	11.64	25.24	29.10	2.50	1.15
43		4-4	0.680	11.000	3.100	5460	45.8	1	11.64	28.54	29.30	2.52	1.03
44		4-8	0.680	5.500	3.100	5460	45.8	1	11.64	21.81	25.20	2.17	1.16
45		4-10	0.680	11.000	3.100	5460	45.8	1	11.64	28.54	29.10	2.50	1.02
46		3-5	0.500	3.000	2.300	3730	39.8	1	5.47	9.86	9.00	1.65	0.91
47		3-11	0.680	9.000	1.800	3730	45.6	1	11.59	16.83	15.90	1.37	0.94
48		3-12	0.680	13.500	1.800	3730	45.6	1	11.59	22.33	17.20	1.48	0.77
49		3-8	0.600	6.000	2.300	3730	39.8	0	2.19*	5.54	4.90	2.24	0.88
50		3-18	0.680	9.000	3.100	3730	45.6	0	4.64*	10.01	10.50	2.26	1.05
51		3-20	0.680	13.500	3.100	3730	45.6	0	4.64*	10.01	11.60	2.50	1.16
52		3-4	1.000	12.000	4.500	3730	44.2	0	9.72*	20.95	18.20	1.87	0.87

*The Brown and Whitlock Source does not separate the bearing and friction terms of their strength equation, thus for the case when the bolt is Teflon wrapped, the equation does not apply. However, as the friction term of Kreuger and Osborn's strength equation is about 60% of the total strength for each case tested, the strength of the Brown and Whitlock equation is reduced to 60%.

	CU	WJE
Mean:	1.33	0.87
Std. Dev.:	0.56	0.19

Yield Strength of Steel was not included in the WJE Report, but ultimate strength was. Yield strength was estimated from reported values as being 68% of ultimate strength.

Slip Pull-Out Strength

Cemson University Equation With CU Data

$P_{slip} = f_y*d^2/1.82$ where: f_y = Yield strength of steel
d = Diameter of bolt

Test Number	Bolt Diameter (in)	Steel Tensile Strength (ksi)	Predicted Failure Load (kips)	Actual Failure Load (kips)	P_{actual} / $P_{predicted}$
Table 8.3					
1	0.375	63.4	4.90	3.58	0.73
2	0.375	63.4	4.90	4.30	0.88
3	0.375	63.4	4.90	3.24	0.66
4	0.375	63.4	4.90	3.02	0.62
5	0.375	63.4	4.90	3.80	0.78
6	0.375	63.4	4.90	4.00	0.82
7	0.375	63.4	4.90	3.60	0.73
8	0.500	46.3	6.36	9.62	1.51
9	0.500	46.3	6.36	8.74	1.37
10	0.500	46.3	6.36	6.37	1.00
11	0.500	46.3	6.36	8.80	1.38
12	0.500	46.3	6.36	7.40	1.16
13	0.750	45.3	14.00	19.38	1.38
14	0.750	45.3	14.00	16.65	1.19
15	0.750	45.3	14.00	15.54	1.11
16	0.750	45.3	14.00	17.20	1.23
17	0.750	45.3	14.00	19.00	1.36
18	0.750	45.3	14.00	17.20	1.23
Table 8.4					
1	0.500	46.3	6.36	8.13	1.28
2	0.500	46.3	6.36	5.88	0.92
3	0.500	46.3	6.36	6.50	1.02
4	0.500	46.3	6.36	5.50	0.86
5	0.500	46.3	6.36	5.25	0.83
6	0.500	46.3	6.36	7.75	1.22
Table 8.5					
1	0.500	46.3	6.36	5.75	0.90
2	0.500	46.3	6.36	7.00	1.10
3	0.500	46.3	6.36	6.00	0.94
4	0.500	46.3	6.36	5.50	0.86
5	0.500	46.3	6.36	9.00	1.42
6	0.500	46.3	6.36	8.80	1.38
7	0.750	45.3	14.00	12.50	0.89
8	0.750	45.3	14.00	10.00	0.71
9	0.750	45.3	14.00	11.75	0.84
10	0.750	45.3	14.00	9.50	0.68
11	0.750	45.3	14.00	12.00	0.86
12	0.750	45.3	14.00	11.00	0.79

Mean:	1.02
Std. Dev.:	0.25

Slip Pull-Out Strength

Clemson Equation With WJE Data

$$P_{slip} = f_y * d^2 / 1.82$$

where: f_y = Yield strength of steel
d = Diameter of bolt

Test Number WJE	Bolt Diameter (in)	Steel Tensile Strength (ksi)	Predicted Failure Load (kips)	Actual Failure Load (kips)	$P_{actual} / P_{predicted}$
2-1	0.690	45.8	11.98	18.90	1.58
2-2	0.690	45.8	11.98	22.00	1.84
2-3	0.690	45.8	11.98	21.70	1.81
3-3	1.000	44.2	24.29	47.30	1.95
3-19	0.680	45.6	11.59	28.00	2.42
4-3	0.680	45.8	11.64	29.10	2.50
4-4	0.680	45.8	11.64	29.30	2.52
4-8	0.680	45.8	11.64	25.20	2.17
4-10	0.680	45.8	11.64	29.10	2.50
3-5	0.500	39.8	5.47	9.00	1.65
3-11	0.680	45.6	11.59	15.90	1.37
3-12	0.680	45.6	11.59	17.20	1.48
3-8	0.500	39.8	2.19*	4.90	2.24
3-18	0.680	45.6	4.64*	10.50	2.26
3-20	0.680	45.6	4.64*	11.60	2.50
3-4	1.000	44.2	9.72*	18.20	1.87

Mean:	2.04
Std. Dev.:	0.38

Slip Pull-Out Strength

lemson Equation With UWM Data

$$P_{slip} = f_y * d^2/1.82$$

where: f_y = Yield strength of steel
d = Diameter of bolt

Test Number UWM	Bolt Diameter (in)	Steel Tensile Strength (ksi)	Predicted Failure Load (kips)	Actual Failure Load (kips)	P_{actual} / $P_{predicted}$
1	0.563	50	8.71	18.90	2.17
2	0.563	50	8.71	22.00	2.53
3	0.563	50	8.71	21.70	2.49
4	0.563	50	8.71	47.30	5.43

Mean:	3.16
Std. Dev.:	1.32

Slip Pull-Out Strength

Wiss Janney Elstner Assoc. Equation with CU Data

$P_{slip} = 28 * f'_c{}^{1/2} * (e - d)^2 \quad + \quad 1800 * f_i * (L + e - d) * d$

Bearing Term (>9600d²) Friction Term

where: d = Diameter of bolt
f'_c = Compressive strength of imbedding material (Concrete)
e = Leg extension – see figure
L = Embedment length – see figure

Test Number CU	Bolt Diameter (in)	Embedment (inches)	Leg Extension (in)	Concrete (or Grout) Comp. Strength (psi)	Friction Index	Predicted Failure Load (kips)	Actual Failure Load (kips)	$P_{actual}/P_{predicted}$
Table 8.3								
1	0.375	6.375	1.125	2513	1	6.16	3.58	0.58
2	0.375	6.375	1.125	2513	1	6.16	4.30	0.70
3	0.375	6.375	1.125	2513	1	6.16	3.24	0.53
4	0.375	6.375	1.125	2513	1	6.16	3.02	0.49
5	0.375	6.375	1.125	2513	1	6.16	3.80	0.62
6	0.375	6.375	1.125	2513	1	6.16	4.00	0.65
7	0.375	6.375	1.125	2513	1	6.16	3.60	0.58
8	0.500	6.375	1.500	2513	1	9.04	9.62	1.06
9	0.500	6.375	1.500	2513	1	9.04	8.74	0.97
10	0.500	6.375	1.500	2513	1	9.04	6.37	0.70
11	0.500	6.375	1.500	2513	1	9.04	8.80	0.97
12	0.500	6.375	1.500	2513	1	9.04	7.40	0.82
13	0.750	6.375	2.250	2513	1	16.03	19.38	1.21
14	0.750	6.375	2.250	2513	1	16.03	16.65	1.04
15	0.750	6.375	2.250	2513	1	16.03	15.54	0.97
16	0.750	6.375	2.250	2513	1	16.03	17.20	1.07
17	0.750	6.375	2.250	2513	1	16.03	19.00	1.19
18	0.750	6.375	2.250	2513	1	16.03	17.20	1.07
Table 8.4								
1	0.500	5.625	1.500	3202	1	8.36	8.13	0.97
2	0.500	5.625	1.500	3202	1	8.36	5.88	0.70
3	0.500	5.625	1.500	3202	1	8.36	6.50	0.78
4	0.500	5.625	1.500	3202	1	8.36	5.50	0.66
5	0.500	5.625	1.500	3202	1	8.36	5.25	0.63
6	0.500	5.625	1.500	3202	1	8.36	7.75	0.93
Table 8.5								
1	0.500	5.625	1.500	3202	1	8.36	5.75	0.69
2	0.500	5.625	1.500	3202	1	8.36	7.00	0.84
3	0.500	5.625	1.500	3202	1	8.36	6.00	0.72
4	0.500	5.625	1.500	3202	1	8.36	5.50	0.66
5	0.500	5.625	1.500	3202	1	8.36	9.00	1.08
6	0.500	5.625	1.500	3202	1	8.36	8.80	1.05
7	0.750	5.625	2.250	3202	1	15.02	12.50	0.83
8	0.750	5.625	2.250	3202	1	15.02	10.00	0.67
9	0.750	5.625	2.250	3202	1	15.02	11.75	0.78
10	0.750	5.625	2.250	3202	1	15.02	9.50	0.63
11	0.750	5.625	2.250	3202	1	15.02	12.00	0.80
12	0.750	5.625	2.250	3202	1	15.02	11.00	0.73

Mean:	0.82
Std. Dev.:	0.19

Slip Pull-Out Strength

Wiss JanneyElstner Assoc. Equation with WJE Data

$P_{slip} = 28*f'_c{}^{1/2}*(e - d)^2 \quad + \quad 1800*f_i*(L + e - d)*$ where:

Bearing Term {>9600d²}   Friction Term

f_y = Yield strength of steel
d = Diameter of bolt
f'_c = Compressive strength of imbedding material (Concrete)
e = Leg extension --see figure
L = Embedment length -- see figure

Test Number WJE	Bolt Diameter (in)	Embedment (inches)	Leg Extension (in)	Concrete (or Grout) Comp. Strength (psi)	Friction Index	Predicted Failure Load (kips)	Actual Failure Load (kips)	$P_{actual} / P_{predicted}$
2-1	0.690	7.500	3.100	1980	1	19.54	18.90	0.97
2-2	0.690	9.500	3.100	1980	1	22.03	22.00	1.00
2-3	0.690	10.900	3.100	1980	1	23.77	21.70	0.91
3-3	1.000	12.000	4.500	3730	1	48.85	47.30	0.97
3-19	0.680	13.500	3.100	3730	1	29.50	28.00	0.95
4-3	0.680	8.300	3.100	5460	1	25.24	29.10	1.15
4-4	0.680	11.000	3.100	5460	1	28.54	29.30	1.03
4-8	0.680	5.500	3.100	5460	1	21.81	25.20	1.16
4-10	0.680	11.000	3.100	5460	1	28.54	29.10	1.02
3-5	0.500	3.000	2.300	3730	1	9.86	9.00	0.91
3-11	0.680	9.000	1.800	3730	1	16.83	15.90	0.94
3-12	0.680	13.500	1.800	3730	1	22.33	17.20	0.77
3-8	0.500	6.000	2.300	3730	0	5.54	4.90	0.88
3-18	0.680	9.000	3.100	3730	0	10.01	10.50	1.05
3-20	0.680	13.500	3.100	3730	0	10.01	11.60	1.16
3-4	1.000	12.000	4.500	3730	0	20.95	18.20	0.87

Mean:	0.98
Std. Dev.:	0.11

Slip Pull-Out Strength

Wiss JanneyElstner Assoc. Equation with UWM Data

$P_{slip} = 28*f'_c{}^{1/2}*(e - d)^2 \quad + \quad 1800*f_i*(L + e - d)*$ where:

Bearing Term {>9600d²} Friction Term

f_y = Yield strength of steel
d = Diameter of bolt
f'_c = Compressive strength of imbedding material (Concrete)
e = Leg extension --see figure
L = Embedment length -- see figure

Test Number UWM	Bolt Diameter (in)	Embedment (inches)	Leg Extension (in)	Concrete (or Grout) Comp. Strength (psi)	Friction Index	Predicted Failure Load (kips)	Actual Failure Load (kips)	$P_{actual} / P_{predicted}$
1	0.563	6.000	1.938	3290	1	10.52	14.60	1.39
2	0.563	6.000	1.938	3290	1	10.52	15.20	1.45
3	0.563	8.000	1.938	3290	1	12.54	13.40	1.07
4	0.563	8.000	1.938	3290	1	12.54	15.00	1.20

Mean:	1.27
Std. Dev.:	0.15

Appendix D:

Test Data and Predicted Load Comparison for Proposed Nominal Strength Equation (Without Strength Reduction Factor)

Slip Pull-Out Strength

$$P_{slip} = k_b * f'_c * e * d + k_f * f_i * \pi * (L + e + d) * d$$

k_b = 1.5

k_f = 300

Where:
- f_y = Yield strength of steel
- d = Diameter of bolt
- f'_c = Compressive strength of imbedding material (Concrete)
- e = Leg extension
- L = Embedment length
- k_b = Bearing coefficient
- k_f = Friction coefficient

Test Number			Bolt	Embedment	Leg	f'_c	k_b	k_f	Friction	Predicted	Predicted	Predicted Failure	Actual Failure	$P_{actual} / P_{predicted}$
	CU	WJE	Diameter (in)	(inches)	Extension (in)				Index	Bearing Load	Friction Load	Load (kips)	Load (kips)	
	Table 8.3													
1	1		0.375	6.375	1.125	2513	1.5	300	1	1.59	2.78	4.37	3.58	0.82
2	2		0.375	6.375	1.125	2513	1.5	300	1	1.59	2.78	4.37	4.30	0.98
3	3		0.375	6.375	1.125	2513	1.5	300	1	1.59	2.78	4.37	3.24	0.74
4	4		0.375	6.375	1.125	2513	1.5	300	1	1.59	2.78	4.37	3.02	0.69
5	5		0.375	6.375	1.125	2513	1.5	300	1	1.59	2.78	4.37	3.80	0.87
6	6		0.375	6.375	1.125	2513	1.5	300	1	1.59	2.78	4.37	4.00	0.91
7	7		0.375	6.375	1.125	2513	1.5	300	1	1.59	2.78	4.37	3.60	0.82
8	8		0.500	6.375	1.500	2513	1.5	300	1	2.83	3.95	6.77	9.62	1.42
9	9		0.500	6.375	1.500	2513	1.5	300	1	2.83	3.95	6.77	8.74	1.29
10	10		0.500	6.375	1.500	2513	1.5	300	1	2.83	3.95	6.77	6.37	0.94
11	11		0.500	6.375	1.500	2513	1.5	300	1	2.83	3.95	6.77	8.80	1.30
12	12		0.500	6.375	1.500	2513	1.5	300	1	2.83	3.95	6.77	7.40	1.09
13	13		0.750	6.375	2.250	2513	1.5	300	1	6.36	6.63	12.99	19.38	1.49
14	14		0.750	6.375	2.250	2513	1.5	300	1	6.36	6.63	12.99	16.65	1.28
15	15		0.750	6.375	2.250	2513	1.5	300	1	6.36	6.63	12.99	15.54	1.20
16	16		0.750	6.375	2.250	2513	1.5	300	1	6.36	6.63	12.99	17.20	1.32
17	17		0.750	6.375	2.250	2513	1.5	300	1	6.36	6.63	12.99	19.00	1.46
18	18		0.750	6.375	2.250	2513	1.5	300	1	6.36	6.63	12.99	17.20	1.32
	Table 8.4													
19	1		0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	8.13	1.13

Test Number	CU	WJE	Bolt Diameter (in)	Embedment (inches)	Leg Extension (in)	f'_c	k_b	k_f	Friction Index	Predicted Bearing Load	Predicted Friction Load	Predicted Failure Load (kips)	Actual Failure Load (kips)	$P_{actual} / P_{predicted}$
20	2		0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	5.88	0.82
21	3		0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	6.50	0.90
22	4		0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	5.50	0.76
23	5		0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	5.25	0.73
24	6		0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	7.75	1.08
	Table 8.5													
25	1		0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	5.75	0.80
26	2		0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	7.00	0.97
27	3		0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	6.00	0.83
28	4		0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	5.50	0.76
29	5		0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	9.00	1.25
30	6		0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	8.80	1.22
31	7		0.750	5.625	2.250	3202	1.5	300	1	8.11	6.10	14.20	12.50	0.88
32	8		0.750	5.625	2.250	3202	1.5	300	1	8.11	6.10	14.20	10.00	0.70
33	9		0.750	5.625	2.250	3202	1.5	300	1	8.11	6.10	14.20	11.75	0.83
34	10		0.750	5.625	2.250	3202	1.5	300	1	8.11	6.10	14.20	9.50	0.67
35	11		0.750	5.625	2.250	3202	1.5	300	1	8.11	6.10	14.20	12.00	0.84
36	12		0.750	5.625	2.250	3202	1.5	300	1	8.11	6.10	14.20	11.00	0.77
37		2-1	0.690	7.500	3.100	1980	1.5	300	1	6.35	7.34	13.69	18.90	1.38
38		2-2	0.690	9.500	3.100	1980	1.5	300	1	6.35	8.64	15.00	22.00	1.47
39		2-3	0.690	10.900	3.100	1980	1.5	300	1	6.35	9.55	15.91	21.70	1.36
40		3-3	1.000	12.000	4.500	3730	1.5	300	1	25.18	16.49	41.67	47.30	1.14
41		3-19	0.680	13.500	3.100	3730	1.5	300	1	11.79	11.07	22.87	28.00	1.22
42		4-3	0.680	8.300	3.100	5460	1.5	300	1	17.26	7.74	25.01	29.10	1.16
43		4-4	0.680	11.000	3.100	5460	1.5	300	1	17.26	9.47	26.74	29.30	1.10
44		4-8	0.680	5.500	3.100	5460	1.5	300	1	17.26	5.95	23.21	25.20	1.09
45		4-10	0.680	11.000	3.100	5460	1.5	300	1	17.26	9.47	26.74	29.10	1.09
46		3-5	0.500	3.000	2.300	3730	1.5	300	1	6.43	2.73	9.17	9.00	0.98
47		3-11	0.680	9.000	1.800	3730	1.5	300	1	6.85	7.36	14.21	15.90	1.12
48		3-12	0.680	13.500	1.800	3730	1.5	300	1	6.85	10.24	17.09	17.20	1.01
49		3-8	0.500	6.000	2.300	3730	1.5	300	0	6.43	0.00	6.43	4.90	0.76
50		3-18	0.680	9.000	3.100	3730	1.5	300	0	11.79	0.00	11.79	10.50	0.89
51		3-20	0.680	13.500	3.100	3730	1.5	300	0	11.79	0.00	11.79	11.60	0.98
52		3-4	1.000	12.000	4.500	3730	1.5	300	0	25.18	0.00	25.18	18.20	0.72

Mean:	1.03
Standard Deviation:	0.24

Slip Pull-Out Strength--Clemson University Test Data

$$P_{slip} = k_b * f'_c * e * d + k_f * f_i * \pi * (L + e + d) * d$$

$k_b = 1.5$

$k_f = 300$

Where:
- f_y = Yield strength of steel
- d = Diameter of bolt
- f'_c = Compressive strength of imbedding material (Concrete)
- e = Leg extension
- L = Embedment length
- k_b = Bearing coefficient
- k_f = Friction coefficient

Test Number	Bolt Diameter (in)	Embedment (inches)	Leg Extension (in)	f'_c	k_b	k_f	Friction Index	Predicted Bearing Load	Predicted Friction Load	Predicted Failure Load (kips)	Actual Failure Load (kips)	$P_{actual} / P_{predicted}$
Table 8.3												
1	0.375	6.375	1.125	2513	1.5	300	1	1.59	2.78	4.37	3.58	0.82
2	0.375	6.375	1.125	2513	1.5	300	1	1.59	2.78	4.37	4.30	0.98
3	0.375	6.375	1.125	2513	1.5	300	1	1.59	2.78	4.37	3.24	0.74
4	0.375	6.375	1.125	2513	1.5	300	1	1.59	2.78	4.37	3.02	0.69
5	0.375	6.375	1.125	2513	1.5	300	1	1.59	2.78	4.37	3.80	0.87
6	0.375	6.375	1.125	2513	1.5	300	1	1.59	2.78	4.37	4.00	0.91
7	0.375	6.375	1.125	2513	1.5	300	1	1.59	2.78	4.37	3.60	0.82
8	0.500	6.375	1.500	2513	1.5	300	1	2.83	3.95	6.77	9.62	1.42
9	0.500	6.375	1.500	2513	1.5	300	1	2.83	3.95	6.77	8.74	1.29
10	0.500	6.375	1.500	2513	1.5	300	1	2.83	3.95	6.77	6.37	0.94
11	0.500	6.375	1.500	2513	1.5	300	1	2.83	3.95	6.77	8.80	1.30
12	0.500	6.375	1.500	2513	1.5	300	1	2.83	3.95	6.77	7.40	1.09
13	0.750	6.375	2.250	2513	1.5	300	1	6.36	6.63	12.99	19.38	1.49
14	0.750	6.375	2.250	2513	1.5	300	1	6.36	6.63	12.99	16.65	1.28
15	0.750	6.375	2.250	2513	1.5	300	1	6.36	6.63	12.99	15.54	1.20
16	0.750	6.375	2.250	2513	1.5	300	1	6.36	6.63	12.99	17.20	1.32
17	0.750	6.375	2.250	2513	1.5	300	1	6.36	6.63	12.99	19.00	1.46
18	0.750	6.375	2.250	2513	1.5	300	1	6.36	6.63	12.99	17.20	1.32
Table 8.4												
1	0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	8.13	1.13

Test Number CU	Bolt Diameter (in)	Embedment (inches)	Leg Extension (in)	f'c	k_b	k_f	Friction Index	Predicted Bearing Load	Predicted Friction Load	Predicted Failure Load (kips)	Actual Failure Load (kips)	P_{actual} / $P_{predicted}$
2	0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	5.88	0.82
3	0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	6.50	0.90
4	0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	5.50	0.76
5	0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	5.25	0.73
6	0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	7.75	1.08
Table 8.5												
1	0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	5.75	0.80
2	0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	7.00	0.97
3	0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	6.00	0.83
4	0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	5.50	0.76
5	0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	9.00	1.25
6	0.500	5.625	1.500	3202	1.5	300	1	3.60	3.59	7.20	8.80	1.22
7	0.750	5.625	2.250	3202	1.5	300	1	8.11	6.10	14.20	12.50	0.88
8	0.750	5.625	2.250	3202	1.5	300	1	8.11	6.10	14.20	10.00	0.70
9	0.750	5.625	2.250	3202	1.5	300	1	8.11	6.10	14.20	11.75	0.83
10	0.750	5.625	2.250	3202	1.5	300	1	8.11	6.10	14.20	9.50	0.67
11	0.750	5.625	2.250	3202	1.5	300	1	8.11	6.10	14.20	12.00	0.84
12	0.750	5.625	2.250	3202	1.5	300	1	8.11	6.10	14.20	11.00	0.77

Mean:	1.00
Standard Deviation:	0.24

Slip Pull-Out Strength--With Wiss Janney Elstner Associates Data

$$P_{slip} = k_b * f'_c * e * d + k_f * f_i * \pi * (L + e + d) * d$$

$k_b = 1.5$

$k_f = 300$

Where:
- f_y = Yield strength of steel
- d = Diameter of bolt
- f'_c = Compressive strength of imbedding material (Concrete)
- e = Leg extension
- L = Embedment length
- k_b = Bearing coefficient
- k_f = Friction coefficient

Test Number WJE	Bolt Diameter (in)	Embedment (inches)	Leg Extension (in)	f'_c	k_b	k_f	Friction Index	Predicted Bearing Load	Predicted Friction Load	Predicted Failure Load (kips)	Actual Failure Load (kips)	$P_{actual} / P_{predicted}$
2-1	0.680	7.500	3.100	1980	1.5	300	1	6.35	7.34	13.69	18.90	1.38
2-2	0.690	9.500	3.100	1980	1.5	300	1	6.35	8.64	15.00	22.00	1.47
2-3	0.680	10.900	3.100	1980	1.5	300	1	6.35	9.55	15.91	21.70	1.36
3-3	1.000	12.000	4.500	3730	1.5	300	1	25.18	16.49	41.67	47.30	1.14
3-19	0.680	13.500	3.100	3730	1.5	300	1	11.79	11.07	22.87	28.00	1.22
4-3	0.680	8.300	3.100	5460	1.5	300	1	17.26	7.74	25.01	29.10	1.16
4-4	0.680	11.000	3.100	5460	1.5	300	1	17.26	9.47	26.74	29.30	1.10
4-8	0.680	5.500	3.100	5460	1.5	300	1	17.26	5.95	23.21	25.20	1.09
4-10	0.680	11.000	3.100	5460	1.5	300	1	17.26	9.47	26.74	29.10	1.09
3-5	0.500	3.000	2.300	3730	1.5	300	1	6.43	2.73	9.17	9.00	0.98
3-11	0.680	9.000	1.800	3730	1.5	300	1	6.85	7.36	14.21	15.90	1.12
3-12	0.680	13.500	1.800	3730	1.5	300	1	6.85	10.24	17.09	17.20	1.01
3-8	0.500	6.000	2.300	3730	1.5	300	0	6.43	0.00	6.43	4.90	0.76
3-18	0.680	9.000	3.100	3730	1.5	300	0	11.79	0.00	11.79	10.50	0.89
3-20	0.680	13.500	3.100	3730	1.5	300	0	11.79	0.00	11.79	11.60	0.98
3-4	1.000	12.000	4.500	3730	1.5	300	0	25.18	0.00	25.18	18.20	0.72

Mean:	1.09
Standard Deviation:	0.20

Slip Pull-Out Strength--UWM Test Data

$$P_{slip} = \phi(k_b{*}f'_c{*}e{*}d + k_f{*}f_i{*}\pi{*}(L + e + d){*}d)$$

k_b = 1.5
k_f = 300
ϕ = 1.00

Where: f_y = Yield strength of steel
d = Diameter of bolt
f'_c = Compressive strength of imbedding material (Concrete)
e = Leg extension
L = Embedment length
f_i = Friction Index
k_b = Bearing coefficient
k_f = Friction coefficient

Test Number	Bolt Diameter (in)	Embedment (inches)	Leg Extension (in)	f'_c	k_b	k_f	Friction Index	ϕ	Predicted Bearing Load	Predicted Friction Load	Predicted Failure Load (kips)	Actual Failure Load (kips)	$P_{actual} / P_{predicted}$
1	0.563	6.000	1.938	3290	1.5	300	1	1	5.38	4.51	9.88	14.60	1.48
2	0.563	6.000	1.938	3290	1.5	300	1	1	5.38	4.51	9.88	15.20	1.54
3	0.563	8.000	1.938	3290	1.5	300	1	1	5.38	5.57	10.94	13.40	1.22
4	0.563	8.000	1.938	3290	1.5	300	1	1	5.38	5.57	10.94	15.00	1.37

Mean:	1.40
Standard Deviation:	0.12

Appendix E:
Test Data and Predicted Load Comparison for Proposed Design Equation (With Strength Reduction Factor)

Slip Pull-Out Strength

$$P_{slip} = \phi(k_b * f'_c * e * d + k_f * f_i * \pi * (L + e + d) * d)$$

k_b = 1.5
k_f = 300
ϕ = 0.65

Where: f_y = Yield strength of steel
d = Diameter of bolt
f'_c = Compressive strength of imbedding material (Concrete)
e = Leg extension
L = Embedment length
f_i = Friction index
k_b = Bearing coefficient
k_f = Friction coefficient

Test Number			Bolt Diameter (in)	Embedment (inches)	Leg Extension (in)	f'_c	k_b	k_f	Friction Index	ϕ	Predicted Bearing Load	Predicted Friction Load	Predicted Failure Load (kips)	Actual Failure Load (kips)	$P_{actual} / P_{predicted}$
	CU	WJE													
	Table 8.3														
1	1		0.375	6.375	1.125	2513	1.5	300	1	0.65	1.03	1.81	2.84	3.58	1.26
2	2		0.375	6.375	1.125	2513	1.5	300	1	0.65	1.03	1.81	2.84	4.30	1.51
3	3		0.375	6.375	1.125	2513	1.5	300	1	0.65	1.03	1.81	2.84	3.24	1.14
4	4		0.375	6.375	1.125	2513	1.5	300	1	0.65	1.03	1.81	2.84	3.02	1.06
5	5		0.375	6.375	1.125	2513	1.5	300	1	0.65	1.03	1.81	2.84	3.80	1.34
6	6		0.375	6.375	1.125	2513	1.5	300	1	0.65	1.03	1.81	2.84	4.00	1.41
7	7		0.375	6.375	1.125	2513	1.5	300	1	0.65	1.03	1.81	2.84	3.60	1.27
8	8		0.500	6.375	1.500	2513	1.5	300	1	0.65	1.84	2.57	4.40	9.62	2.18
9	9		0.500	6.375	1.500	2513	1.5	300	1	0.65	1.84	2.57	4.40	8.74	1.99
10	10		0.500	6.375	1.500	2513	1.5	300	1	0.65	1.84	2.57	4.40	6.37	1.45
11	11		0.500	6.375	1.500	2513	1.5	300	1	0.65	1.84	2.57	4.40	8.80	2.00
12	12		0.500	6.375	1.500	2513	1.5	300	1	0.65	1.84	2.57	4.40	7.40	1.68
13	13		0.750	6.375	2.250	2513	1.5	300	1	0.65	4.13	4.31	8.44	19.38	2.30
14	14		0.750	6.375	2.250	2513	1.5	300	1	0.65	4.13	4.31	8.44	16.65	1.97
15	15		0.750	6.375	2.250	2513	1.5	300	1	0.65	4.13	4.31	8.44	15.54	1.84
16	16		0.750	6.375	2.250	2513	1.5	300	1	0.65	4.13	4.31	8.44	17.20	2.04
17	17		0.750	6.375	2.250	2513	1.5	300	1	0.65	4.13	4.31	8.44	19.00	2.25
18	18		0.750	6.375	2.250	2513	1.5	300	1	0.65	4.13	4.31	8.44	17.20	2.04
	Table 8.4														
19	1		0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	8.13	1.74

Test Number			Bolt Diameter (in)	Embedment (inches)	Leg Extension (in)	f'_c	k_b	k_f	Friction Index	ϕ	Predicted Bearing Load	Predicted Friction Load	Predicted Failure Load (kips)	Actual Failure Load (kips)	$P_{actual} / P_{predicted}$
	CU	WJE													
20	2		0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	5.88	1.26
21	3		0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	6.50	1.39
22	4		0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	5.50	1.18
23	5		0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	5.25	1.12
24	6		0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	7.75	1.66
	Table 8.5														
25	1		0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	5.75	1.23
26	2		0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	7.00	1.50
27	3		0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	6.00	1.28
28	4		0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	5.50	1.18
29	5		0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	9.00	1.92
30	6		0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	8.80	1.88
31	7		0.750	5.625	2.250	3202	1.5	300	1	0.65	5.27	3.96	9.23	12.50	1.35
32	8		0.750	5.625	2.250	3202	1.5	300	1	0.65	5.27	3.96	9.23	10.00	1.08
33	9		0.750	5.625	2.250	3202	1.5	300	1	0.65	5.27	3.96	9.23	11.75	1.27
34	10		0.750	5.625	2.250	3202	1.5	300	1	0.65	5.27	3.96	9.23	9.50	1.03
35	11		0.750	5.625	2.250	3202	1.5	300	1	0.65	5.27	3.96	9.23	12.00	1.30
36	12		0.750	5.625	2.250	3202	1.5	300	1	0.65	5.27	3.96	9.23	11.00	1.19
37		2-1	0.690	7.500	3.100	1980	1.5	300	1	0.65	4.13	4.77	8.90	18.90	2.12
38		2-2	0.690	9.500	3.100	1980	1.5	300	1	0.65	4.13	5.62	9.76	22.00	2.26
39		2-3	0.690	10.900	3.100	1980	1.5	300	1	0.65	4.13	6.21	10.34	21.70	2.10
40		3-3	1.000	12.000	4.500	3730	1.5	300	1	0.65	16.37	10.72	27.09	47.30	1.75
41		3-19	0.680	13.500	3.100	3730	1.5	300	1	0.65	7.67	7.20	14.86	28.00	1.88
42		4-3	0.680	8.300	3.100	5460	1.5	300	1	0.65	11.22	5.03	16.25	29.10	1.79
43		4-4	0.680	11.000	3.100	5460	1.5	300	1	0.65	11.22	6.16	17.38	29.30	1.69
44		4-8	0.680	5.500	3.100	5460	1.5	300	1	0.65	11.22	3.87	15.09	25.20	1.67
45		4-10	0.680	11.000	3.100	5460	1.5	300	1	0.65	11.22	6.16	17.38	29.10	1.67
46		3-5	0.500	3.000	2.300	3730	1.5	300	1	0.65	4.18	1.78	6.96	9.00	1.61
47		3-11	0.680	9.000	1.800	3730	1.5	300	1	0.65	4.45	4.78	9.23	15.90	1.72
48		3-12	0.680	13.500	1.800	3730	1.5	300	1	0.65	4.45	6.68	11.11	17.20	1.55
49		3-8	0.500	6.000	2.300	3730	1.5	300	0	0.65	4.18	0.00	4.18	4.90	1.17
50		3-18	0.680	9.000	3.100	3730	1.5	300	0	0.65	7.67	0.00	7.67	10.50	1.37
51		3-20	0.680	13.500	3.100	3730	1.5	300	0	0.65	7.67	0.00	7.67	11.60	1.51
52		3-4	1.000	12.000	4.500	3730	1.5	300	0	0.65	16.37	0.00	16.37	18.20	1.11

Mean:	1.58
Standard Deviation:	0.36

Slip Pull-Out Strength--Clemson University Test Data

$$P_{slip} = \phi(k_b{*}f'_c{*}e{*}d + k_f{*}f_i{*}\pi{*}(L + e + d){*}d)$$

k_b = 1.5
k_f = 300
ϕ = 0.65

Where:
f_y = Yield strength of steel
d = Diameter of bolt
f'_c = Compressive strength of imbedding material (Concrete)
e = Leg extension
L = Embedment length
f_i = Friction Index
k_b = Bearing coefficient
k_f = Friction coefficient

Test Number	Bolt Diameter (in)	Embedment (inches)	Leg Extension (in)	f'_c	k_b	k_f	Friction Index	ϕ	Predicted Bearing Load	Predicted Friction Load	Predicted Failure Load (kips)	Actual Failure Load (kips)	$P_{actual} / P_{predicted}$
Table 8.3													
1	0.375	6.375	1.125	2513	1.5	300	1	0.65	1.03	1.81	2.84	3.58	1.26
2	0.375	6.375	1.125	2513	1.5	300	1	0.65	1.03	1.81	2.84	4.30	1.51
3	0.375	6.375	1.125	2513	1.5	300	1	0.65	1.03	1.81	2.84	3.24	1.14
4	0.375	6.375	1.125	2513	1.5	300	1	0.65	1.03	1.81	2.84	3.02	1.06
5	0.375	6.375	1.125	2513	1.5	300	1	0.65	1.03	1.81	2.84	3.80	1.34
6	0.375	6.375	1.125	2513	1.5	300	1	0.65	1.03	1.81	2.84	4.00	1.41
7	0.375	6.375	1.125	2513	1.5	300	1	0.65	1.03	1.81	2.84	3.60	1.27
8	0.500	6.375	1.500	2513	1.5	300	1	0.65	1.84	2.57	4.40	9.62	2.18
9	0.500	6.375	1.500	2513	1.5	300	1	0.65	1.84	2.57	4.40	8.74	1.99
10	0.500	6.375	1.500	2513	1.5	300	1	0.65	1.84	2.57	4.40	6.37	1.45
11	0.500	6.375	1.500	2513	1.5	300	1	0.65	1.84	2.57	4.40	8.80	2.00
12	0.500	6.375	1.500	2513	1.5	300	1	0.65	1.84	2.57	4.40	7.40	1.68
13	0.750	6.375	2.250	2513	1.5	300	1	0.65	4.13	4.31	8.44	19.38	2.30
14	0.750	6.375	2.250	2513	1.5	300	1	0.65	4.13	4.31	8.44	16.65	1.97
15	0.750	6.375	2.250	2513	1.5	300	1	0.65	4.13	4.31	8.44	15.54	1.84
16	0.750	6.375	2.250	2513	1.5	300	1	0.65	4.13	4.31	8.44	17.20	2.04
17	0.750	6.375	2.250	2513	1.5	300	1	0.65	4.13	4.31	8.44	19.00	2.25
18	0.750	6.375	2.250	2513	1.5	300	1	0.65	4.13	4.31	8.44	17.20	2.04
Table 8.4													
1	0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	8.13	1.74

Test Number	Bolt Diameter (in)	Embedment (inches)	Leg Extension (in)	f'_c	k_b	k_f	Friction Index	ϕ	Predicted Bearing Load	Predicted Friction Load	Predicted Failure Load (kips)	Actual Failure Load (kips)	$P_{actual} / P_{predicted}$
CU													
2	0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	5.88	1.26
3	0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	6.50	1.39
4	0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	5.50	1.18
5	0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	5.25	1.12
6	0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	7.75	1.66
Table 8.5													
1	0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	5.75	1.23
2	0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	7.00	1.50
3	0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	6.00	1.26
4	0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	5.50	1.16
5	0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	9.00	1.92
6	0.500	5.625	1.500	3202	1.5	300	1	0.65	2.34	2.34	4.68	8.80	1.88
7	0.750	5.625	2.250	3202	1.5	300	1	0.65	5.27	3.96	9.23	12.50	1.35
8	0.750	5.625	2.250	3202	1.5	300	1	0.65	5.27	3.96	9.23	10.00	1.08
9	0.750	5.625	2.250	3202	1.5	300	1	0.65	5.27	3.96	9.23	11.75	1.27
10	0.750	5.625	2.250	3202	1.5	300	1	0.65	5.27	3.96	9.23	9.50	1.03
11	0.750	5.625	2.250	3202	1.5	300	1	0.65	5.27	3.96	9.23	12.00	1.30
12	0.750	5.625	2.250	3202	1.5	300	1	0.65	5.27	3.96	9.23	11.00	1.19

Mean:	1.54
Standard Deviation:	0.38

Slip Pull-Out Strength--With Wiss Janney Elstner Associates Data

$$P_{slip} = \phi(k_b * f'_c * e * d + k_f * f_i * \pi * (L + e + d) * d)$$

$k_b = 1.5$
$k_f = 300$
$\phi = 0.65$

Where: f_y = Yield strength of steel
d = Diameter of bolt
f'_c = Compressive strength of imbedding material (Concrete)
e = Leg extension
L = Embedment length
f_i = Friction Index
k_b = Bearing coefficient
k_f = Friction coefficient

Test Number WJE	Bolt Diameter (in)	Embedment (inches)	Leg Extension (in)	f'_c	k_b	k_f	Friction Index	ϕ	Predicted Bearing Load	Predicted Friction Load	Predicted Failure Load (kips)	Actual Failure Load (kips)	$P_{actual} / P_{predicted}$
2-1	0.690	7.500	3.100	1980	1.5	300	1	0.65	4.13	4.77	8.90	18.90	2.12
2-2	0.690	9.500	3.100	1980	1.5	300	1	0.65	4.13	5.62	9.75	22.00	2.26
2-3	0.690	10.900	3.100	1980	1.5	300	1	0.65	4.13	6.21	10.34	21.70	2.10
3-3	1.000	12.000	4.500	3730	1.5	300	1	0.65	16.37	10.72	27.09	47.30	1.75
3-19	0.680	13.500	3.100	3730	1.5	300	1	0.65	7.67	7.20	14.86	28.00	1.88
4-3	0.680	8.300	3.100	5460	1.5	300	1	0.65	11.22	5.03	16.25	29.10	1.79
4-4	0.680	11.000	3.100	5460	1.5	300	1	0.65	11.22	6.16	17.38	29.30	1.69
4-8	0.680	5.500	3.100	5460	1.5	300	1	0.65	11.22	3.87	15.09	25.20	1.67
4-10	0.680	11.000	3.100	5460	1.5	300	1	0.65	11.22	6.16	17.38	29.10	1.67
3-5	0.500	8.000	2.300	3730	1.5	300	1	0.65	4.18	1.78	5.96	9.00	1.51
3-11	0.680	9.000	1.800	3730	1.5	300	1	0.65	4.45	4.78	9.23	15.90	1.72
3-12	0.680	13.500	1.800	3730	1.5	300	1	0.65	4.45	6.66	11.11	17.20	1.55
3-8	0.500	6.000	2.300	3730	1.5	300	0	0.65	4.18	0.00	4.18	4.90	1.17
3-18	0.680	9.000	3.100	3730	1.5	300	0	0.65	7.67	0.00	7.67	10.50	1.37
3-20	0.680	13.500	3.100	3730	1.5	300	0	0.65	7.67	0.00	7.67	11.60	1.51
3-4	1.000	12.000	4.500	3730	1.5	300	0	0.65	16.37	0.00	16.37	18.20	1.11

Mean:	1.68
Standard Deviation:	0.31

Slip Pull-Out Strength--UWM Test Data

$$P_{slip} = \phi(k_b * f'_c * e * d + k_f * f_i * \pi * (L + e + d) * d)$$

k_b = 1.5
k_f = 300
ϕ = 0.65

Where:
f_y = Yield strength of steel
d = Diameter of bolt
f'_c = Compressive strength of imbedding material (Concrete)
e = Leg extension
L = Embedment length
f_i = Friction index
k_b = Bearing coefficient
k_f = Friction coefficient

Test Number	Bolt Diameter (in)	Embedment (inches)	Leg Extension (in)	f'_c	k_b	k_f	Friction Index	ϕ	Predicted Bearing Load	Predicted Friction Load	Predicted Failure Load (kips)	Actual Failure Load (kips)	$P_{actual} / P_{predicted}$
1	0.563	6.000	1.938	3290	1.5	300	1	0.65	3.50	2.93	6.42	14.60	2.27
2	0.563	6.000	1.938	3290	1.5	300	1	0.65	3.50	2.93	6.42	15.20	2.37
3	0.563	8.000	1.938	3290	1.5	300	1	0.65	3.50	3.62	7.11	13.40	1.88
4	0.563	8.000	1.938	3290	1.5	300	1	0.65	3.50	3.62	7.11	15.00	2.11

Mean:	2.16
Standard Deviation:	0.18

July 1996

DESIGN OF HOOKED ANCHOR BOLTS IN CONCRETE AND MASONRY
PROPOSED CODE PROVISIONS AND COMMENTARY

Prepared for: National Codes and Standards Council

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4. Design Strength Based on Steel

4.1 Tension

The tensile design strength of hooked anchors based on steel, $\phi_s P_s$, shall be:

$$\phi_s P_s = \phi_s A_s f_y \qquad (4.1.1)$$

where, $\phi_s = 0.9$

4.2 Shear

The shear design strength of hooked anchors based on steel, $\phi_s V_s$, shall be:

$$\phi_s V_s = \phi_s \, 0.6 A_s f_y \qquad (4.2.1)$$

where, $\phi_s = 0.9$

4.3 Combined Tension and Shear

Where tension and shear act simultaneously, the following interaction condition shall be satisfied:

$$\left(\frac{P_u}{\phi_s P_s}\right)^2 + \left(\frac{V_u}{\phi_s V_s}\right)^2 \leq 1.0 \qquad (4.3.1)$$

5.1.2 Anchor Slip-pullout

The design strength for slip-pullout of hooked anchors shall be: (5.1.4)

$$\phi_{s/p} P_{s/p} = \phi_{s/p} \left[1.5 f' e d_b + 300 \pi f_l \, (l_e + e + d_b) d_b \right] n$$

where, $\phi_{s/p} = 0.65$

5.2 Shear

The design strength in shear, $\phi_v V_c$, shall be:

For $d_{eb} \geq 10 d_b$: (5.2.1a)

$$\phi_v V_c = \left(\phi_v \; 628 d_b^2 \lambda \sqrt{f'} \right) n$$

and, for $d_{eb} \leq 10 d_b$, the lesser of: (5.2.1b)

$$\phi_v V_c = \left(\phi_v \; 2 \pi d_{eb}^2 \lambda \sqrt{f'} \right) n_s$$

and (5.2.1c)

$$\phi_v V_c = \phi_v \; 2 d_{eb} (\pi d_{eb} + 2 b) \lambda \sqrt{f'}$$

where, $\phi_v = 0.85$

5.3 Combined Shear and Tension

When tension and shear act simultaneously, the following interaction condition shall be satisfied:

(5.3.1)

$$\left(\frac{P_u}{\phi_p P_c} \right)^2 + \left(\frac{V_u}{\phi_v V_c} \right)^2 \leq 1.0$$

$P_{c/b}$ Nominal strength based on concrete/masonry breakout, lbs

P_s Nominal tension strength of steel, lbs

$P_{s/p}$ Nominal strength based on anchor slip-pullout, lbs

V_c Nominal shear strength based on concrete failure, lbs

V_s Nominal shear strength of steel, lbs

x Distance between outermost anchors in direction perpendicular to y, in

y Distance between outermost anchors in direction perpendicular to x, in

z Smaller dimension between outermost anchors in a group; i.e. lesser of x and y, in

λ Adjustment factor for concrete density
= 1.0 for nwt concrete
= 0.85 for light weight concrete

$\phi_{c/b}$ Strength reduction factor for concrete/masonry breakout
= 0.85

ϕ_p Strength reduction factor for concrete/masonry; $\phi_{c/b}$ or $\phi_{s/p}$

ϕ_s Strength reduction factor for steel
= 0.9

$\phi_{s/p}$ Strength reduction factor for anchor slip-pullout
= 0.65

ϕ_v Strength reduction factor for shear in concrete
= 0.85

R3. Strength Reduction Factors

It is generally recognized that the presence of cracks in concrete / masonry reduces its anchorage effectiveness[6]. And, since the presence of tension could lead to potential cracking, a strength reduction factor of 0.7 is included for anchors located in the tension region of a member.

In the majority of applications, the hooked anchors are installed after the member, such as a masonry wall, has been completed. In such situations, there is always a concern with respect to anchor location, alignment, and quality of the grout. Even in pre-installed applications, the anchors often get out of alignment during construction. Thus, unless special inspection is provided, a strength reduction factor of 0.65 should be included in design.

R4. Design Strength Based on Steel

Use of yield strength is made, which is consistent with common design practice. Alternatively, LRFD[7] specifications for fasteners, where calculations are based on ultimate strength, may be used.

R4.3 Combined Tension and Shear

Under combined tension and shear loading, the connection safety is ensured by using an interaction condition involving load to strength ratios for tension and shear. The exponent on these ratios ranging from 1 to 2 has been used. For simplicity of calculations, a value of 1 has frequently been used, even though a value of 2 (a circle interaction curve) has been shown[5, 8] to be more accurate and is thus included here. However, contrary to current practice[1,9], the ϕ factor in this chapter has been separated for tension and shear and placed inside the squared terms. This is done to recognize:

1. Tension and Shear failures have different levels of ductility. Use of two different ϕ factors more accurately reflects the conservatism required as each component of force has a greater or lesser percentage of the total applied force. While no distinction is made in the steel interaction, it is considered in the concrete / masonry interaction (see R5.3).

2. Because the interaction diagram is a circle, squaring ϕ reduces the allowable design load by the full ϕ, rather that its square root.

3. As either tension or shear tends toward zero, the interaction equation reduces to the general $\phi F_n \geq F_u$ statement of strength design.

R5.3 Combined Shear and Tension

Conceptually, the slip-pullout failure mode does not have the same interaction with shear failure as does the tension breakout. However, at this time, no data is available to substantiate this. Therefore, slip-pullout is conservatively included in the interaction equation. Also, use of different ϕ factors for tension and shear and placing them inside the squared terms is made as discussed in section R4.3.

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Table 2: Allowable Tension, Pounds*

2 Inch Leg Extension

NCMA Allowable Loads

l_e	Bolt Size, d_b, inches							
	1/4	3/8	1/2	5/8	3/4	7/8	1	1 1/8
$4d_b$	80	180	310	490	710	960	1260	1600
$6d_b$	180	400	710	1105	1590	2160	2820	3570
$8d_b$	310	710	1260	1960	2820	3850	5025	6350
$10d_b$	360	790	1440	2230	3120	4320	5690	7130

Proposed Design Procedure Allowable Loads

(Net Values Including Slip-Pullout Eqn. 5.1.4)

l_e	Bolt Size, d_b, inches							
	1/4	3/8	1/2	5/8	3/4	7/8	1	1 1/8
$4d_b$	105	235	418	653	941	1280	1672	2102
$6d_b$	235	529	807	1074	1368	1687	2033	2406
$8d_b$	366	600	867	1168	1503	1871	2273	2709
$10d_b$	381	633	927	1261	1637	2055	2513	3013

*Assumtions:

$f' = 2500$ psi
$f_y = 36$ ksi
Leg Extension = 2 inches
Dead Load = Live Load
Anchor in Tension Region of Member
No Special Inspection of Anchor Installation

Table 4: Allowable Shear, Pounds*

NCMA Allowable Loads

f'	Bolt Diameter, Inches							
	1/4	3/8	1/2	5/8	3/4	7/8	1	1 1/8
1500	210	480	850	1330	1780	1920	2050	2170
2000	210	480	850	1330	1900	2060	2200	2340
2500	210	480	850	1330	1900	2180	2330	2470
3000	210	480	850	1330	1900	2280	2440	2590
3500	210	480	850	1330	1900	2370	2540	2680

Proposed Design Procedure Allowable Loads
(Based on Steel Eqn. 4.2.1 and Concrete / Masonry Eqn. 5.2.1a)

f'	Bolt Diameter, Inches							
	1/4	3/8	1/2	5/8	3/4	7/8	1	1 1/8
1500	253	569	1011	1580	2276	3098	4046	5121
2000	292	657	1168	1825	2628	3577	4672	5913
2500	326	735	1306	2040	2938	3999	5223	6611
3000	358	805	1430	2235	3219	4381	5722	7242
3500	386	869	1545	2414	3476	4732	6180	7822

Allowable Steel Loads

	410	923	1642	2565	3694	5028	6567	8311

*Assumtions:
fy = 36 ksi
Dead Load = Live Load
Anchor in Tension Region of Member
No Special Inspection of Anchor Installation