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STATISTICAL ANALYSIS OF MASONRY FASTNERS

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Abstract

Data on the behaviour of both headed and bent-bar bolts loaded in tension was used as the basis for a study of reliability of masonry fastening. All of the data was for single bolts (no bolt groups), and the majority of data was for bent-bar bolts remote from a free edge of masonry. Measured capacities were compared with nominal capacities from two design methodologies: the strength design fastening provisions of the 2002 MJSC Building Code Requirements for Masonry Structures, and the ACI 318M-02 Building Code Requirements for Structural Concrete. Monte Carlo techniques were used to predict the probability of failure for each methodology. Results of this study indicate that the 2002 MSJC fastening provisions can produce fastenings with low levels of reliability.

Key Words

Fasteners, bolts, masonry, reliability

Notation

A_b = bolt area, mm^2

A_{No} = projected area of the breakout body for a single bolt, unaffected by adjacent edges, mm^2

B_{an} = nominal tensile strength of a bolt, N

A_N = projected area of the breakout body for a bolt, including the effects of adjacent edges, mm^2

A_{pt} = projected area on the masonry surface of a right circular cone, mm^2

d_b = bolt diameter, mm

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e = projected leg extension of bolt, measured from inside edge of bolt at bend to farthest point of fastener in the plane of the hook, mm

f'_m = specified compressive strength of the masonry, MPa

f_y = bolt yield stress, MPa

l_b = effective embedment length, mm

N_b = capacity of a single bolt loaded in tension, unaffected by adjacent edges, ACI 318M-02

Y_2 = modification factor to account for small edge distances

f = strength reduction factor
= 0.9 steel yield
= 0.5 masonry breakout
= 0.65 masonry pullout

1 Introduction

This paper reports partial results from a larger project intended to assess reliability of fastening to masonry. The project involves reliability assessment of fasteners loaded in tension only, in shear only, and fasteners loaded in combination of tension and shear. This paper reports statistics and reliability results for fasteners loaded in pure tension.

ACI 318M-02 uses the term “anchorage” for attachment to concrete structures. When used with masonry the term anchorage refers to ties, anchors and fasteners. In the context of masonry in this paper, the term fastener is most appropriate.

Data for testing of fasteners for masonry is sparse when compared to that available for testing of anchorage to concrete. The database for concrete anchorage consists of about 1800 individual tests, but only about 300 tests comprise the database for masonry fastening. This number includes tests done on both clay and concrete, and tests done on fasteners loaded in tension, shear, or combinations of tension and shear.

Test data related to the capacity of single bolts (no bolt groups) in masonry are evaluated. This test data is compared to nominal capacities from two sets of masonry fastening provisions: Chapter 3 of the 2002 MSJC Code (Strength Design) and an alternate framework adapted from ACI 318M-02 Appendix D for design of anchorage to concrete. The mean, standard deviation and coefficient of variation (COV) for the ratio of test value to nominal value are evaluated, in addition to a measure of reliability for this type of fastener.

2 Design Provisions for Tensile Fasteners

2.1 Masonry Tensile Breakout

2.1.1 2002 MSJC

The nominal tensile breakout capacity is computed using Equation (1).

$$B_{an} = 0.332 A_{pt} \sqrt{f'_m} \qquad (1)$$

$$A_{pt} = p\, l_b^2$$

A_{pt} is modified when the fastener is near a free edge of masonry.

2.1.2 ACI 318M-02

The nominal tensile breakout capacity is computed using Equations (2) and (3).

$$B_{an} = \frac{A_N}{A_{No}} \Psi_2 N_b \tag{2}$$

$$N_b = 4.10\sqrt{f'_m}\, h_{ef}^{1.5} \tag{3}$$

Equations (2) and (3) are ACI-318M-02 Equations D-4 and D-7, respectively, adapted for use with masonry. Y_2 is a factor that modifies capacity when the fastener is near a free edge of masonry.

2.2 Masonry Tensile Pullout

2.2.1 2002 MSJC

The nominal tensile pullout capacity is computed using Equation (4).

$$B_{an} = 1.5 f'_m e_b d_b + \left[3.07p\,(l_b + e_b + d_b)\, d_b\right] \tag{4}$$

2.2.2 ACI 318M-02

The nominal tensile pullout capacity is computed using Equation (5):

$$B_{an} = 0.9\, f'_m e_b d_b \tag{5}$$

Equation (5) is ACI-318M-02 Equation D-14, adapted for use with masonry.

2.3 Steel Tensile Yield - 2002 MSJC and ACI 318M-02

2002 MSJC fastener provisions use yield stress to compute steel capacity. ACI 318M-02 bases capacity on steel tensile strength. Other than this difference, steel capacity provisions for both methodologies are identical. Because masonry fasteners typically use A36 or A307 steel, yield stress is used in this paper to evaluate capacity for both methodologies.

The nominal yield capacity of the fastener steel is given by Equation (6):

$$B_{an} = A_b f_y \tag{6}$$

Equation (6) is ACI 318M-02 Equation D-3, adapted for use with masonry.

2.4 Design Strength

Design strengths for both 2002 MJSC and ACI 318M-02 are obtained by multiplying nominal strength by the appropriate strength reduction factor (ϕ). Other than as used in Section 4.2, ϕ factors are not included in generation of statistics given in this paper.

3 Statistics for Existing Test Data

Statistics presented in this paper were computed for database of 158 tensile tests. Of these tests, 94 were for breakout of concrete masonry, 13 were for breakout of clay masonry, 27 were for pullout of concrete masonry and 24 were for pullout of clay masonry. The source of most of the data is given in Allen, et al (2000). Data not available in Allen are reported in Brown, et al (2001) and Weigel, et al (2002).

Statistical analyses are summarized in Table 1 and 2. Plots of the data and trend lines are shown in Figures 1 through 8. In the tables, the column entitled “Bias” is the bias of the data with respect to embedment depth, as measured by the slope of the trend lines given in the figures. The column entitled “Mean”, “Standard Deviation” and “COV” (coefficient of variation) in the tables indicate the value of those respective quantities for the ratio of test value to nominal value. Nominal values are calculated using either the 2002 MJSC or ACI 318M-02 methodology.

Table 1 Fastener Statistics - 2002 MSJC

Material	Bias	Mean	Standard Deviation	COV
Breakout				
Concrete	-0.0215	1.200	0.401	0.334
Clay	-0.0119	1.007	0.144	0.143
Pullout				
Concrete	0.00529	1.566	0.438	0.280
Clay	-0.00323	0.772	0.268	0.347

Table 2 Fastener Statistics - ACI 318M-02

Material	Bias	Mean	Standard Deviation	COV
Breakout				
Concrete	-0.0178	2.088	0.555	0.266
Clay	-0.00593	1.007	0.190	0.189
Pullout				
Concrete	0.0289	3.817	0.881	0.231
Clay	-0.00114	1.767	0.584	0.331

4 Reliability Analysis

4.1 Ductile versus Non-ductile Design

Two design scenarios are addressed in this paper - ductile and non-ductile. The purpose of ductile design is to insure that, should failure occur, it will happen in the steel portion of the fastening. With ductile design, the masonry capacity must exceed the fastener steel strength. In non-ductile design, the masonry capacity simply must exceed the applied load.

4.2 Design

An unfactored load distribution with mean 1.0 and COV = 0.2 is assumed. If only 95% fractile loads are considered, then the minimum design load is 1 + 1.645(0.2) = 1.329, with a COV = 0.2. Applying a load factor of 1.6, the factored load is 2.126.

Next, a steel strength is selected to meet this load requirement. Using the ϕ factor of 0.9 for steel tensile yield, the required nominal strength of the fastener steel is 2.126 / 0.9 = 2.362. Because typical fastener steels exhibit significant overstrength, the expected fastener steel strength will be higher than this value. Assuming a mean overstrength factor of 1.25, the expected steel strength is 1.25(2.362) = 2.953, with an assumed COV = 0.16.

The next step is to compute the required masonry strength. These calculations depend on whether ductile or non-ductile design is to be used. If the design is non-ductile, the masonry strength must exceed only the applied load. The required nominal strength, for the case of masonry breakout, is 2.126 / 0.5 = 4.252 where ϕ = 0.5 for masonry breakout. If ductile design is used, the value is 2.953 / 0.5 = 5.906.

Finally, the expected masonry strength is computed. This involves multiplying the required masonry strength by the mean ratio taken from either Table 1 or 2, as appropriate. For the case of concrete masonry breakout and ductile design, the expected masonry strength is 1.200(5.906) = 7.087, with a COV = 0.334.

4.3 Reliability

Structural reliability is normally given in terms of β, the reliability index. The value of fastener capacity minus the load carried by the fastener may be treated as a random variable. Negative values of this random variable represent a "failure" condition. As shown in Figure 9, β represents the number of standard deviations below the mean to which the random variable must fall to reach the failure condition. Large values of β indicate high reliability.

4.4 Monte Carlo Analysis

Given the masonry and steel distribution obtained in Section 4.2, a Monte Carlo analysis was conducted to obtain "failure" probabilities. For each combination of masonry material and failure type, 20 simulations involving 1,000,000 samples were executed. Results of these analyses were averaged and are presented in Tables 3, 4 and 5.

Table 3 2002 MSJC Reliability Index for Ductile Fastening

Material and Failure Type	Probability Fastening Deficient	β
Concrete Tensile Breakout	0.00710	2.45
Clay Tensile Breakout	0.00667	2.48
Concrete Tensile Pullout	0.00207	2.87
Clay Tensile Pullout	0.0372	1.79

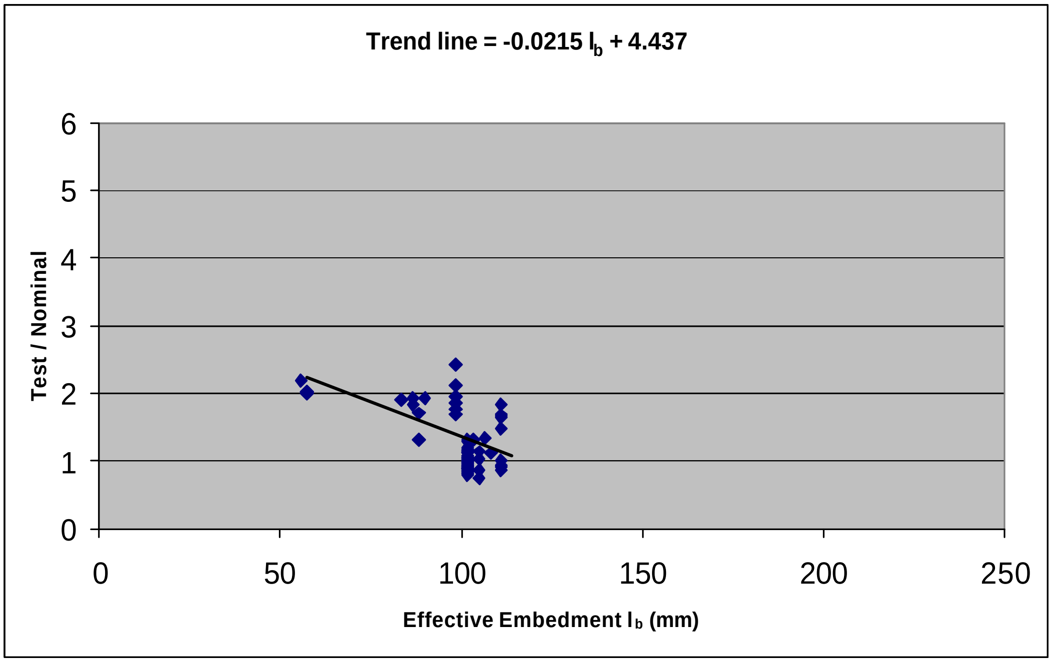

Figure 1 Concrete Masonry Tensile Breakout - 2002 MSJC

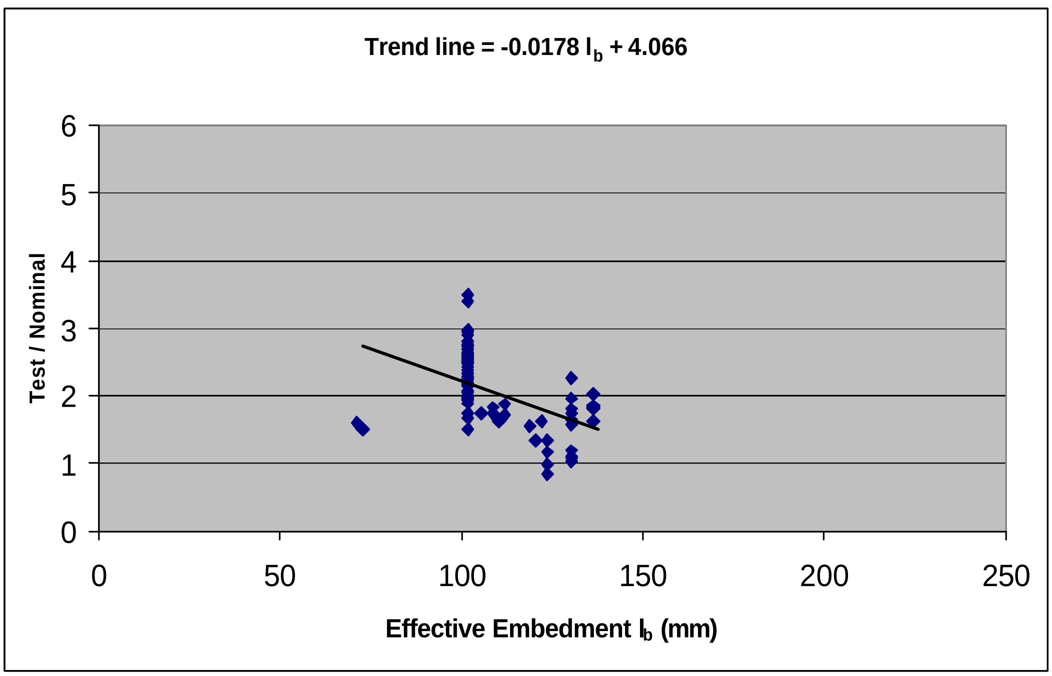

Figure 2 Concrete Masonry Tensile Breakout - ACI 318M-02

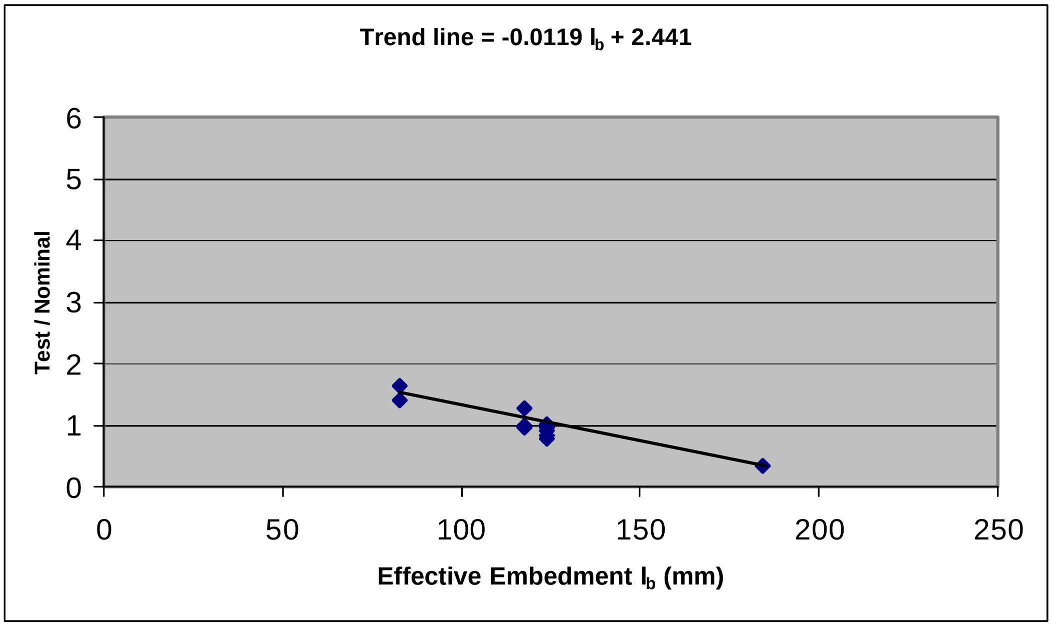

Figure 3 Clay Tensile Breakout - 2002 MSJC

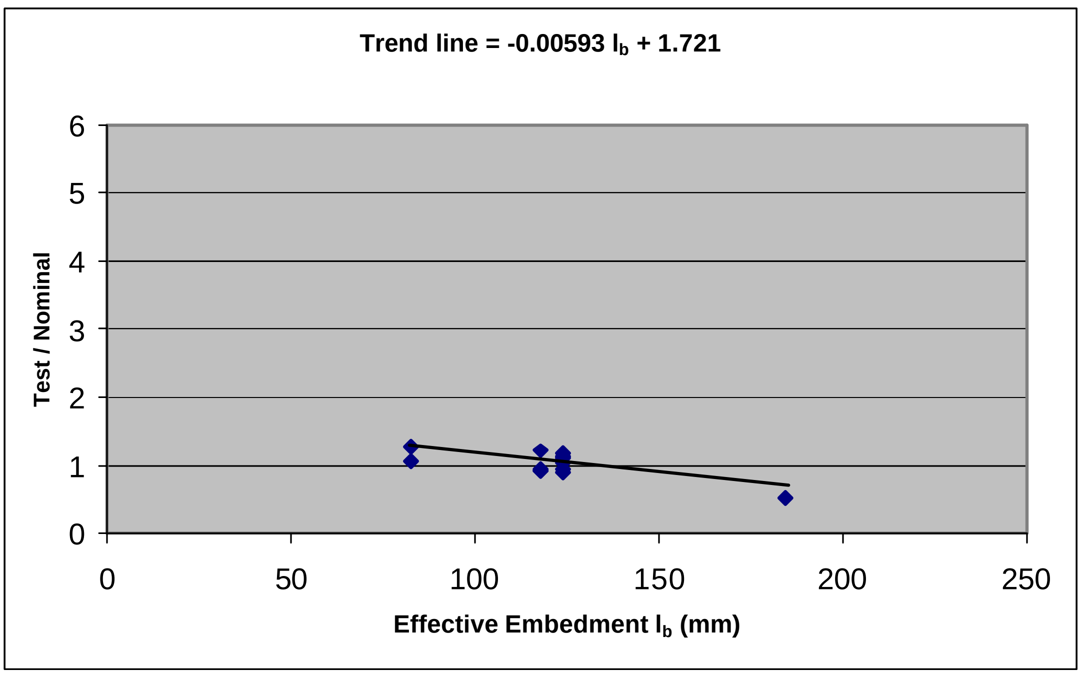

Figure 4 Clay Tensile Breakout - ACI 318M-02

Table 4 2002 MSJC Reliability Index for Non-ductile Fastening

Material and Failure Type	Probability Fastening Deficient	β
Concrete Tensile Breakout	0.0317	2.21

Clay Tensile Breakout	0.0186	2.09
Concrete Tensile Pullout	0.00442	2.62
Clay Tensile Pullout	0.0887	1.35

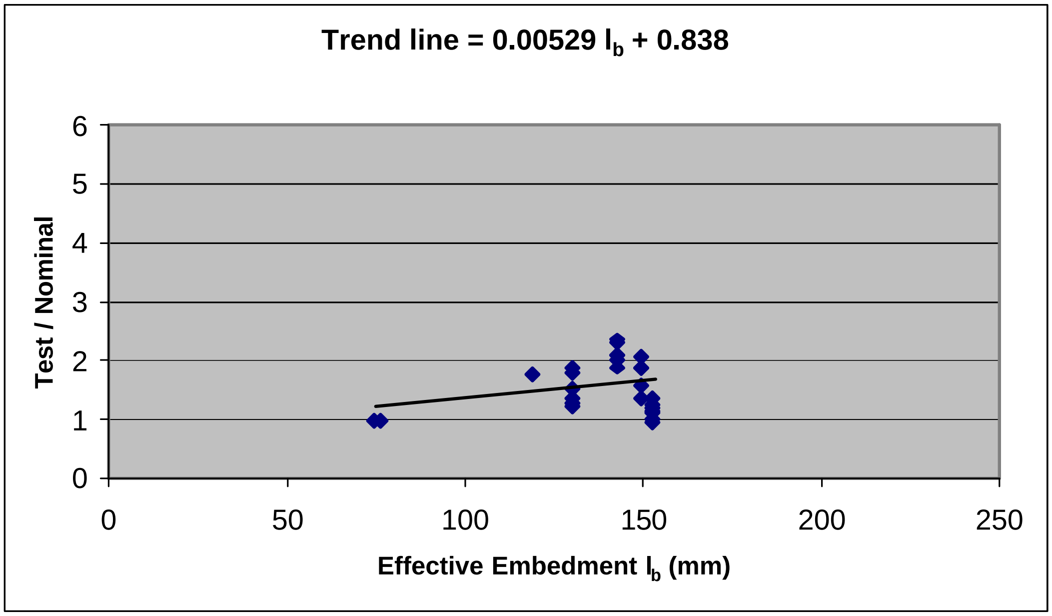

Figure 5 Concrete Masonry Tensile Pullout - 2002 MSJC

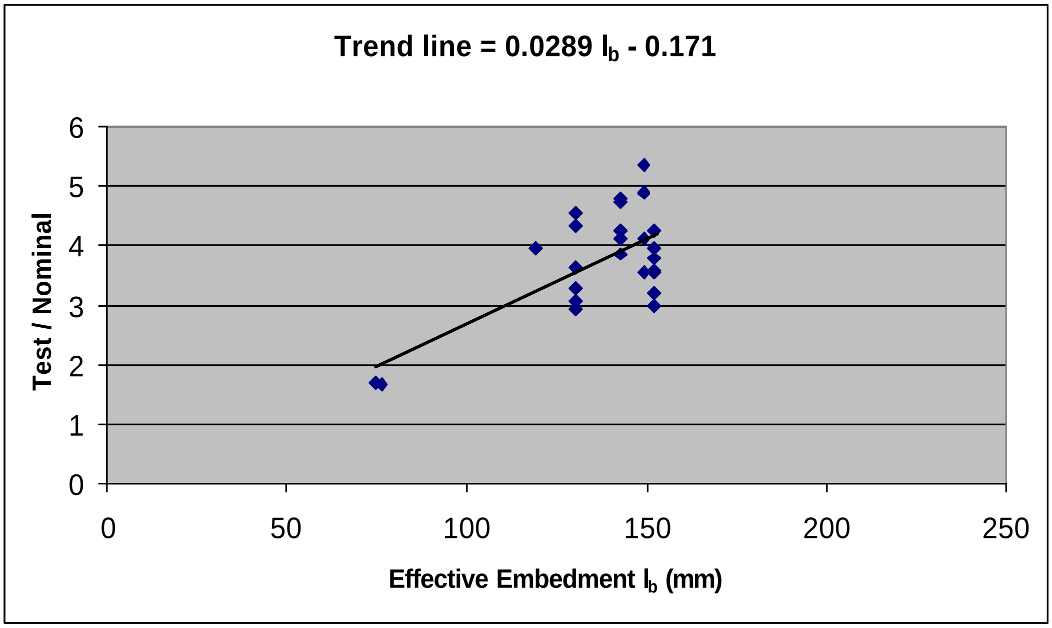

Figure 6 Concrete Masonry Tensile Pullout - ACI 318M-02

Table 5 2002 ACI 318M-02 Reliability Index for Ductile Fastening

Material and Failure Type	Probability Fastening	β

	Deficient	
Concrete Tensile Breakout	0.000617	3.23
Clay Tensile Breakout	0.000238	3.50
Concrete Tensile Pullout	0.00117	3.05
Clay Tensile Pullout	0.00611	2.51

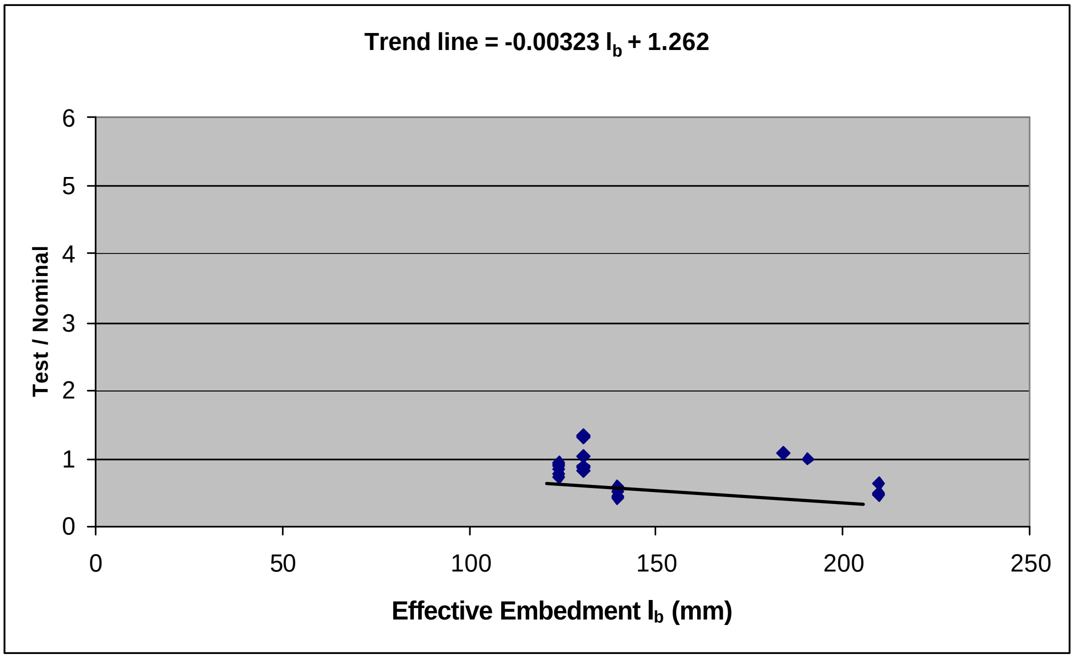

Figure 7 Clay Tensile Pullout - 2002 MSJC

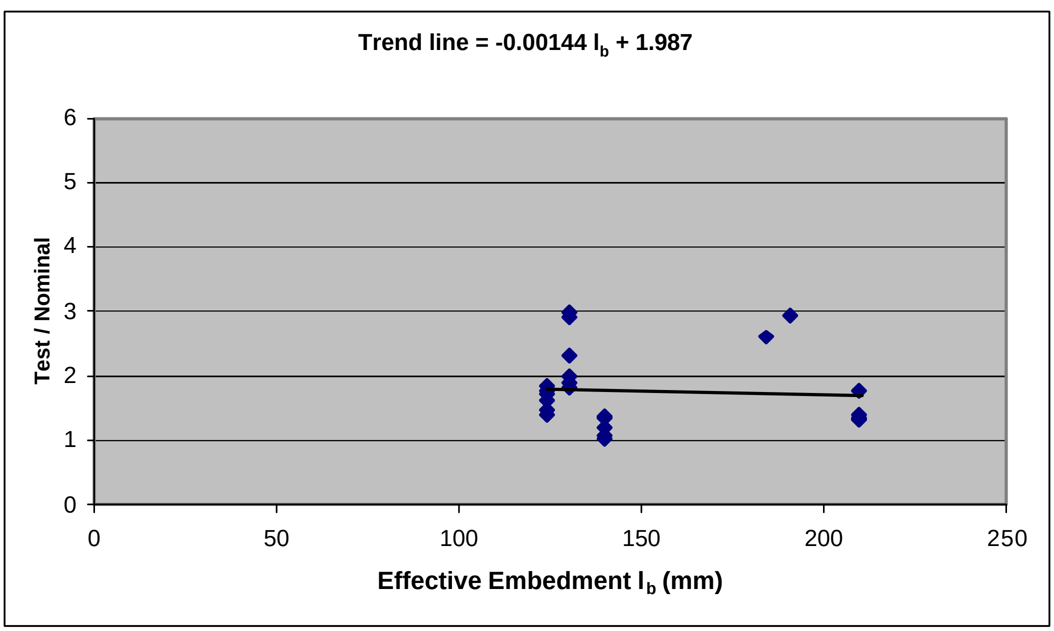

Figure 8 Clay Tensile Pullout - ACI 318M-02

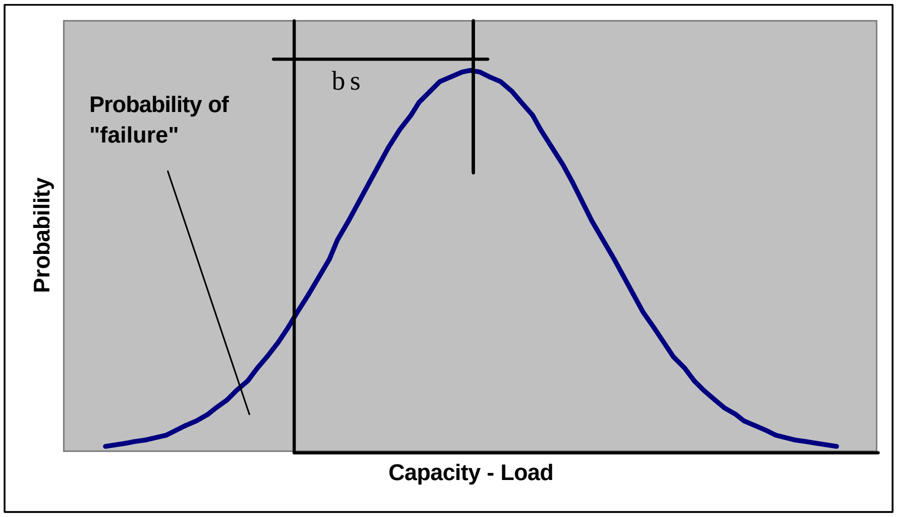

Figure 9 Reliability Index b

5 Conclusions

Results of this study show that in most cases currently available masonry fastening provisions exhibit significant bias and scatter. For some cases, 2002 MSJC fastener provisions produce design with low reliability. The relatively low number of data points is partially responsible for this condition. Additional testing and analysis must be done to overcome these problems.

6 References

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