



PERFORMANCE OF ANCHOR BOLTS IN CONCRETE MASONRY UNDER COMBINED TENSION AND SHEAR LOADING

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ABSTRACT

The objective of this research was to investigate the interaction behavior of anchor bolts in grouted concrete masonry under combined tension and shear loading. The behavior of anchor bolts under combined loading is not well understood, leading to current design procedures that incorporate a conservative linear interaction relationship.

For this project, combinations of tension and shear loads were applied to anchor bolts embedded in nominal 200-mm (8-inch) thick concrete-masonry walls. The anchors were J-bolts with a 19-mm (3/4-inch) diameter and 90° bends and were embedded to an effective embedment depth of 102 mm (4 inches), in accordance with MSJC-1999 and UBC-1997 specifications. The masonry walls were fully-grouted, unreinforced walls that measured nominally 1.0 meters (40 inches) square. In addition to pure shear and pure tension tests, a series of tests were conducted in which anchor bolts were loaded to a certain percentage of the average pure shear capacity and then simultaneously loaded in tension to failure. Similarly, in another series of tests, anchor bolts were loaded to a certain percentage of the average pure tensile capacity and then simultaneously loaded in shear to failure. A total of 64 anchor bolts were tested.

Results from this testing indicate that the interaction design curve should be altered from a linear interaction to an elliptical interaction. It is recommended that an elliptical interaction with exponents of 5/3 be used for the combined tension and shear loading of anchor bolts in concrete masonry. The elliptical interaction equation provides a more rational design basis and will allow designers to more efficiently use anchor bolts.

Key words: anchor bolts, concrete masonry, tension, shear, combined loading

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INTRODUCTION AND OBJECTIVES

Anchor bolts are often used in masonry construction. A common design situation is the loading associated with combined lateral and gravity loads, causing both tension and shear loading on the anchor bolt. This loading application can occur due to eccentrically-loaded anchors or during earthquakes, hurricanes, and other loading conditions that combine lateral loads with gravity loads. The behavior of anchor bolts under combined loading is not well understood, leading to the adoption of conservative design procedures in the past.

Current code provisions for the design of anchor bolts in masonry specify a linear interaction between design tension and design shear strengths (MSJC, 1999; ICBO, 1997; ICC, 2000). Limited test data from previous research suggests that the behavior of anchor bolts in masonry may follow an elliptical interaction line (Whitlock, 1983). Furthermore, test results for anchor bolts in concrete have resulted in an elliptical interaction relationship for tension/shear interaction (ICBO, 1997; ICC, 2000). Curvilinear interactions result in greater allowable anchor bolt strengths that can be utilized by the designer and may provide a more uniform margin of safety for all conditions of combined tension and shear loading.

The primary objective of this research was to obtain a better understanding of the interaction behavior of anchor bolts in grouted concrete masonry under combined tension and shear loading. A secondary objective was to determine whether there are differences in the tension/shear interaction behavior of anchor bolts when the shear loading is applied parallel to the bedjoint of the wall versus perpendicular to the bedjoint of the wall.

LITERATURE REVIEW

Anchor Bolts in Masonry

For combined tension and shear loading of anchor bolts in masonry, both working stress design (WSD), Equation 1, and strength design (SD), Equation 2, methods use a linear interaction between tension and shear design strengths. The WSD procedures are given in the Masonry Standards Joint Committee (MSJC-1999), Section 2.1.2.2.4, and the Uniform Building Code (UBC-1997), Section 2107.1.5.4 (MSJC, 1999; ICBO, 1997). The SD procedure is given in the UBC-1997, Section 2108.1.5.2 (ICBO, 1997).

$$\left(\frac{b_a}{B_a}\right) + \left(\frac{b_v}{B_v}\right) \leq 1.0 \quad (1)$$

$$\left(\frac{b_a}{\phi B_a}\right) + \left(\frac{b_v}{\phi B_v}\right) \leq 1.0 \quad (2)$$

Where:

b_a = total computed design tensile force on anchor bolt; in SD this is a factored force (same as b_{tu} in UBC) (N or lbs)

b_v = total computed design shear force on anchor bolt; in SD this is a factored force (same as b_{su} in UBC) (N or lbs)

B_a = design strength of anchor bolt in tension; in WSD this is an allowable load; in SD it is a nominal capacity (N or lbs)
 B_v = design strength of anchor bolt in shear; in WSD this is an allowable load; in SD it is a nominal capacity (N or lbs)
 ϕ = strength-reduction factor

Note that the SD procedures in the International Building Code (IBC-2000), Section 2108.6.4, use the same equation as for WSD because the ϕ -factors are already applied to the B_a and B_v terms (ICC, 2000).

WSD provisions in the MSJC-1999 incorporate a minimum factor of safety of five for “variability and the possibility that anchor bolts may be used in a nonredundant manner” (MSJC, 1999). Past test results show average factors of safety of approximately 8 to 9 (Whitlock, 1983; Tubbs, 1999), based on test results in which a failure cone develops in the masonry. If edge distances, center-to-center spacing between bolts, or embedment depths are limited, additional reductions in strength must be taken.

There is limited research pertaining to combined tension and shear loading of anchor bolts in masonry. Previous studies have primarily investigated monotonic and cyclic loading of the bolts in tension or shear, not both applied simultaneously. Provisions for combined tension and shear loading of anchor bolts in masonry have been established through past experience and through previous research by Whitlock (1983). A linear interaction is used for combined shear and tension loading in all United States masonry codes. However, previous test results have shown that this may be overly conservative. Whitlock (1983) proposed that this interaction line is elliptical, but he noted that additional testing was necessary to determine the most appropriate interaction relationship. However, the masonry code specification committees proposed that the straight-line interaction curve continue to be used since it provided simplicity and additional conservatism in the absence of extensive test data for establishing a curvilinear interaction relationship (MSJC, 1999).

Whitlock (1983) suggested Equations 3 and 4 for anchor strength under combined tension and shear loading. Equation 3 is for anchor strength based on masonry capacity and Equation 4 is for anchor strength based on steel capacity. These equations were based on those found in the 1971 Precast and Prestressed Concrete Institute (PCI) Design Handbook.

$$\left(\frac{b_a}{B_a}\right)^{4/3} + \left(\frac{b_v}{B_v}\right)^{4/3} \leq 1.0 \quad (3)$$

$$\left(\frac{b_a}{B_{as}}\right)^2 + \left(\frac{b_v}{B_{vs}}\right)^2 \leq 1.0 \quad (4)$$

Where:

B_{as} = design strength of the anchor steel in tension (N or lbs)

B_{vs} = design strength of the anchor steel in shear (N or lbs)

In Equations 1 - 4 there is no distinction between shear loading parallel to the bedjoint versus shear loading perpendicular to the bedjoint. However, past research for clay units has indicated that the shear capacity in the direction perpendicular to bed joints (vertical

loading) is higher than the shear capacity in the direction parallel to the bed joints (lateral loading) (Kelly et al, 1975).

Anchor Bolts in Concrete

Current code requirements for anchor bolts in concrete use an elliptical interaction for combined tension and shear loading. The WSD procedure, Equation 5, is given in the UBC-1997, Section 1923.1. The SD procedure, Equations 4 and 6, is given in the UBC-1997, Section 1923.3.4. Equations 5 and 6 are for anchor strength based on concrete capacity and Equation 4 is for anchor strength based on steel capacity.

$$\left(\frac{b_a}{B_a}\right)^{5/3} + \left(\frac{b_v}{B_v}\right)^{5/3} \leq 1.0 \quad (5)$$

$$\left(\frac{1}{\phi}\right) * \left[\left(\frac{b_a}{B_a}\right)^{5/3} + \left(\frac{b_v}{B_v}\right)^{5/3}\right] \leq 1.0 \quad (6)$$

McMackin, Slutter, and Fisher (1973) conducted research on headed steel anchor bolts in concrete under combined tension and shear loading. The bolts were tested in a series of loading combinations by varying the loading angle of the actuator. Angles included were 0° (pure tension), 30°, and 60°. There were multiple series of tests, including anchors with a full embedment depth of 178 mm (7 inches) and anchors with a partial embedment depth of 102 mm (4 inches). The partial embedment depth is comparable to that seen when using anchor bolts in masonry. The authors concluded that Equation 5 best represented the combined tension/shear interaction behavior of the anchor bolts with partial embedment, with the B_a term including a reduction for partial embedment of the anchor.

EXPERIMENTAL PROGRAM

For this study, anchor bolt specimens were cast into masonry walls constructed from nominal 200-mm by 200-mm by 400-mm (8-inch by 8-inch by 16-inch) ASTM C90 concrete masonry units. The units were obtained from a local block producer and selected from the same lot to provide uniformity. The blocks were arranged in running bond to form panels that were nominally 1.0 m by 1.0 m (40 inches by 40 inches). Local masons constructed the wall panels to ensure construction typical of that on an actual job site. Faceshell bedding with Type “S” mortar was employed throughout construction. High slump grout from a local ready-mix supplier was obtained for all walls. The anchor bolts consisted of cast-in-place bolts that were nominally 19-mm (¾-inch) diameter ASTM 307, grade C, J-bolts with a 90° bend. Bolts were purchased from a local hardware supplier. Slightly oversized holes were drilled through the faceshell of blocks prior to wall construction to accommodate the anchor bolts. Bolts were approximately centered in the cores and were placed at an effective embedment depth of 102 mm (4 inches). Spacing, edge distances and embedment depths were sufficient to provide full strength in accordance with code provisions.

Twenty-five wall panels were constructed, each containing four anchor bolts, resulting in

a total of 100 anchor bolts. However, during testing of some of the bolt specimens, cracks propagated through the masonry walls to untested bolts, resulting in unusable bolts. A total of 64 bolts were actually tested. Table 1 summarizes the details of the test specimens.

Table 1: Testing Matrix

Percent Tension	Percent Shear	Number of Specimens	Load Direction Relative to Bed Joints
100	0	10	
0	100	10	parallel
failure	25	5	parallel
failure	50	5	parallel
failure	75	5	parallel
50	failure	2	parallel
0	100	5	perpendicular
100	0	5	
0	100	5	perpendicular
failure	25	1	perpendicular
failure	50	5	perpendicular
failure	75	1	perpendicular
75	failure	5	perpendicular

Total bolts tested = 64

Material Properties

The average measured yield and ultimate strengths for the anchor bolts were 465 MPa (67 ksi) and 540 MPa (78 ksi), respectively. Following ASTM standard procedures, samples of the grout and mortar used to construct the wall panels were collected and tested. The resulting net average ultimate compressive strengths of grout and mortar were 53 MPa (7600 psi) and 22 MPa (3100 psi), respectively. In addition, seven grouted masonry prisms were fabricated at the time of construction. The average compressive strength of the prisms was 20 MPa (2900 psi).

Test Setup

All pure shear and pure tension tests conformed to ASTM E 488 (1996). Test procedures for combined loading were developed based on the procedures in ASTM E 488. Wall panels were laid flat on a pallet. For all tests, hydraulic actuators were used to apply the loads to the anchor bolts. Actuators were positioned such that the axis of the actuator was coincident with the centroidal axis of the bolt.

For all testing, the bolt was attached to each actuator by steel fixtures that conformed to ASTM E 488 specifications. Details of the attachment between the actuators and the anchor bolt can be seen in Figure 1. A hinge was provided at the end of each hydraulic actuator to minimize any load contribution on the bolt from friction.



Figure 1: Details of the Attachment Between the Actuators and the Anchor Bolt

For this project, two actuators were employed to apply combined loading on the anchor bolts, one loading the bolt in pure tension and the other loading the bolt in pure shear. The average pure tension and pure shear capacities of the embedded anchor bolts were found for a representative sample of the anchor bolts. These capacities were used as a basis for the combined loading of anchor bolts. For example, in one set of the combined loading tests, the bolts were loaded in shear to a chosen percentage of the average pure shear capacity. The shear load was held approximately constant and the tension actuator simultaneously loaded the bolt in tension to failure. The process was repeated for various percentages of pure shear capacity and for various percentages of pure tension capacity. Fifteen bolts were tested in pure tension. Twenty-seven bolts were tested in which the shear load was applied parallel to the bedjoint to the units. Twenty-two bolts were tested in which the shear load was applied perpendicular to the bedjoint of the units.

Loading was applied at an approximately constant displacement rate until failure was achieved either in the form of significant masonry cracking, bolt failure, or significant drop in load resisted by the actuator. Load rate was selected so that the failure would occur between one minute and three minutes. The test setup for combined loading can be seen in Figure 2.

A representative “Time versus Load” curve for a combined loading test can be seen in Figure 3. The top line represents a shear load that was held approximately constant while a tension load (the lower line in the plot) was simultaneously applied. Tension load was increased until failure of the anchor. For the test represented in Figure 3, the anchor bolt was loaded in shear to 50 percent of the average pure shear capacity then loaded in tension to failure. Fifty percent of the average pure shear capacity of the bolt was 34.6 kN (7.8 kips). The tension capacity of the anchor under combined loading was 39.5 kN (8.9 kips).

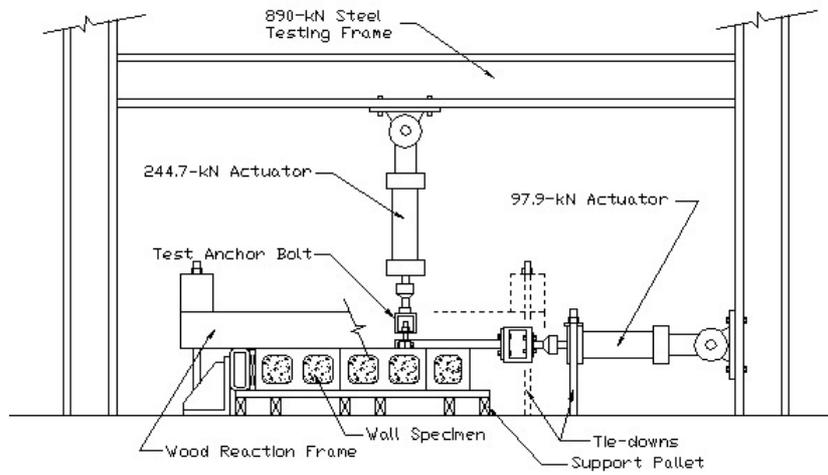


Figure 2: Combined Tension and Shear Test Setup

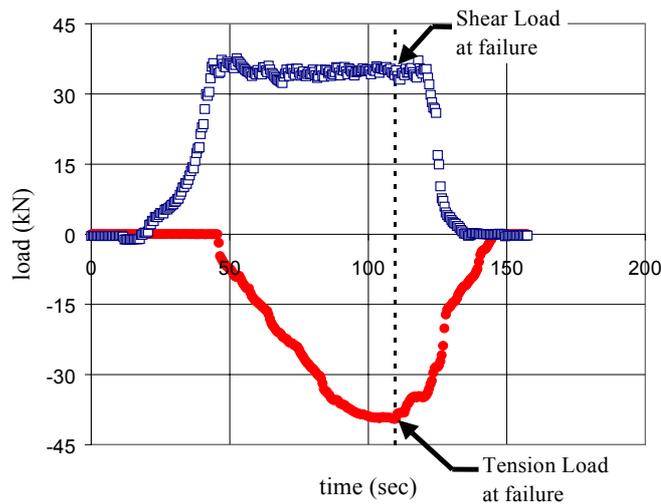


Figure 3: Time Versus Load Curve for a Typical Anchor Bolt Test

RESULTS

Table 2 shows the percentages of average pure load capacities resisted by the anchors under various combinations of tension and shear loading for each series of tests. A majority of the anchors (56 out of 64 total anchors) failed due to radial cracking in the block propagating from the anchor. An anchor bolt that failed by radial cracking can be seen in Figure 4. Only one anchor failed by steel failure. Some of the anchors started to pull out of the block by straightening of the hook at the end of the bolt, as shown in Figure 5. This happened in 13 out of 15 of the pure tension tests. Straightening of the anchor bolt was also seen in combinations of tension and shear loading that approached pure tensile load (e.g., 25% average pure shear capacity, tension loaded to failure and

Table 2: Summary of Test Results

Direction of Loading	Series	Number of Tests	Percent of Pure Shear Capacity	Percent of Pure Tension Capacity
Parallel to Bedjoint	Pure Tension	10	0	100
	Pure Shear	10	100	0
	50% Shear	5	46	76
	25% Shear	5	23	89
	50% Tension	2	80	50
	75% Shear	5	69	69
Perpendicular to Bedjoint	Pure Tension	5	0	100
	Pure Shear (Phase 1)	5	100	0
	Pure Shear (Phase 2)	5	100	0
	50% Shear	5	48	88
	75% Shear	1	71	71
	75% Tension	5	50	78
	25% Shear	1	24	93



Figure (4): Radial Cracking



Figure (5): Straightening of a Bolt

75% average pure tension capacity, shear loaded to failure). All but one of these pullouts occurred in conjunction with other failure modes. Other failure modes observed included crushing/spalling of the block around the anchor, yielding of the anchor steel, cracking of

block parallel or perpendicular to the load, and tension failure cone formation. In order to normalize this test data to compare the results with various prediction models on a consistent basis, the shear data points were non-dimensionalized by taking the actual shear load at failure (V) and dividing it by the average pure shear capacity (V_u), resulting in an x-coordinate of (V/V_u). Similarly, the actual tension loads at failure (T) were divided by the average pure tension capacity (T_u), resulting in a y-coordinate of (T/T_u). The average pure shear loads corresponded to the direction of loading, either parallel or perpendicular to the bedjoint.

DISCUSSION OF RESULTS

Equation 7 represents the current allowable interaction curve for combined tension and shear loading of anchor bolts in masonry. Equation 8 represents the suggested interaction curve from Whitlock (1983) based on masonry capacity. Equation 9 represents the current allowable interaction curve for combined tension and shear loading of anchor bolts in concrete based on concrete capacity. Equation 10 represents the interaction curve suggested based on steel capacity (Whitlock, 1983, Salmon and Johnson, 1996, and Segui, 1999). The four interaction curves are superimposed with the non-dimensionalized data from this study in Figure 6.

$$\left(\frac{T}{T_u}\right) + \left(\frac{V}{V_u}\right) = 1.0 \quad (7)$$

$$\left(\frac{T}{T_u}\right)^{4/3} + \left(\frac{V}{V_u}\right)^{4/3} = 1.0 \quad (8)$$

$$\left(\frac{T}{T_u}\right)^{5/3} + \left(\frac{V}{V_u}\right)^{5/3} = 1.0 \quad (9)$$

$$\left(\frac{T}{T_u}\right)^2 + \left(\frac{V}{V_u}\right)^2 = 1.0 \quad (10)$$

In order to evaluate the fit of the data to the various equations a statistical analysis was performed. The elliptical interaction curve with a 5/3 exponent best represents the data. The linear line is the most conservative representation of the data. The coefficient of determination (R^2) value for the linear interaction was 0.77, for the elliptical interaction with a 4/3 exponent the R^2 was 0.81, for the elliptical interaction with an exponent of 5/3 the R^2 value was 0.83, and for the circular interaction the R^2 value was 0.79.

The ability of the linear and elliptical relationships to predict strengths was evaluated by projecting a line from the origin of the tension/shear interaction diagram (Figure 6) through each data point, with the length of this radial line representing the test strength under combined loading. The point at which this radial line crossed the interaction equation line was also found and defined as the predicted strength value. A ratio of 1.00 indicates that the interaction equation accurately predicts the observed anchor bolt

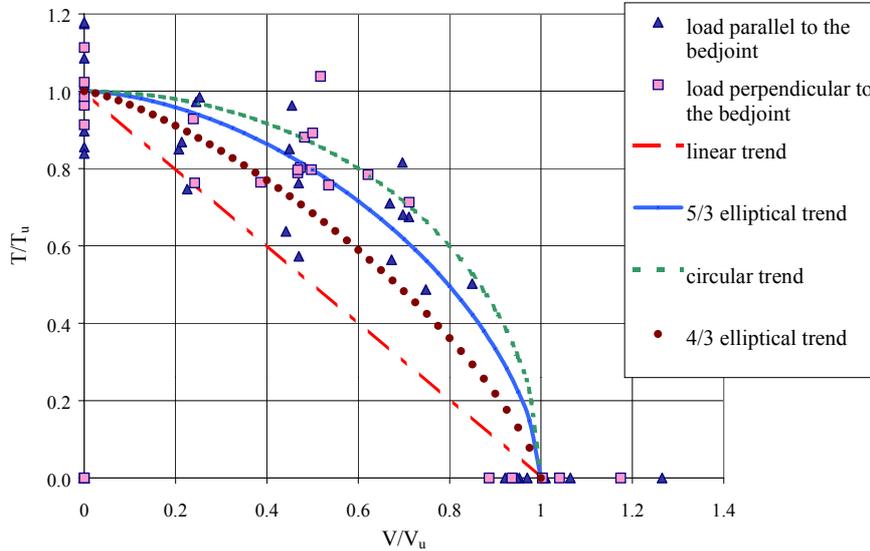


Figure 6: Plot of All Data Points With Superimposed Interaction Curves

performance, while ratios under 1.00 overpredict the observed anchor bolt performance. The test strength to predicted strength ratios are summarized in Table 3.

Table 3: Test Strength to Predicted Strength Ratios

		Pure Tension	25% Shear	50% Shear	75% Shear	75% Tension	50% Tension	Pure Shear
linear	average	1.00	1.12	1.29	1.39	1.28	1.29	1.00
	max	1.18	1.51	1.56	1.51	1.41	1.35	1.27
	min	0.84	0.97	1.04	1.24	1.15	1.24	0.89
elliptical	average	1.00	0.95	1.00	1.05	0.99	1.00	1.00
	max	1.18	1.05	1.22	1.15	1.07	1.05	1.27
	min	0.84	0.81	0.79	0.94	0.90	0.95	0.89

From Table 3 it is evident that the elliptical equation with the 5/3 exponent provides a more accurate and consistent prediction of strength for the various combinations of tension and shear. The linear interaction equation under-predicts test strengths and the ratios vary for the combinations of tension and shear. Both equations have some ratios of actual to predicted strength slightly under 1.00. However, the MSJC-1999 applies a safety factor of five to determine allowable tension and shear anchor bolt capacities in masonry, producing a conservative design for all loading combinations.

The proposed interaction curves are compared to data that has been non-dimensionalized using average pure tension and pure shear capacities. The average pure tension and pure shear capacities are used as a baseline. Therefore an appropriate interaction curve for combined tension and shear should similarly fall on a mean trend line. Approximately half of the data is located above and half of the data is located below the elliptical

interaction equation with an exponent of $5/3$. In contrast, nearly all of the data is located above the linear interaction equation.

The MSJC-1999 recognizes a curvilinear interaction behavior, but “for simplicity and conservatism” a straight-line interaction between allowable tension and shear strengths is currently required. This research project has contributed substantial data on combined loading of anchor bolts in masonry that supports the use of the elliptical interaction with an exponent of $5/3$ for the design of anchor bolts under combined tension and shear. With easy access to calculators, computer programs and spreadsheets to perform calculations, curvilinear design equations are just as easy to use as linear equations. This should no longer be a reason to maintain the linear interaction relationship.

The average pure shear capacity of the bolts was 8 percent higher in the tests with the shear loading perpendicular to the bedjoint versus with the shear loading parallel to the bedjoint. This slight increase is consistent with previous data (Kelly et al, 1975). However, when the direction of shear loading was changed between loading parallel to the bedjoint and loading perpendicular to the bedjoint, the non-dimensionalized tension/shear interaction behavior remained essentially the same. Therefore, a single tension/shear interaction equation appears to be sufficient to address all shear loading directions.

CONCLUSIONS

An elliptical interaction with a $5/3$ exponent, Equation 9, provides a better representation of the actual behavior exhibited by the combined tension and shear loading of an anchor bolt in masonry than the current linear interaction equation. The linear interaction is unnecessarily conservative, resulting in inefficient utilization of anchor bolts. An elliptical interaction will make it possible for designers to design for higher allowable bolt strength when bolts are subjected to combined tension and shear loading. Furthermore, an elliptical interaction will apply a more consistent factor of safety for various combinations of tension and shear.

Combined tension and shear loading parallel to the bedjoint does not result in different interaction behavior than combined loading perpendicular to the bedjoint. Therefore a single tension/shear interaction equation is sufficient to address all shear loading directions.

From this research it is recommended that an elliptical interaction with a $5/3$ exponent, Equation 5, be used for the design of combined tension/shear interaction for anchor bolts in concrete masonry. The elliptical interaction equation utilizes a more rational design basis and will allow designers to more efficiently use anchor bolts.

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