Structural Practices

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Mechanical Anchor Strength in Stone Masonry

By Kelly Streeter, P.E. and Keith Luscinski

Mechanical anchor systems are commonly installed in historic masonry materials despite the lack of manufacturer-specified design values for this type of substrate. Scaffolding lateral supports, signage installations and telecommunication mounting systems all use these mechanical fasteners in natural stone materials.

The current lack of codes, guidelines or recommendations for tensile and shear design criteria in historic masonry materials leaves structural engineers to improvise the design and specification of these anchors. Guidelines such as *Appendix A, Guidelines for Seismic Retrofit of Existing Buildings* in the International Existing Building Code (IBC), ASTM Standard *E488-96: Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements* and *Acceptance Criteria for Expansion Anchors in Concrete and Masonry Elements* [ICC Evaluation Services 2005] are only relevant to concrete and brick masonry. Although field-testing is employed for some projects, more commonly an arbitrary reduction of the ultimate strength is used when designing these elements for use in natural stone. The creation of an empirical design equation for these values is arduous because, unlike concrete and concrete masonry units, historic building stone units are not manufactured materials, and their physical properties such as density and compressive strength vary from quarry to quarry and within quarry strata.

The primary method for determining design values is a factor of safety approach. Factors of safety are divisors that are applied to the experimental average ultimate strength to allow for field conditions that invariably differ from a well-controlled laboratory environment. Currently, the factor of safety recommended for the design values in both shear and tension for both anchor types used in concrete is 4.0.

A statistical COV (Coefficient of Variation) method is being considered as a change in approach, as methods in Strength Design of masonry becomes more widely used. The Coefficient of Variation for Mechanical Anchors is listed as between 10 – 15% [Powers Fasteners 2005].

Methods and Materials

The first task of this study included an online survey of the preservation engineering community, titled *The Engineering Judgment Survey*. A simple design problem was presented, asking for the selection of design values for a hypothetical installation.

The laboratory portion of the study was designed as a screening experiment to evaluate a reasonably large number of variables (*Figure 1*) in order to determine which factors influence the response – in this case, the ultimate strength of the anchor installations.

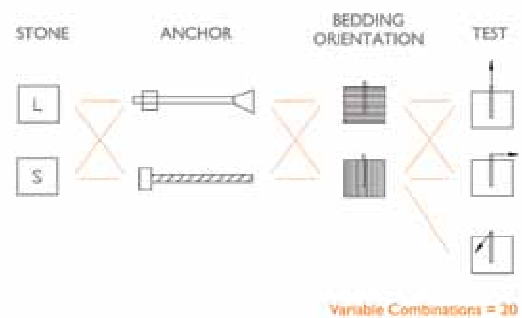

Figure 1: Test specimens and variables.

The primary (control) variables examined were:

1) type of stone (L=limestone; S=sandstone)
2) orientation of bedding planes
3) type of anchor
4) type of test: tension or shear

The secondary (measured) variables were:

1) pulse velocity (all specimens)
2) compression tests (limited specimens)
3) failure mode (all specimens)

Type of Stone

The study utilized 10-inch cubes of both Ohio Sandstone (S) and Indiana Limestone (L), prepared and donated by Old World Stone in Burlington, Ontario. Each specimen was examined and marked with a unique specimen number, and each face was marked to control the bedding orientation during comparison of anchor strength as a function of stone "grain".

Bedding Orientation

The orientation of the stone bedding plane relative to the axis of the bolt installation is a significant variable. Unlike concrete, limestone and sandstone are anisotropic materials and the anchors perform differently when installed in different orientations.

For the tension tests, there are only two unique bedding orientations to study: perpendicular and parallel to the bolt installation. However, for the shear tests there are three different combinations of bedding orientation and pull direction to record.

Type of Anchor

One mechanical anchor was installed in the center of each face of each block following the manufacturer's instructions for their installation in concrete. While a specific manufacturer's anchors were used in this study, the methodology can be applied to other anchors. Powers Wedge-Bolt anchors (*Figure 2*) were installed

Figure 2: Wedge-Bolt (left) and Power-Stud (right).

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Figure 3: Tension failure modes: large cone (left) and bolt fracture (right).

with an embedment length of 2⅛ inches for the tension tests and 2¼ inches for the shear tests, following the minimum embedment recommendations listed in the specifications [Powers Fasteners 2005]. Powers Power-Stud anchors (*Figure 2*) were installed with an embedment length of 2 inches for both the tension and shear tests.

Before any anchors were placed, pitch-catch Ultrasonic Pulse Velocity (UPV) measurements were taken through the stone cubes along all three perpendicular axes. UPV may be used in concrete to nondestructively determine compressive strength and help to determine anchor installation strength. Although there are no ASTM documents describing the relationship between UPV and compressive strength in natural stone, the goal was to determine the value of studying this variable in future research as a potential indicator of mechanical anchor installation strength.

Engineering Judgment Survey Results

The Engineering Judgment Survey showed that structural engineers tend to be extremely conservative when designing these anchors in tension and shear – probably due to the large variation of compressive values between and within types of natural stone. Even though the commonly accepted minimum Indiana Limestone compressive strength value is 4,000 psi [Indiana University], the designers were more likely to use the 2,000 psi concrete design value available from the anchor manufacturers. This is even more surprising in sandstone: with an accepted average compressive strength of approximately 10,250 psi [Richardson 1917], engineers were again more likely to use the 2,000 psi value.

The only method to accurately determine compressive strength of stone is destructive, which is not an option in many cases involving historic structures. Therefore, the study investigated whether available nondestructive methods could be used to predict the compressive strength of the samples in a controlled laboratory environment. This methodology could ultimately increase the confidence of structural engineers in the field, allowing them to use more realistic values and therefore fewer anchors when designing these installations.

Experimental Results

Failure Modes: Tension

The number of different tensile failure modes observed in the laboratory was unexpected, and presented another significant variable to track and analyze. In addition to the more classic failure modes of large cone failure and bolt fracture (*Figure 3*), four other failure modes were observed.

Figure 4 displays four of the unexpected failure modes: small cone failure (a combination of partial pull out and then cone failure), cube splitting, face delamination and bolt pull out. The varied failure modes had a significant impact on the analysis of the data, especially for the tension specimens.

Ultimate Tension Results

The results demonstrate, with just two exceptions, that the average ultimate tension strengths of Power-Studs and Wedge-Bolts in both stone types exceed the published design strength of these bolts in 4000 psi concrete. The predominant failure mode in sandstone varies by bedding orientation, with face delamination being the most common when the bolts were installed perpendicular to the bedding plane. Cube splitting and large cone failure were more common when the bolts were installed parallel to the bedding plane of the sandstone.

The failure modes were more varied among the limestone blocks. In the Power-Stud limestone specimens, bolt failure was the most common, with the bolts breaking at the threads. The anchor-to-limestone bond exceeded the material strength of the anchor in 19 of the 24 samples. In contrast, only 2 of the 17 Power-Stud sandstone samples tested developed full strength of the anchor. In other words, the block failed first. It is not clear why this occurred; given sandstone's greater compressive strength, we wouldn't expect to see substrate-based failure in such a large number of specimens.

Overall, the Power-Stud seems to be an excellent choice for limestone installations loaded

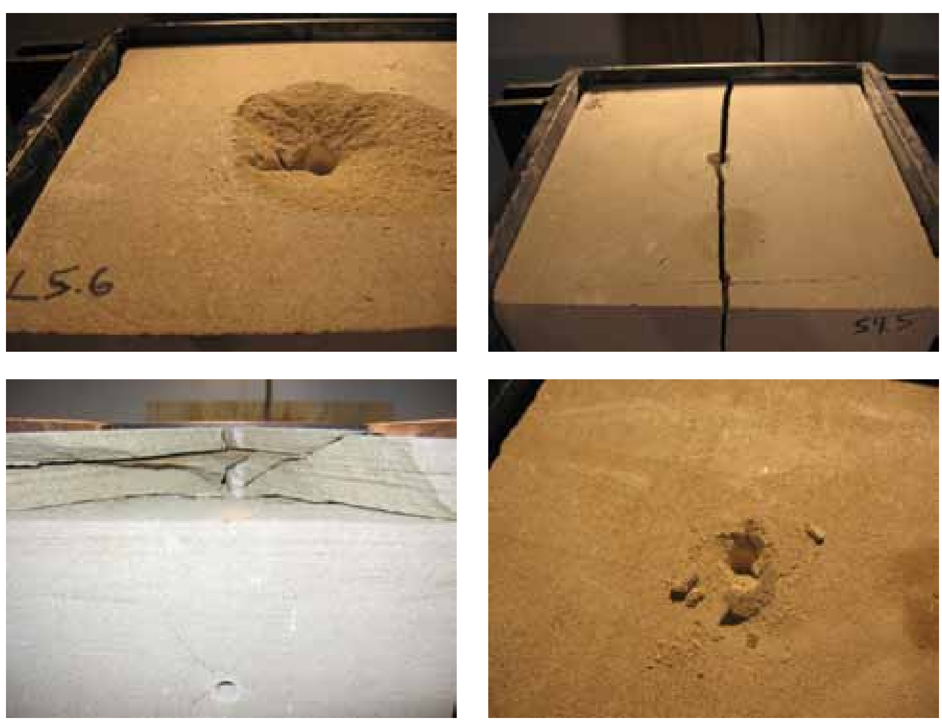

Figure 4: Tension failure modes: small cone (upper left), cube splitting (upper right), face delamination (lower left), anchor pull-out (lower right).

Figure 5: Sandstone specimens that failed by cube splitting.

in tension, regardless of bedding orientation. In sandstone, however, the Wedge-Bolts exhibited greater ultimate strength with lower variability between tests.

Regardless of the observed failure mode, these results suggest that the published design values for installation in 4,000 psi concrete are appropriate, and in some cases conservative, for all variable combinations tested. These test results indicate that use of 2,000 psi concrete design values in Indiana Limestone and Ohio Sandstone is overly conservative.

Ultimate Shear Results

The Engineering Judgment Survey responses and the lab results for the shear tests showed an equally conservative tendency to underestimate the ultimate shear capacity of the anchors. With the exception of two specimen configurations, the laboratory data demonstrated that the ultimate shear strength of the bolt installations exceeds the published design values in 6,000 psi concrete, whereas the engineers surveyed chose to use the 2,000 psi concrete published.

From the tests in both limestone and sandstone, the Wedge-Bolt is the superior choice over the Power-Stud for bolt installation in shear, with ultimate shear values exceeding the 6,000 psi concrete design level in every installation. As expected, the Wedge-Bolts provide much greater shear strength – in some cases two or three times greater than the Power-Stud. This trend is consistent with the higher published ultimate shear values of the Wedge-Bolts in concrete.

Compressive Strength

The destructively-determined compressive strength of the stone is a good predictor of bolt failure in tension in the limited number of tests performed. The selection of specimens to be tested destructively was based on the commonality of the variables, including failure mode, which greatly limited the sample size of compressively tested specimens. Destructive testing was not performed on any shear test samples due to budget constraints.

Destructive testing of historic materials is obviously best avoided whenever possible; therefore, ultrasonic pulse velocity and Schmidt hammer tests were also employed, with the hope that they would have some predictive value in determining ultimate anchor strength.

The pulse velocity data showed promise for further research in attempting to predict ultimate tension and shear installation strengths regardless of bolt and stone type. The next step for further research is to study limestone and sandstone samples from different sources with compressive strengths that vary over a larger range. The resulting data would likely increase confidence in the apparent linear and possibly predictive trends.

The Schmidt hammer results did not have any predictive value for any documented variable. The surface hardness of natural stone, as tested using the Schmidt hammer test, does not appear to be an accurate measure of the compressive strength of the sample.

Conclusions

The Engineering Judgment Survey confirms that engineers tend to be overly conservative when designing post-installed mechanical anchors in natural stone materials when a testing program is not feasible.

The overall performance of the anchors in limestone and sandstone was very promising. In tension, the Power-Stud proved to be an excellent choice for both Indiana Limestone and Ohio Sandstone installations, with capacities exceeding the 6,000 psi concrete designated values. For shear, the Wedge-Bolts exceeded the 6,000 psi concrete design values in all Indiana Limestone and Ohio Sandstone installations, regardless of bedding orientation and pull direction.

Experimental Design Drawbacks

The main flaw in the experimental design of the research was the use of such small stone cube samples. The decision to use the 10-inch samples size was driven primarily by a desire to maintain critical edge distances while maintaining manageable sample sizes.

Although the minimum edge distances were maintained by using 10-inch cubes, the published ultimate strengths of the anchors in concrete do not mention the case where those critical edge distances are realized in all four directions – an unlikely condition in the field. As illustrated by the photos in *Figure 5*, edge distances did determine the failure mode observed on several samples. If edge distances had been greater, it is anticipated that a different failure mode and higher ultimate strength values would be realized in the samples where cube splitting was observed. This would have increased the sample size of meaningful data.▪

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