The Effects of Hole Cleaning on Post-Installed Anchor Systems in Concrete

A Major Qualifying Project proposal to be submitted to the faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the Degree of Bachelor of Science.

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Abstract

This project aimed to confirm the relationship between installation technique and anchor performance according to HILTI specifications. Controlled testing was performed in order to collect sufficient data to accurately determine a relationship. Testing results were used to predict anchor performance and impact of installation errors.

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We would like to acknowledge the following people for their support and contributions to the project:

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1 Introduction

Post installed anchors are used in construction to facilitate the connection of structural elements to existing cured concrete. One notable use of post-installed anchors is in the Big Dig, where concrete panels were suspended from the ceiling as part of the tunnel ventilation system. A catastrophic failure of the anchors resulted in the release of three ton concrete ceiling panels into lanes of traffic. The National Transportation Safety Board investigated the incident and concluded that "*…that the probable cause of the July 10, 2006, ceiling collapse…was the use of an epoxy anchor adhesive with poor creep resistance, that is, an epoxy formulation that was not capable of sustaining long-term loads.* This is cause to examine post-installed anchoring systems and how the installation process affects the performance of the anchor and potentially public safety.

HILTI offers many anchoring systems. Although HILTI anchor systems were not used in the Big Dig their systems will be used to analyze the effect of the installation process and creep resistance. During the examination of HILTI post installed anchor systems, different types of anchors were reviewed. The investigation of the installation process will occur through controlled laboratory testing and observation. HILTI offers five different adhesive systems and more than half a dozen mechanical systems for specific conditions.

The anchoring systems offered by HILTI were designed to connect objects to concrete after curing. The adhesive systems provide a permanent anchor while some of the mechanical systems provide an anchor but can also be removed if only needed for temporary use or use in cracked concrete. The adhesive systems will be the primary focus in this project.

2 Background

2.1 Concrete Base Material

Since this project examined the effects of proper drill hole cleaning on post-installed anchors set in concrete, some properties of concrete were taken into consideration. Although these characteristics were useful to their application, they also had an effect on how well an anchor performed.

The sample's strength can affect anchors by determining how a given anchor system will fail. For example, a failure in low strength concrete will be more likely to result in a conical concrete blow out. Similarly, a high strength concrete will have a higher tendency to exhibit ductile fracture or pull-out. This concept can be utilized to minimize damage and costs in the event of a failure. Depending on the situation, it may be more beneficial to replace a bolt, rather than a concrete structure.

2.2 Loadings

Before an effective anchor bolt can be designed, it is crucial to know the magnitude and type of all loads that it will be expected to withstand. Due to the variety of proprietary and application specific bolts, the type of loads must be known first in order to achieve the desired outcome.

2.2.1 Static Loads

Static loads are forces that are constantly being applied to the structure and anchor. The major source for static loads is the weight of the actual structure and how it is distributed throughout its connections. These loads are present in virtually every structure and must be accommodated. The loads are fairly predictable once construction materials, material weight, and quantities are known.

2.2.2 Dynamic Loads

Determining dynamic loads is more involved than determining static loads. First off, dynamic loads develop from different sources which include environmental factors and human interaction. Second, they can be of varying magnitude as well as location. Environmental loads can be a result of wind, snow, seismic activity and other forms of weather. These can be calculated by analyzing historic trends and known extremes.

Once the anticipated loads have been determined and the structural elements designed, it is time to look at how these loads will be carried to the different anchors and connections. With regard to anchors, the loads will result in primarily tension and shear forces, which are explained in more detail below. These forces are crucial in determining anchor design because they are ultimately what the anchor will need to resist.

2.3 Types of Anchoring Systems

Many types of anchors that have been developed have distinct advantages and disadvantages. Most anchors can be classified into two main categories: cast-in-place and post-installed. Anchors are placed in the appropriate category based on the time of installation. Cast-in-place anchors are installed prior to concrete pouring, so that they are correctly positioned when the concrete hardens. Post-installed anchors are installed after the concrete has cured.

2.3.1 Cast-in-Place

Cast-in-place anchors refer to anchors that are set in concrete during the initial construction. They are positioned either before the concrete is poured or before it has fully hardened. There are several types of cast-in-place anchors which are suitable in various applications, as shown in Figure 1.

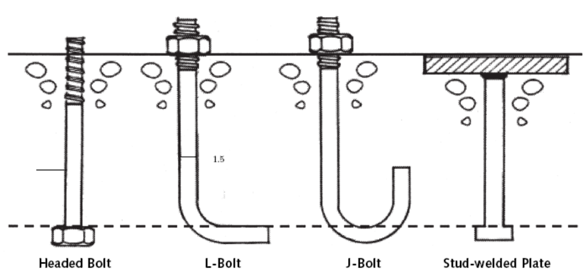


Figure 1: Cast-in-place Anchors

Engineers must know the design specification of the bolt before construction in order to use cast-in-place anchors. There is the possibility that the anchor can be placed in the wrong location during construction, resulting in delayed construction time and loss of money. They also limit design changes that may be needed.

2.3.2 Post-Installed

There are two main categories of post-installed anchors, mechanical and adhesive. Both types of anchors are installed into concrete that has already cured. Since the anchors are installed after the concrete has cured this allows for a more flexible design. More will be explained about post-installed anchors in the following sections.

2.4 Working Principles

Since mechanical and adhesive anchors transfer load in different ways, the working principles on post-installed anchors must be examined. Each anchor utilizes a combination of these principles in a unique way that is designed for a specific use. In order to select an appropriate anchor it is necessary to understand how the anchor secures itself to the base material.

2.4.1 Bonding

Bonding is the process by which a threaded rod is placed into a hole which has been drilled in concrete and secured with a structural adhesive. The adhesive typically consists of a two-part epoxy, polyester or vinylester system which must be mixed prior to installation. Since the load is carried through the bonding agent along the length of the rod, the anchor's capacity is directly related to the embedment depth. Figure 2 gives a visual representation of the how bonding between an adhesive and concrete transfers a load. The difference in diameter between the hole and rod is also important because the adhesive used may have a specific drill hole diameter relative to the rod diameter where performance is highest.

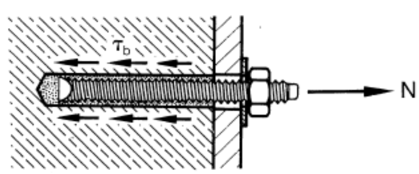


Figure 2: Illustration of Bonding Forces

2.4.2 Friction

Expansion anchors use friction between the anchor and concrete transfer load. Friction occurs when expansion causes the sleeve of a mechanical anchor to expand and press against the side walls of a drill hole as shown in Figure 3. The resistance created by the frictional force transfers the load from the anchor to the concrete. The expansion stresses generated by the anchor corresponds to the frictional force that is created, which dictates the capacity of the anchor. (Hilti, 2006)

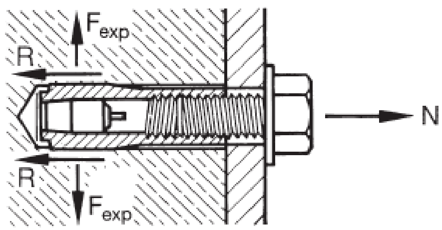


Figure 3: Illustration of Friction Forces

2.4.3 Keying

Keying is the process in which the load is transferred to the concrete by forces in the same direction of the loading. (Wollmershauser, 2006) Keying occurs when a surface of the anchor expands so that it is no longer perpendicular to the surface of the concrete. Figure 4 shows how the angled surface transfers the load to the concrete.

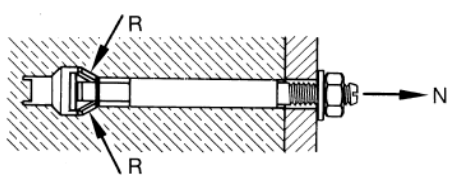


Figure 4: Illustration of Keying Forces

2.5 Adhesive Systems

The performance of adhesive anchor systems depends on the two main components, the type of adhesive and the type of threaded rod, as well as their suitability for any given application. Different adhesives can be more suitable for a combination of factors including temperature, embedment depth, gel time, base material, loading, installation condition, and corrosion resistance. HILTI's adhesive products and their suitability are discussed in the following section. Threaded rod selection can be influenced by expected loading, diameter, installation conditions, and base material.

2.5.1 HILTI Adhesives

Table 1: HILTI Adhesive Products shows the different HILTI adhesive products along with an image and description (HILTI, 2006)

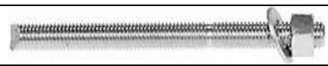
Table 1: HILTI Adhesive Products

HVU Capsules	**A heavy duty, two component adhesive anchor consisting of a self-contained adhesive capsule and either a threaded rod with nut and washer or an internally threaded insert.**
	
HIT HY 150 MAX	**MAX holding power. MAX performance.**
	
HIT ICE	**Specifically formulated for cold weather fastenings, installed when the base material temperatures drop as low as -10°F (-23°C).**
	
HIT HY 20 Adhesive	**Fastening through masonry construction. Can be used where the quality of brick and mortar is inconsistent, and where voids are present between wythes of brick walls.**
	
HIT RE 500 Epoxy Anchoring System	**A high strength, two part adhesive epoxy with a long working (gel) time. Used in solid based concrete applications.**
	

2.5.2 Threaded Rods

Table 2: HILTI Threaded Rod shows the different HILTI threaded rods along with an image and description (HILTI, 2006).

Table 2: HILTI Threaded Rod

HAS Threaded Rod	**Threaded rods for use with HVU capsules and HIT adhesive anchoring systems.**
	
HIT TZ Rod	**A time and money saving anchor to be used with HIT HY 150.**
	

2.5.3 Installation

Once design specifications have been determined, the first step is to drill the hole with an appropriately sized drill bit and drill. For a lot of systems the next step is to clean the hole to remove any debris, which may create a barrier between the base material and the adhesive, decreasing performance. This can be easily done by either using a metal wire brush or blowing out the debris with a bulb or compressed air. Next, the adhesive must be dispensed into the hole. This can be done differently depending upon the type of adhesive. Most of HILTI's adhesive products are two part adhesives, which means that they are comprised of two separate chemical agents that must be mixed before installation. Cartridge systems have individual tubes for each component and when dispensed mix in a special nozzle to exact proportions. The components of a HILTI cartridge system can be seen in **Figure** 5.

Figure 5: HILTI Cartridge System

Capsule systems contain the components in separate capsules that break when the threaded rod is drilled in place. HILTI primarily uses cartridge systems to dispense adhesives although they also manufacture capsule systems. After the adhesive has been dispensed, the threaded rod is inserted into the hole and allowed to rest while the adhesive has time to fully cure before any loading can be applied.

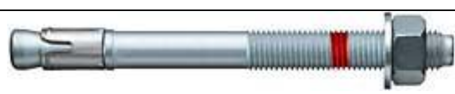
2.6 Mechanical Systems

The performance of the mechanical systems depends on the strength of the anchor and the suitability for the given application. Undercut anchors, expansion or sleeve anchors, and screw in anchors all have different mechanical uses. The condition of concrete will influence the style of anchor to use. Cracked concrete would lead to the use of undercut anchors while anchors that screw in are best for quick installation without pre-drilled holes.

2.6.1 HILTI Systems

Table 3: HILTI Mechanical Anchors shows the various HILTI mechanical anchors along with an image and description from the HILTI North American Product Guide.

Table 3: HILTI Mechanical Anchors

HDA Undercut	**2003 IBC compliant self-undercutting mechanical anchor for heavy duty and safety fastenings into concrete. Combines high load capacity with close edge distances. ICC-ES ESR-1546 supports ACI 318 design.**
	
HSL-3 Expansion	**2003 IBC compliant heavy-duty expansion anchor. Designed for high performance in static and dynamic load applications. ICC-ES ESR-1545 supports ACI 318 design.**
	
HSL-I M12 Flush	**Try the HSL mechanical expansion anchor for your heavy-duty applications.**
	
HSLG-R Stainless Steel	**Try the HSL mechanical expansion anchor for your heavy-duty applications.**
	
HILTI Kwik Bolt TZ	**2003 IBC compliant high-performing medium-duty expansion anchor. Especially suited for seismic and cracked concrete applications. ICC-ES ESR-1917 supports ACI 318 design.**
	
Kwik Bolt 3 (KB3)	**With performance values that meet or exceed the Kwik Bolt II, the new KB3 boasts the best approval rating in its class.**
	

2.6.2 Installation

Once design specifications have been determined, the first step is to drill the hole with an appropriately sized drill bit and drill. For a lot of systems the next step is to clean the hole to remove any debris. This can be easily done by either using a bulb or compressed air. After the hole is properly cleaned insert the anchor. Using a drill undercut or expand the anchor locking it in place.

2.7 Building Codes and Standards

There is the need to have standards that engineers must follow in the engineering and construction industry in order to prevent failures due to poor planning and cutting corners. The main purpose of establishing building codes is to protect the health, safety, and welfare of those affected by the project by stating the minimum required level of safety that is necessary. These codes are typically established by governing bodies on a national and local level. They can vary between city, region, and country. For this project A.S.T.M standards as well as International Building Codes (IBC) will be adhered to. To determine the compressive strength and indirect tensile strength of concrete cylinders we will follow the ASTM C873-04 and C496/C496M-04. The steel the anchors will be made from will concur with ASTM F568M-04 Class 5.8 steel.

3 Methodology

The purpose of this study was to evaluate the effects of installation technique of post-installed adhesive anchors with regards to the effectiveness of the bond. The experiment was designed so that the only variable is the condition of the drill hole prior to the anchor installation. This was to be accomplished by keeping most of the other variables constant by using the same concrete batch, anchors, sample dimensions, as well as curing times.

All project work was completed on the Worcester Polytechnic Campus between August and May of the 2007-2008 academic school year. The project used buckets to form 11.25 in. diameter in order to test concrete and anchor strength. A 3/8" diameter anchor utilizing adhesive bonding was used for testing. The anchors were installed in concrete that had cured for 28 days or more and tested using the Instron testing machine in the Materials and Structures Lab in Kaven Hall. Drill hole cleanliness and diameter were taken into consideration for testing procedure.

Prior to the above testing, smaller scale tests were used to determine the sample size and predict results. These utilized HIT TZ Rods, HAS-E Rods, and HIT RE 500 Epoxy. Existing concrete blocks were used for the base material.

3.1 Experimental Testing Design

Before the actual testing was performed, many variables in the testing setup needed to be identified and isolated. To accomplish this, a total of five preliminary tests were performed. This allowed us to create an accurate, as well as repeatable test procedure by determining how the various materials would respond to testing.

3.2 Preliminary Testing

The first three preliminary tests were performed using HILTI HIT RE 500 Epoxy and 3/8" HIT TZ rods and 5/8" HAS-E rods. These tests were intended to provide an understanding of the anchor behavior, rod and adhesive properties as well as securing the test sample in the testing machine. Two 3/8" rods and one 5/8" rod were installed into a concrete block measuring 2 ft X 2 ft X 1.5 ft, which had cured for over one year. The block was then secured into the Instron Testing Machine using an aluminum I-beam and threaded rod as shown in Figure 6. A gripping fixture that consisted of a steel block that had been tapped with the appropriate diameter and thread was used to grip the anchors. The anchor failed at a loading of approximately 8,500 pounds, which is shown in Figure 7.

Figure 6: Preliminary Test 1: 3/8" TZ rods.

Figure 7: Failure of TZ anchor Test 1 and gripping fixture

Test 2: 3/8 " TZ rod was tested and failed due to ductile steel failure at a maximum loading of 8,739.50 pounds. Figure 8 shows the Load vs. Deformation response for Test 2 It is important to note that the deformation values come from a variety of sources, including the steel anchor rod, concrete, the reaction I-beam deflection, as well as slippage.

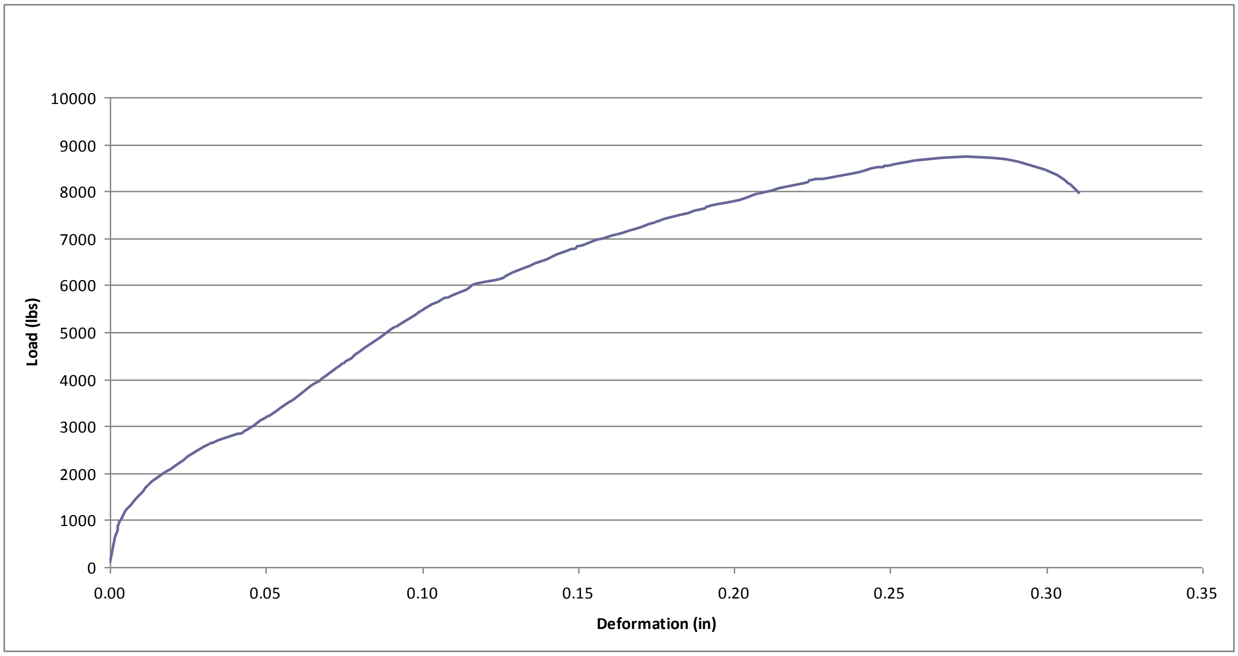


Figure 8: Load vs. Deformation behavior for Test 2, 3/8" HIT TZ rod

Test 3: The 5/8" HAS-E rod was tested in tension. A concrete edge failure occurred at a loading of 22,366 pounds. Due to the size of the block, the required edge distance was not adequate. As shown if Figure 9, several fracture planes were created, ultimately exposing the anchor and epoxy.

Figure 9: Preliminary Test 3: Concrete Edge Failure

During the test, the I-beam and the threaded rod were deformed as a result of the high loading. This makes it difficult to calculate an accurate deformation or strain in the rod. Figure 10 and Figure 11 show the extent of the deformation in the threaded rod and I-beam.

Figure 10: I-Beam Deformation in Preliminary Testing

Figure 11: Threaded Rod Deformation

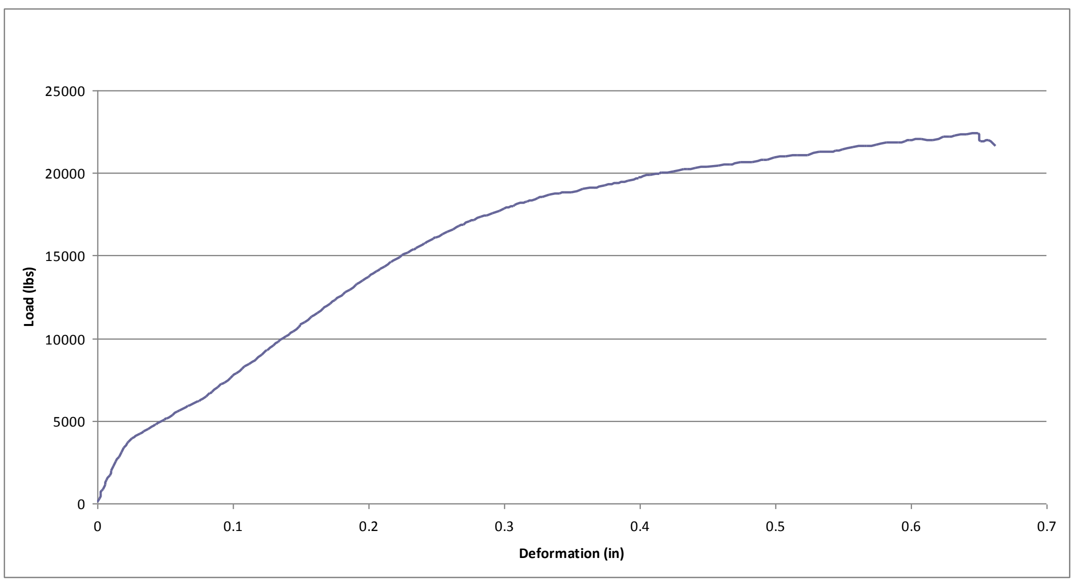


Figure 12: Test 3 Load vs. Deformation Curve

3.3 *Preliminary Testing Observations*

Through the preliminary testing, it was made evident that changes must be made to the testing set up. These changes allowed for a consistent test that could be repeated. The primary concern that arose from this round of testing was the required loading that was needed to cause failure. This was achieved by a combination of changes. By using a 3/8" rod, the load was drastically reduced. Since the maximum loading was reduced, there were lower stresses exerted on the I-beam during tests. To minimize interference that resulted from the supports, two 1" by 3" steel bars were used to secure the sample. Four threaded rods were also used. This limited any deformation and settling resulting from applied loads.

The size and shape of the concrete base sample had to be adjusted for future tests. Plastic buckets, as shown in Figure 13, were used as forms for the samples. These were chosen for convenience as well as to minimize the amount of concrete used per sample. The samples were cylinders with approximate dimensions of 11" diameter by 10" high, as shown in Figure 14. Test cylinders measuring 6" diameter by 12" length samples were used to test for compressive strength and indirect tensile strength of the concrete according to ASTM standards C873-04 and C 496/C 496M-04.

Figure 13: Bucket for Forms

Figure 14: Sample with Installed Anchor

We used HIT RE 500 and HY 150 Epoxy and 3/8" HAS-E Rod. The HAS-E rod was chosen because it required a smaller edge distance.

3.4 Revised Testing Procedure

Two more tests were performed after problems in the first set of tests were addressed. Tests four and five consisted of 3/8” HIT-TZ rods that were installed into cylindrical samples using HIT-RE 500 Epoxy, as shown in Figure 15. The samples were loaded into the Instron testing machine using the two steel bars and threaded rods, as shown in Figure 16. The samples were formed from concrete with an unknown max compressive strength.

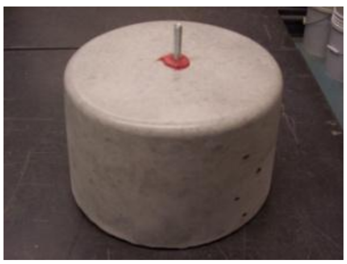


Figure 15: Test 4 and 5 Sample

Figure 16: Test 4 and 5 Set Up.

Test 4 failed at a loading of 7,840 pounds, concrete failure occurred in a spider web pattern originating from the anchor. Test 5 failed at a loading of 7,962 pounds, concrete failure also occurred, as shown in Figure 17 and Figure 18. A plane was formed along the diameter of the cylinder. The concrete failure can be partially explained by the HIT-TZ rods. The geometry of the rod creates a horizontal compressive force when tension is applied. This force created internal tensile force within the sample and contributed to its failure.

Figure 17: Test 4 Failure

Figure 18: Test 5 Failure

3.5 Revised Testing Observations

According to the HILTI manual, the ultimate steel strength in a 3/8" TZ rod is 7,210 pounds. The tests show that the ultimate strength is between 8,500 pounds and 8,740 pounds. This additional strength could be contributed to a built-in safety factor. The ultimate tensile strength in a 5/8" HAS Super is 28,760 pounds. Since the edge distance was not met, the ultimate strength was multiplied by a load adjustment factor of .76, which was determined by the embedment depth and provided edge distance. This gives an adjusted maximum tensile strength of 22,433 pounds, which is close to the value determined by test 3; 22,366 pounds. Through these tests, we learned that the sample needed to be securely fastened in order to gain accurate results.

The minimum edge distance must also be provided in order to see how the anchor and epoxy reacts. Smaller diameter anchors were beneficial to use due to their lower load capacities and smaller edge distances. They allowed less concrete to be used per sample. Most importantly, these tests showed that our test setup needed to be improved before our next round of testing.

In order to provide adequate edge distance, a steel plate with a 10.5" diameter hole cut out of the middle, as shown in Figure 19 was used.

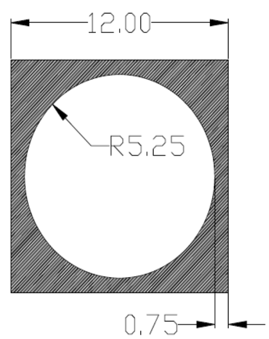


Figure 19: Steel Ring Dimensions

The inner radius of the ring was equal to the edge distance of the selected anchor. Figure 20 and Figure 21 show the experimental setup, which is explained below. The ring was placed on top of the sample and the steel bars were placed on top of the ring. The threaded rods were secured to the base of the machine using T-slot connections and bolted through the steel bars, where they were be anchored.

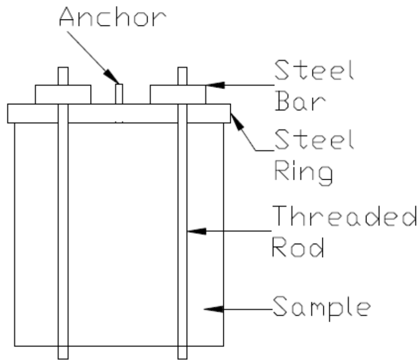


Figure 20: Proposed Setup

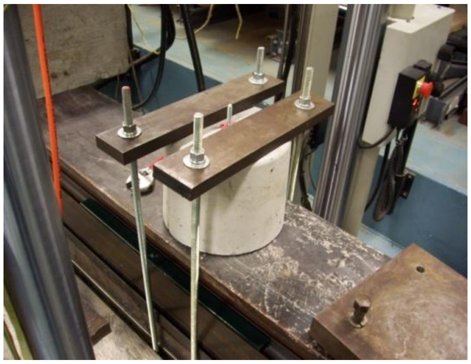


Figure 21: Testing setup without steel ring

This set up allowed the sample to be secured to the base while not interfering with the required edge distance, as shown in Figure 22. The steel ring overlapped the outside edge of the sample. There is also 3/16" between the required edge distance and the inside of the steel ring.

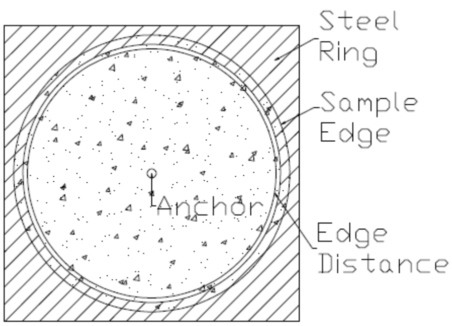


Figure 22: Steel Ring and Sample

Concrete was ordered from a local ready-mix facility, to allow for consistent mix and a large pour. The target compressive strength was 4,000 psi. When the concrete was delivered, we performed a slump test, air content test as well as calculated the specific gravity of the mixed concrete. The mix design for the batch was requested so the properties of the concrete could be calculated and compared to test results.

3.6 Additional Test Specifications

The holes were drilled to the specified depth using the appropriate size drill bit. The drill holes were divided into four different conditions before the epoxy was applied. The different conditions were:

1. Cleaned: the drill hole will be blown out with compressed air. This will be the control condition, which should be consistent with published values.
2. Uncleaned; the drill hole will not be cleaned. No additional debris or liquid will be introduced into the drill hole. Only material in the drill hole as a result of drilling will be present.
3. Oversized diameter: anchors will be installed into drill holes that are double the rod diameter.
4. Wet: the drill hole will be completely filled with Worcester City tap water.

The amount epoxy in each hole and curing time were held constant according to installation instruction in the HILTI manual. Table 4: Required Epoxy per Anchor shows the design volume of epoxy required for each test and the total number of anchors.

Table 4: Required Epoxy per Anchor

Variable	Number of Anchors	Volume of Epoxy (in^3)
Cleaned	10	3.5
Uncleaned	10	3.5
Concrete Dust	10	3.5
Wet	10	3.5
Total	40	14

The epoxy was then applied and the anchor inserted. The epoxy was allowed to cure and harden according to the manufacturer's specifications. The sample was loaded in the Instron Testing Machine until failure.

Sample size was determined using the "Java applets for power and sample size" found on http://www.stat.uiowa.edu/~rlenth/Power/ and an equation that determines sample size using power level. We calculated our sample of size of n=10 per condition. A larger sample size will be impractical for us to test with our current resources. (Note that a sample size refers to "n" tests per condition).

Table 5: Sample Size and Power Level

Sample Size, n	1-B (Power)
5	0.5025
6	0.5992
10	0.8484
11	0.8837
16	0.9719
36+	1.00

Using statistical methods and considering the limitations of the project we have determined that 10 samples per variable was reasonable. We anticipate the anchors will fail and some valuable data will be recorded for clean holes. Contaminating the hole with dust or water is expected to decrease the capabilities of the epoxy and we expect the epoxy to fail in the other tests. The anchors being requested are ISO 898 Class 5.8 which is equivalent to ASTM F568M-04 Class 5.8. Under these conditions the Grade 36 steel is rated to have a tensile strength between 58ksi and 80ksi and this is consistent with our preliminary tests and observations.

3.7 Materials Tests

In order for the performance on the anchors to be measured and analyzed, the properties of the other materials involve must be determined. Without knowing how the other materials would behave during testing, it was nearly impossible to single out the anchor's behavior. The following tests were performed to accomplish this.

3.7.1 Concrete Direct Compressive Strength

First the ends of the cylindrical samples were capped with sulfur in the following method in order to limit slipping in the machine. Molten sulfur was poured into an oiled pan and the sample was placed in the pan. After the sulfur has hardened, the excess was removed and the process was repeated for the other end.

The sample was then placed in the Tinius Olsen testing machine where it was loaded steadily until failure as shown in Figure 23.

Figure 23: Concrete Cylinder Tested in Compression

The maximum loading was recorded and used with the sample's diameter to determine the maximum compressive strength.

A strain gauge was attached to the sample and used to calculate the Modulus of Elasticity for the concrete

This was repeated for each cylinder that was tested

3.7.2 Concrete Indirect Tensile Strength

The cylindrical sample was placed on its side in the Tinius Olsen testing machine. The sample was loaded until failure and the results were used to calculate the tensile strength of the concrete.

3.7.3 Steel Anchor Tension Test

Anchors were tested in the Tinius-Olsen testing machine under direct tensile loading. Two steel rods were tapped to the appropriate diameter and thread size and used to grip the anchors in the machine. Approximately 2-3 inches of the anchors threads were removed in a lathe to all allow a strain gauge to be attached to the rod, as shown in Figure 24.

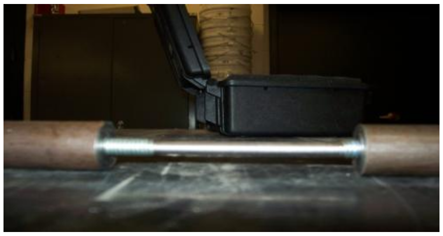


Figure 24: Reduced Diameter in Grip

The diameter of each anchor was measured individually and entered into the testing program. Using an attached stain gauge, the Modulus of Elasticity was determined and the rod was loaded until failure. Stress was also determined by the testing program.

3.8 Anchor Tests

According to the experimental design, tests were performed using 3/8" HAS-E rods on the various combinations of epoxies, and drill hole conditions, and drill hole diameter. A total of six conditions were tested and are described in the following sections. One anchor was installed in each of the samples. Holes were drilled using a rotary hammer drill and concrete drill bits

All tests will be performed using the Instron testing machine and the methods described in the experiment design. Loads were applied to the anchor at a rate of 0.5" per minute. Failure was marked by an 80% reduction in load.

The stress in each rod will be calculated using the actual cross sectional area of the rod and dividing the load by it. Also the bond to concrete strength of the epoxy was calculated using the surface area inside the hole. For simplicity the bottom of the hole was ignored for the HIT HY 150 MAX tests because no bond strength was listed.

3.8.1 HIT-RE 500, Standard Diameter, Cleaned

Holes were drilled with a 7/16” drill bit in one pass. Prior to installation, concrete dust was removed using compressed air. A wire brush was used to remove additional debris and was blown with compressed air again. Enough adhesive to fill the drill hole was dispensed into the drill hole using a manual dispenser. A 3/8” HAS-E rod was inserted into the hole in a twisting motion. The adhesive was allowed to set and cure for a minimum of 24 hours. This set of tests served as the control group. These results were used to gauge the following test results for the other HIT-RE 500 tests.

3.8.2 HIT-RE 500, Standard Diameter, Un-Cleaned

Holes were drilled with a 7/16” drill bit in one pass. Compressed air and a wire brush were not used to remove debris. Whatever concrete dust that was left after the drill bit was removed remained in the drill hole. Enough adhesive to fill the drill hole was dispensed into the drill hole using a manual dispenser. A 3/8” HAS-E rod was inserted into the hole in a twisting motion. The adhesive was allowed to set and cure for a minimum of 24 hours. This test determined if improper cleaning of the drill hole had a negative effect on the capacity of the anchor.

3.8.3 HIT-RE 500, Oversized Diameter, Cleaned

Holes were drilled first with a ½” drill bit, and then a 1” drill bit resulting in a final diameter of 1” prior to installation, concrete dust was removed using compressed air. A wire brush was used to remove additional debris and was blown out with compressed air again. Enough adhesive to fill the drill hole was dispensed into the drill hole using a manual dispenser. A 3/8” HAS-E rod was inserted into the hole in a twisting motion. The adhesive was allowed to set and cure for a minimum of 24 hours. This test was used to determine if a hole diameter outside the specified range would affect the performance of the anchor.

3.8.4 HY 150, Standard Diameter, Cleaned, Dry

Holes were drilled with a 7/16” drill bit in one pass. Prior to installation, concrete dust was removed using compressed air. A wire brush was used to remove additional debris and was blown out with compressed air again. Enough adhesive to fill the drill hole was dispensed into the drill hole using a manual dispenser. A 3/8" HAS-E rod was inserted into the hole in a twisting motion. The adhesive was allowed to set and cure for a minimum of 24 hours. This set of tests served as the control group. The results were used to gauge the results of the other HY 150 tests.

3.8.5 HY 150, Standard Diameter, Cleaned, Wet

Holes were drilled with a 7/16" drill bit in one pass. Prior to installation, concrete dust was removed using compressed air. A wire brush was used to remove additional debris and was blown out with compressed air again. The drill hole was filled with Worcester City tap water. Enough adhesive to fill the drill hole was dispensed into the drill hole using a manual dispenser. The water was displaced as the adhesive was dispensed. A 3/8" HAS-E rod was inserted into the hole in a twisting motion. The adhesive was allowed to set and cure for a minimum of 24 hours. This set of tests was designed to show if the HY 150 adhesive's effectiveness was affected by water.

3.8.6 HY 150, Oversized Diameter, Cleaned, Wet

Anchors for this test were installed into two 30" x 6" x 6" beams. Because the beam was only 6" wide the effective edge distance was assumed to be 3". Holes were drilled first with a ½" drill bit, and then a 1" drill bit resulting in a final diameter of 1" prior to installation, concrete dust was removed using compressed air. A wire brush was used to remove additional debris and was blown own with compressed air again. The drill hole was filled with Worcester City tap water. Enough adhesive to fill the drill hole was dispensed into the drill hole using a manual dispenser. The water was displaced as the adhesive was dispensed. A 3/8" HAS-E rod was inserted into the hole in a twisting motion. The adhesive was allowed to set and cure for a minimum of 24 hours. This test was used to determine interaction between an improperly sized drill hole and the presence of water.

3.9 Design Project

In order to analyze the impact of installation on performance, the test results will be used to design a concrete panel similar to that of the Big Dig. A concrete panel with dimensions of 100" by 100” and a depth of 12” will be suspended. If a concrete with a unit weight of 150 pcf is used, the total weight of the panel will be 10,417 pounds. The minimum depth, spacing and edge distance for each adhesive is met by the geometry of the panel.

HILTI’s technical guide incorporates a factor of safety of approximately 4 into their design values, which is only applicable when the anchors are properly installed. When shortcuts are taken and the anchors are not installed properly, this factor of safety significantly drops. More anchors would be required to achieve a factor of safety of 4 and the costs associated with each anchor would also rise.

The design project will compare the cost effectiveness of proper installation of the anchors versus improper installation while maintaining a factor of safety of 4.

4 Results

The results of each individual round of testing are located in the following sections. Figure 25 shows the combined maximum loads for each test along with the standard deviation. The chart contains two boxes which represent the standard deviations from each test. The test average is where the two boxes meet.

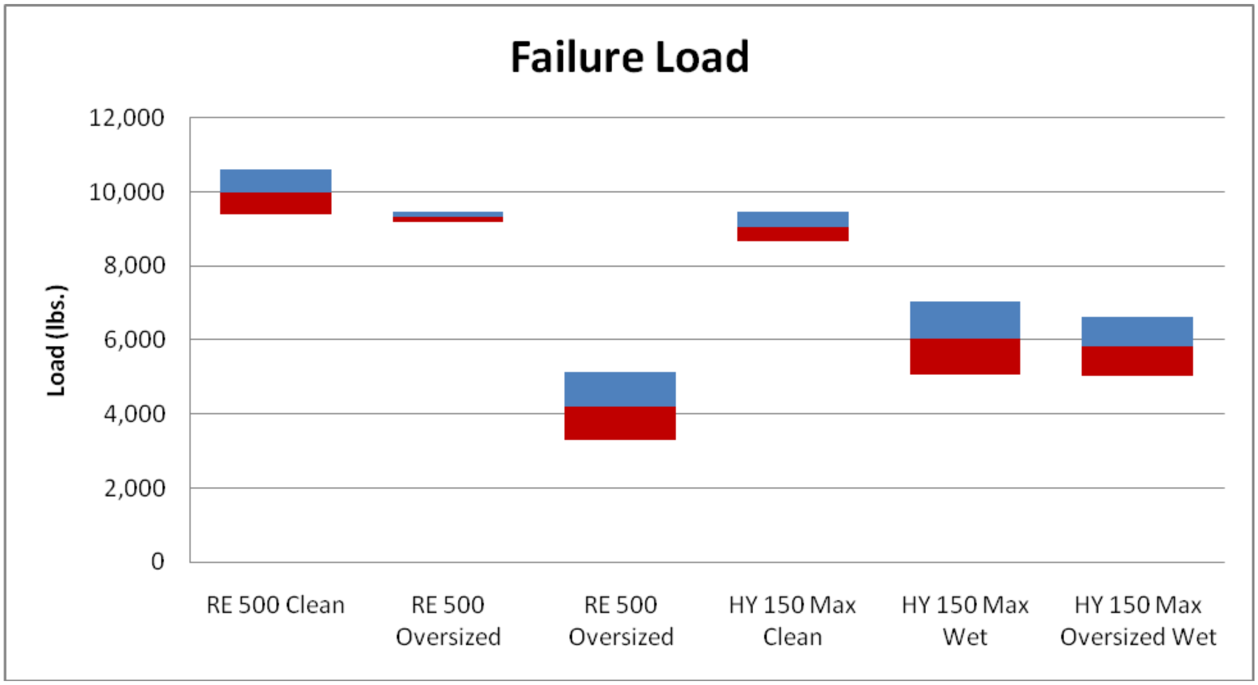


Figure 25: Combined Failure Load

Figure 26 shows the combined bond stresses for each test along with the standard deviation. The chart contains two boxes which represent the standard deviations from each test. The test average is where the two boxes meet.

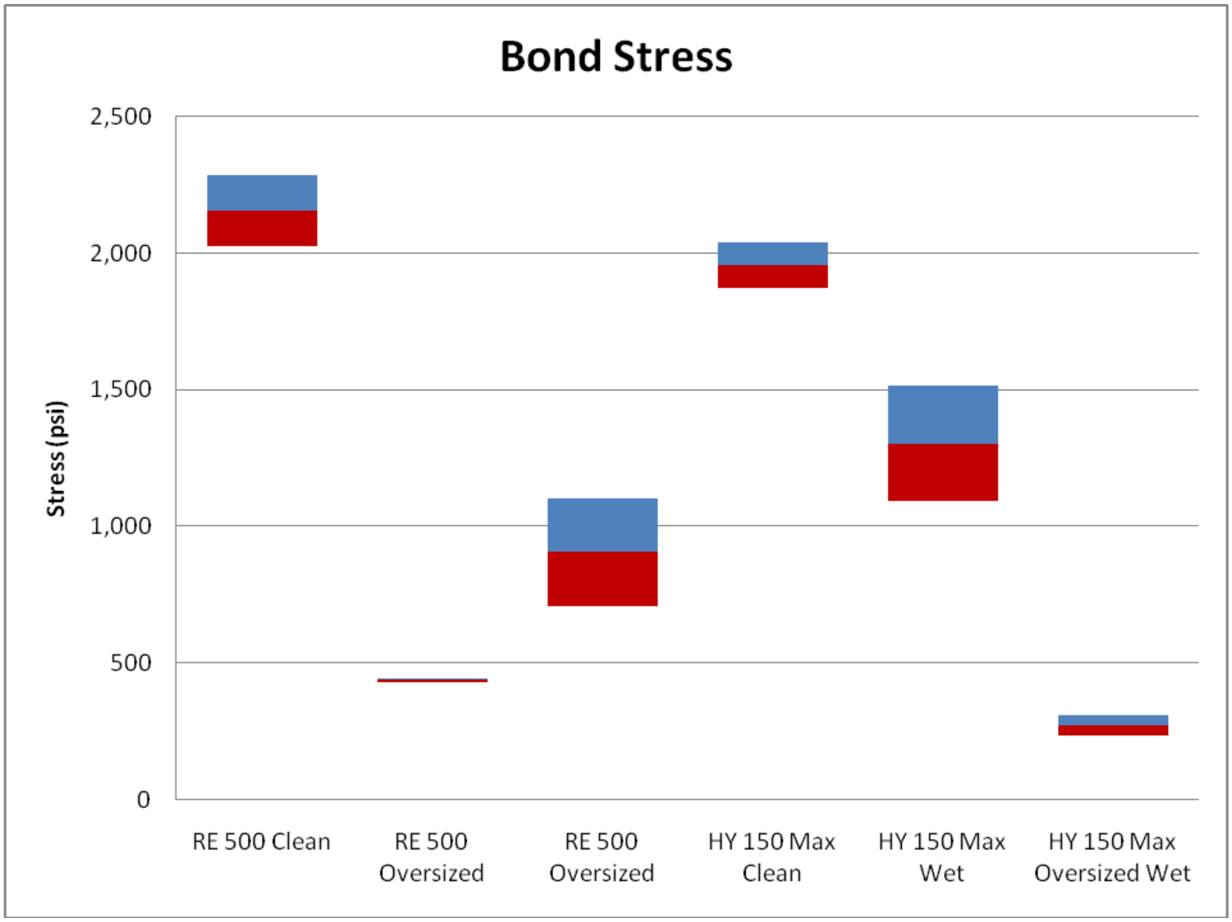


Figure 26: Combined Bond Stress

4.1 Material Test Results

The results of each material test defined in section 3.7 are listed in the following sections.

4.1.1 Concrete Direct Compressive Test

A total of 9 tests were performed to determine the average compressive strength of the concrete. The elastic modulus was calculated as 2,661,770 psi using tests 7 through 9. The individual stress load, average stress load, and standard deviation are presented below.

Table 6: Concrete Compression Test Results

Test Sample	Compressive Strength (psi)
1	**4,868**
2	**5,023**
3	**5,335**
4	**4,806**
5	**4,975**
6	**4,669**
7	***5,160***
8	***5,200***
9	***5,250***
Average	**5,032**
SD	**223**

4.1.2 Concrete Indirect Tensile Test

A total of 6 tests were performed to determine the indirect tensile strength of the concrete. The peak load and tensile strength are presented below.

Table 7: Concrete Indirect Tension Tests Results

Indirect Tensile Test		
Sample	Peak Load (lbf)	Tensile Stress (psi)
1	**44,208**	**390.9**
2	**41,262**	**364.8**
3	**49,307**	**436.0**
4	**46,261**	**409.0**
5	**50,625**	**447.6**
6	**40,753**	**360.3**
Average	**45,403**	**401.4**

4.1.3 Steel Anchor Tension Test

A total of 6 3/8" HAS-E steel anchors were tested to determine the tensile strength and the modulus of the steel. The data is presented below.

Table 8: Steel Anchor Tension Test Results

	Stress (psi)	Modulus (psi)
1	**109,980**	**34,879,780**
2	**123,739**	**32,429,870**
3	**124,418**	**27,409,020**
4	**121,853**	***26,412,250***
5	**139,057**	**27,132,950**
6	**136,482**	***41,564,330***
Average	**125,922**	**31,638,033**
SD	**10,600**	**5,918,723**

The Modulus for tests 4 and 6 may not be accurate. Test 4 had the teeth for the strain gauge was directly over the point of deformation and the gauge slipped because of this. Test 6 had the point of deformation outside of the teeth so a large part of the deformation was not measured.

4.2 Anchor Test Results

The following sections contain the test results for the anchor tests using HIT RE 500 and HY 150 Max adhesives. 3/8" HAS E threaded rods were used for each test. Each test was loaded until failure.

4.2.1 HIT-RE 500, Standard Diameter, Cleaned

A total of 10 tests were performed. Each test resulted in concrete failure as shown in Figure 27. The individual test results are shown in Table 9.

Figure 27: Concrete Failure, HIT RE 500 Cleaned

Table 9 HIT-RE 500, Standard Diameter, Cleaned Results

Test Number	1	2	3	4	5	6	7	8	9	10
Max Load (lbs)	**10,601**	**10,606**	**10,061**	**8,941**	**9,605**	**9,454**	**10,944**	**9,780**	**9,826**	**10,215**
Max Stress in Rod (psi)	**149,974**	**150,044**	**142,334**	**126,489**	**135,883**	**133,747**	**154,826**	**138,359**	**139,010**	**144,513**
Bond Stress (psi)	**2,286**	**2,288**	**2,170**	**1,928**	**2,072**	**2,039**	**2,360**	**2,109**	**2,119**	**2,203**

A brief statistical analysis is shown in Table 10 below. The average load at failure was 10,003 lbs with a standard deviation of ±608 lbs.

Table 10 HIT-RE 500, Standard Diameter, Cleaned Statistical Analysis

	Max Load (lbs)	Max Rod Stress (psi)	Max Bond Stress (psi)
SD	**608**	**8,597**	**131**
Average	**10,003**	**141,518**	**2,158**
Max	**10,944**	**154,826**	**2,360**
Min	**8,941**	**126,489**	**1,928**

Since each test failed in the concrete, the capacity of the rod was not reached. Data published by HILTI has the bond strength of the HIT RE 500 at 1800psi and the data collected averages the bond strengths to 2158psi, 20% higher.

4.2.2 HIT-RE 500, Standard Diameter, Un-Cleaned

A total of 10 tests were performed. Each test resulted in anchor pullout. The individual test results are shown in Table 11 HIT-RE 500, Standard Diameter Un-Cleaned Test Results and a statistical analysis in Table 12 HIT-RE 500, Standard Diameter, Un-cleaned Statistical Analysis.

Table 11 HIT-RE 500, Standard Diameter Un-Cleaned Test Results

Test Number	1	2	3	4	5	6	7	8	9	10
Max Load (lbs)	**5,480**	**3,617**	**5,073**	**4,310**	**4,685**	**3,762**	**2,336**	**4,852**	**3,513**	**4,421**
Max Stress in Rod (psi)	**77,529**	**51,177**	**71,773**	**60,977**	**66,274**	**53,223**	**33,045**	**68,644**	**49,704**	**62,544**
Bond Stress (psi)	**1,182**	**780**	**1,094**	**930**	**1,010**	**811**	**504**	**1,047**	**758**	**954**

Table 12 HIT-RE 500, Standard Diameter, Un-cleaned Statistical Analysis

	Max Load (lbs)	Max Rod Stress (psi)	Max Bond Stress (psi)
SD	**919**	**13,000**	**198**
Average	**4,205**	**59,489**	**907**
Max	**5,480**	**77,529**	**1,182**
Min	**2,336**	**33,045**	**504**

There is a higher standard deviation in this set of tests which can be contributed to the amount of concrete dust which was left in the drill hole. The failure created a conical blow-out that started at a distance from the concrete surface.

4.2.3 HIT-RE 500, Oversized Diameter, Cleaned

A total of 10 tests were performed. Each test resulted in steel failure of the anchor as shown in Figure 28. The individual test results are shown in Table 13 and a statistical analysis in Table 14.

Figure 28: Ductile Steel Failure in Oversized HIT RE 500 Test

Table 13: HIT-RE 500 Oversized Diameter Test Results

Test Number	1	2	3	4	5	6	7	8	9	10
Max Load (lbs)	**9,320**	**9,012**	**9,215**	**9,249**	**9,386**	**9,287**	**9,521**	**9,418**	**9,447**	**9,351**
Max Stress in Rod (psi)	**131,846**	**127,492**	**130,371**	**130,841**	**132,782**	**131,386**	**134,691**	**133,241**	**133,653**	**132,294**
Bond Stress (psi)	**2,010**	**1,944**	**1,988**	**1,995**	**2,024**	**2,003**	**2,053**	**2,031**	**2,038**	**2,017**

Table 14: HIT-RE 500 Oversized Diameter Test Statistical Analysis

	Max Load (lbs)	Max Rod Stress (psi)	Max Bond Stress (psi)
SD	**143**	**2,020**	**31**
Average	**9,321**	**131,860**	**2,010**
Max	**9,386**	**132,782**	**443**
Min	**9,012**	**127,492**	**425**

The anchors failed at an average stress of 9,321 lbs. and had a standard deviation of ±143 lbs.

4.2.4 HY 150 Max, Standard Diameter, Cleaned, Dry

A total of five tests were performed. Each test resulted in concrete failure as shown in Figure 29 and Figure 30. The individual test results are shown in Table 15 and a statistical analysis in Table 16.

Table 15: HY 150 Max, Cleaned, Dry Test Results

Test Number	1	2	3	4	5
Max Load (lbs)	**8,718**	**9,271**	**8,581**	**9,324**	**9,430**
Max Stress in Rod (psi)	**123,341**	**131,164**	**121,399**	**131,911**	**133,412**
Bond Stress (psi)	**1,880**	**2,000**	**1,851**	**2,011**	**2,034**

Table 16: HY 150 Max, Cleaned, Dry, Statistical Analysis

	Max Load (lbs)	Max Rod Stress (psi)	Max Bond Stress (psi)
SD	**386**	**5,468**	**83**
Average	**9,065**	**128,246**	**1,955**
Max	**9,430**	**131,911**	**2,034**
Min	**8,581**	**121,399**	**1,851**

Figure 29: Concrete Failure, HY 150 Max Cleaned

Figure 30: Concrete Failure, HY 150 Max Cleaned

4.2.5 HY 150 Max, Standard Diameter, Cleaned, Wet

A total of five tests were performed. Each test resulted in anchor pull-out. The individual test results are shown in Table 17 and a statistical analysis in Table 18.

Table 17: HY 150 Max, Cleaned, Wet Test Results

Test Number	1	2	3	4	5
Max Load (lbs)	**6,646**	**6,422**	**4,307**	**6,407**	**6,455**
Max Stress in Rod (psi)	**94,026**	**90,848**	**60,934**	**90,635**	**91,320**
Bond Stress (psi)	**1,434**	**1,385**	**929**	**1,382**	**1,392**

Table 18: HY 150 Max, Cleaned, Wet Statistical Analysis

	Max Load (lbs)	Max Rod Stress (psi)	Max Bond Stress (psi)
SD	**978**	**13,829**	**211**
Average	**6,047**	**85,553**	**1,304**
Max	**6,646**	**92,026**	**1,434**
Min	**4,307**	**60,934**	**929**

4.2.6 HY 150 Max, Oversized Diameter, Cleaned, Wet

A total of six tests were performed. Each test resulted in anchor pull-out. The individual test results are shown Table 19 in and a statistical analysis in Table 20.

Table 19: HY 150 Max, Oversized, Wet, Test Results

Test Number	1	2	3	4	5	6
Max Load (lbs)	**6,038**	**6,646**	**6,229**	**4,375**	**6,169**	**5,583**
Max Stress in Rod (psi)	**85,414**	**94,022**	**88,123**	**61,896**	**87,269**	**78,985**
Bond Stress (psi)	**1,302**	**1,433**	**1,343**	**944**	**1,330**	**1,204**

Table 20: HY 150 Max, Oversized, Wet, Statistical Analysis

	Max Load (lbs)	Max Rod Stress (psi)	Max Bond Stress (psi)
SD	**795**	**11,246**	**171**
Average	**5,840**	**82,618**	**1,260**
Max	**6,646**	**92,026**	**314**
Min	**4,375**	**60,934**	**206**

4.3 Design Problem

The design project will compare the cost effectiveness of installation technique with regards to a constant factor or safety. In order to make calculations, assumptions were made regarding the size and weight of a concrete block and the associated costs of materials and installation. The concrete block was 100" x 100" x 12", as shown in Figure 31, and weighed 10,417lbs assuming the concrete was 150lbs per cubic foot. A tube of adhesive was assumed to cost $26.00 and one anchor to cost $1.00. From our testing we estimated the time to drill one hole is 20 minutes, 10 minutes to properly clean a bore hole, and 5 minutes for installation. A worker's wages were estimated to be $30.00 an hour. This would make the cost to drill one hole $10.00, clean one hole $5.00 and $2.50 to install the anchor.

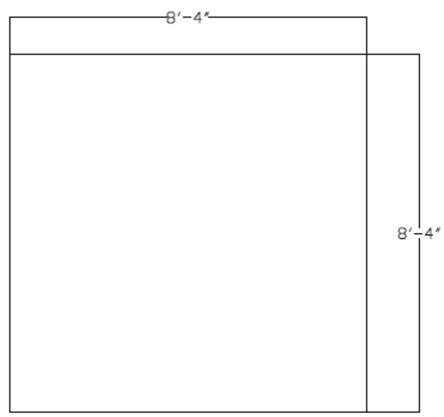


Figure 31: Design Project Dimensions

4.3.1 HIT RE 500 Design

The allowable load for design was calculated to be 1/4th of the ultimate loads determined through testing. This is consistent with HILTI specifications. Using the allowable loads, the number of anchors required to suspend the 10,417 pound concrete panel with a factor of safety of approximately 4 were determined, as shown in Table 21.

Table 21: HIT RE 500 Design Values

HIT RE 500	Ultimate Load (lbs per rod)	Allowable Load (lbs per rod)	# Rods	FS
Cleaned	10,003	2,501	4	3.84
Uncleaned	4,205	1,051	10	4.04
Oversized Diameter	9,321	2,330	5	4.47

Using the above mentioned costs, the cost per panel in order to reach a factor of safety close to four for each case was calculated and is shown below.

Table 22: HIT RE 500 Panel Costs

HIT RE 500	Cost ($ per panel)
Cleaned	76
Uncleaned	140
Oversized Diameter	95

To illustrate to cumulative impact of improperly installing anchors, a chart was created which shows the differences between the installation techniques over a range of costs and factor of safety values, which is shown in Figure 32. As the number of anchors increases, the cost with improperly installed anchors rises unnecessarily high.

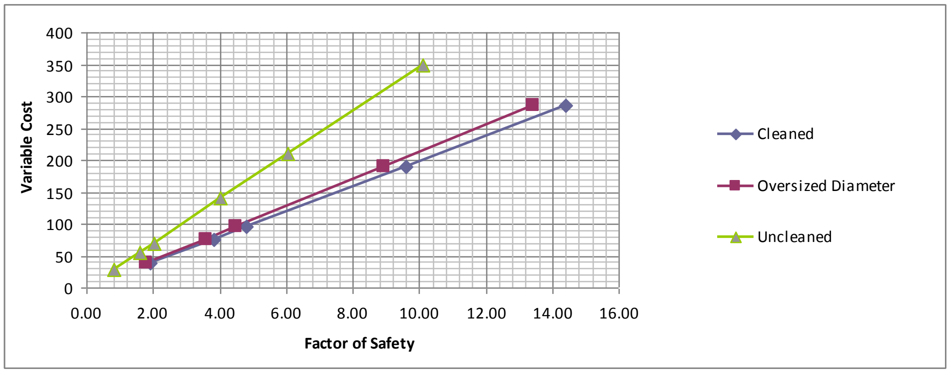


Figure 32: HIT RE 500 Cost Effectiveness

4.3.2 HIT HY 150 Max Design

The values for the allowable loads and costs were calculated by the same process as the HIT RE 500 values and are shown in Table 23 and Table 24 respectively.

Table 23: HIT HY 150 Max Design Values

HIT HY 150 Max	Ultimate Load (lbs per rod)	Allowable Load (lbs per rod)	# of Rods	FS
Cleaned, Dry	9065	2266	5	4.35
Cleaned, Wet	6047	1512	7	4.06
Oversized Diam., Wet	5840	1460	7	3.92

Table 24: HIT HY 150 Max Panel Costs

HIT HY 150 Max	Cost ($ per panel)
Cleaned, Dry	95
Cleaned, Wet	133
Oversized Diam., Wet	133

A similar chart was created for the HIT HY 150 Max adhesive and in Figure 33. It shows that the costs for contaminated drill holes are overall, considerably higher than the drill holes without contaminants. In the event that the drill holes become contaminated it will be cost effective to use a proper adhesive system for installation due to the increase of costs to compensate for contamination.

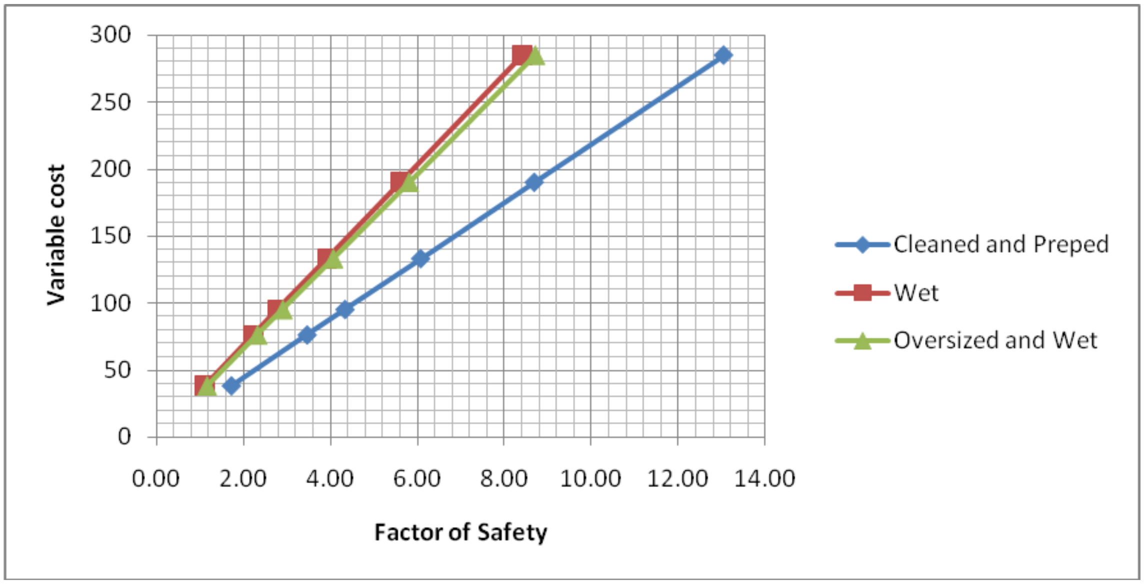


Figure 33: HIT HY 150 Max Cost Effectiveness

4.3.3 Load Distribution

Upon installation the anchors should be placed evenly to ensure and even distribution of loading to each anchor, as shown in Figure 34. The factors of safety calculated are assuming that the load is evenly distributed and moment does not come into play. In the event an anchor does fail it not only distributes that load over the remaining anchors but may add an additional stress on the anchors due to moment causing more anchors to fail even though the direct tension capacity has not been exceeded. For example if two anchors support one concrete panel, one anchor at each end, and one anchor fails it is guaranteed the other anchor will fail given the anchors used are 3/8 inch rods. The remaining rod would be under the full 10,417 lbs vertical load and given an edge distance of 8 inches the rod would be under a moment of 36,458 ft-lbs.

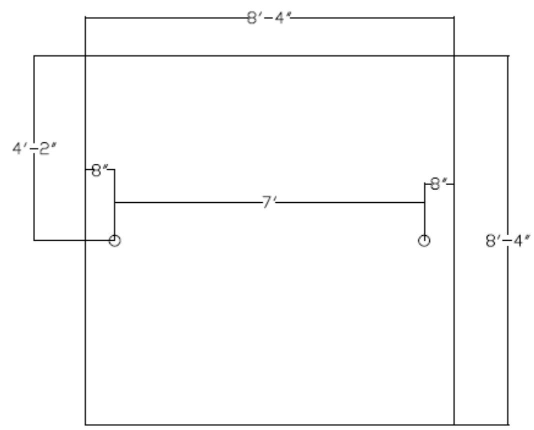


Figure 34: Design Problem Anchor Location

5 Conclusions

As the tests collectively show, the method in which an anchor is installed has potential to drastically affect the performance. Many of the conditions that lead to poor installation are caused by human error or cost-cutting measures. Less predictable conditions are the result of material properties that cannot so easily be compensated for. To compensate for these properties, a safety factor must be used to modify the effective capacity of the anchor system. This section will discuss these problem factors, such as the one shown in Figure 35, resulting from the tests and how they can be avoided during construction and design.

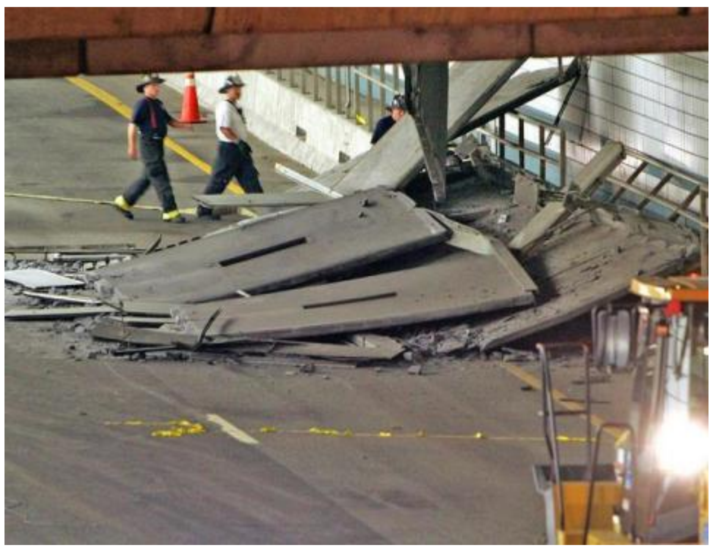


Figure 35: Big Dig Panel Collapse, news.thomasnet.com

5.1 Concrete

Six concrete cylinders, shown in Figure 36, were tested in order to determine the compressive strength of the concrete. The samples were cured for 48 days at the time of testing. The average compressive strength was approximately 5,000 psi with a standard deviation of 223 psi. The 95% confidence interval given the number of samples and standard deviation ranges from 4.8 ksi to 5.2 ksi. The concrete samples were slightly larger than the target compressive strength of 4,000 psi.

Figure 36: Capped Concrete Test Cylinders

5.2 Steel Rod

Six rods were tested to determine the ultimate strength of the 3/8" steel HAS-E rods. The average ultimate strength of the steel rods was 126 ksi. The rods were narrowed in the middle to allow a strain gage to take a measurement, which is shown in Figure 37. This allowed the modulus of elasticity to be determined. The average modulus of elasticity was 31,600 ksi. The data may have errors due to induced stresses on the rod which were a result of milling. According to ISO 898 Class 5.8 standards, the minimum ultimate strength of the steel is rated at F_u =72.5 ksi. For an average strength of 126ksi and an area of 0.1105 in^2 we can calculate a loading of 13. 9 kips for the ultimate strength of the steel rods. The HILTI anchor manual provides ultimate and allowable loads for the HAS-E rods of 6,005 lbs and 2,640 lbs respectively. Both these values were calculated using $0.75*F_u*A_{nom}$ for the ultimate strength and $0.33*F_u*A_{nom}$ for the allowable strength of a 3/8" rod. Taking the average stress capacity from test data, 126 ksi, and dividing it by 72.5 ksi we get 1.7, which can be assumed as the factor of safety for the steel strength. In the event the rods fail we can calculate the confidence interval for the strength of the steel rods. Using the formula for confidence interval we determine a 95% confidence to be between 116.5 ksi to 133.5 ksi.

Figure 37: Attached Strain Gauge

5.3 HIT RE 500 Adhesive

A total of thirty tests were completed using 3/8" HAS-E rods and HIT RE 500 adhesive. Three installation techniques were tested which include; a control group installed to HILTI specifications, one group in which the drill holes were improperly cleaned, and one group which had oversized drill holes. Although one of the conditions tested against the control did not create a noticeable drop in performance it is recommended that the HILTI installation specifications should be followed as closely as possible for optimal results.

The control group, which was properly installed, had the highest loading at failure, which is not surprising. The average load for this test series was 10 kips with a standard deviation of 0.6 kips. The actual diameter of the rods was measured to be 3/10 inch. The stress in the rods averaged 141.6 ksi and did not fail. The values for the ultimate stress of the steel rods were calculated to be 125 ksi in section 5.2, and a 95% confidence interval ranges from 116.5 ksi to 133.5 ksi. The value of 141.6 ksi is outside the confidence interval but the milling of the steel rods in order to measure strain may have lowered the strength and therefore the calculated stresses for the original steel rod tests may be lower than actual values. The ultimate bond to concrete capacity for HIT RE 500 and 4 ksi concrete is listed as 10.3 kips, and a bond strength is also given as 1,800 psi. Using the equation for the surface area of the inside side walls of the bore hole, we determined that the bottom of the hole carries approximately 2 kips of load and the side walls carry 8.3 kips of load at failure. Using the assumption that the bottom of the drill hole holds 2 kips, we calculated the bond strength from the test data, which is 1,726 psi with a standard deviation of 131 psi. This value verifies that the bond strength of the adhesive to be within reason for these tests and our results come close to the data provided in the HILTI manual. This also shows that the slight increase in concrete strength may not improve the bond strength and the reduction experienced could have come from improper installation. This set of data is our control for the rest of the HIT RE 500 tests.

The following test, which was improperly installed, was not cleaned after drilling or prior to anchor installation. The average load for this test series was 4.2 kips with a standard deviation of 0.9 kips. Using the same nominal area for the rod, the rod stress averaged to 59.5 ksi and did not fail. The bottoms of the holes for this test series were never cleaned and it can be assumed that the bottoms of the holes were layered in concrete dust. Therefore the 2 kip load from the bottom of the hole can be ignored for the bond strength calculations. The average bond strength for this test series is 907 psi with a standard deviation of 198 psi. For this test, each sample blew out the concrete in an identical way, shown in Figure 38 and Figure 39.

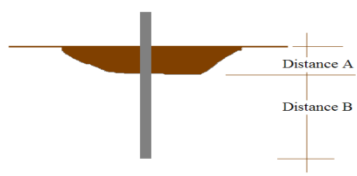


Figure 38: HIT-RE 500 Un-cleaned Anchor Pull-Out

Figure 39: Uncleaned HIT RE-500 Pulled Out Anchor

A portion of concrete on the upper portion of the rod stayed attached while the bottom section of the rod/adhesive slipped out. If we try and calculate the bond strength using only the surface area along Distance A, the bond strength values reach upwards of 3,200 psi, which is not reasonable since the bond strength clean was already tested to be about 1,726 psi in the control test. Therefore, the concrete blows out but the entire surface area withstands the loading from adhesive to concrete. When comparing these results to the control tests, the average bond strength is roughly 50% of the control tests and the average loading is only 42% of what the cleaned holes should withstand. With this data it is obvious that the cleaning of the holes is necessary for the installation of the anchor. Otherwise the anchor will carry roughly 40% of the ultimate load it is designed for. Up to this point, the ultimate strength of the anchors and adhesive has been compared to the data collected. The allowable bond to concrete capacity for the HILTI HIT RE 500 is listed at 2.6 kips and the 4.2 kips load is still more then the allowable load by a factor of roughly 1.6. Therefore, if the anchors are installed without cleaning the holes, it is still safe to assume they should not fail as long as the design allowable capacity is honored.

The final test with the HIT RE 500 epoxy system was done with oversized bore holes (1" in diameter). This system is designed for holes that are twice the diameter of the rod, so we selected a diameter larger outside of the design range. The average load for this test series came to 9.3 kips with a standard deviation of 0. 1 kips. The ultimate stress in the rods averaged 131.9 ksi with a standard deviation of 2 ksi. The average value for the ultimate stress of the steel rods was calculated to be 125 ksi in the previous sections, the 95% confidence interval ranged from 116.5 ksi to 133.5 ksi. Our value falls within the confidence interval but we already concluded that the interval may be on the low side because of milling of rods in the original steel rod test. If we use the first set of test data, clean holes, as a control the 95% confidence interval for that test is 136.3 ksi to 146.9 ksi and these rods did not fail. By comparing this confidence interval to the data collected for the oversized holes we can see that the average ultimate stress is below the interval for the cleaned holes. In this test series the rods, on average, failed earlier then the control test. Only two of the rods failed within the 95% confidence interval calculated from the cleaned hole test. Therefore, the anchors used had imperfections or there were additional stresses acting on the anchor due to the enlarged drill hole. The narrow standard deviation, 2 ksi, for these tests makes it unlikely that the rods were faulty and led us to assume that additional stresses in the rod could be accountable for a lower failure in the rods. After the samples were tested, it could be observed that the HIT RE 500 epoxy had cracks visible from the top of the hole, shown in Figure 40.

Figure 40: Cracked HIT RE 500 Adhesive

The early failure of the steel anchor could have been due to a non uniform failure of the epoxy surrounding the anchor. No certain conclusion for why the failure occurred can be obtained from our data but we can determine that a hole larger than the design parameters fails early for reasons unknown. Even though the rods failure was premature the allowable bond to concrete capacity for the HILTI HIT RE 500 is listed at 2.6 kips and the 9.3 kips load is still more then the allowable load by a factor roughly 3.6. Therefore if the anchors are installed into a cleaned hole with a diameter between 7/16" and 1" it is still safe to assume they will not fail as long as the design allowable capacity is honored.

The three tests conducted with the HIT RE 500 adhesive system and 3/8" rods yielded results pointing to the significant decline of load resistance without proper installation. Although all the results did pass the allowable bond/concrete capacity, each test had a different factor of safety. The allowable loads are determined using a factor of safety in order to give a significant comfort range for the installed anchors because of unintentional flaws in materials and/or human error that may result in improper installation. Therefore, the applied loads have a large factor of safety. Proper installation is imperative and the installation requirements, such as hole size and edge distance, must also be honored.

5.4 HY 150 MAX Adhesive

A total of sixteen tests were completed using 3/8" HAS-E rods and HY 150 MAX adhesive. Three installation techniques were tested including; a control group installed to HILTI specifications. One group had drill holes were contaminated with water, and one group had oversized drill holes contaminated with water. Both of the conditions tested against the control created a noticeable drop in performance. Since the required edge distance and spacing for this adhesive is 6.75 inches and the edge distance provided was 5.25 inches, we will need to use an adjustment factor of 0.93 to calculate the loads we are aiming for. Therefore instead of aiming for an ultimate bond/concrete capacity of 12.2 kips we will aim for 11.4 kips. For optimal performance the HILTI installation specifications should be followed as closely as possible.

The control group, which was properly installed, had the highest loading at failure. The average load for this test series was 9 kips with a standard deviation of 0.4 kips. Using the measured rod diameter of 3/10", the stress in the rod averaged 128.3 ksi and did not fail. The ultimate bond to concrete capacity for HIT HY 150 MAX, 4 ksi concrete, and an edge distance of 5.25 inches is 11.4 kips, but the average bond strength is not given. Using the side wall surface area we can calculate the approximate bond strength from the test data and average to be 1,955 psi with a standard deviation of 83 psi. Since there is no bond strength listed to compare our data to, we compared bond to concrete capacity to the data collected. Comparing the average load from the data, 9 kips, to the ultimate capacity, 11.4 kips, it is observed that the tests failed to reach the ultimate capacity listed for this adhesive system. The results calculated a loading of 79% of the target ultimate capacity but still surpassed the allowable capacity by a factor of 3. Therefore it is a reasonable assumption that if the allowable capacity is honored, the anchor system will not fail. This test series only contained five samples and the statistical power of this data is roughly 0.5. A larger sample size may have given results matching the HITLTI anchor data more closely but these results will still be used as our control group.

In the following test, we used the same anchors and adhesive, except the bore holes were contaminated with Worcester City tap water before installing the anchors. The average ultimate load for this test came to 6 kips with a standard deviation of 1 kip. The large standard deviation is a result of the five samples yielding a significantly lower value for loading at failure. The actual diameter of the rod was measured to be 3/10 inch. The stress in the rod averaged 85.6 ksi and did not fail. Using the surface area of the side walls of the drill hole, the same method as the control test, the average bond strength is calculated to be 1,304 psi with a standard deviation of 211 psi. The results calculated a loading of roughly 67% the ultimate capacity of the control group and roughly 53% the target ultimate capacity but still surpass the allowable capacity in the HILTI manual by a factor of 2. Therefore it is a reasonable assumption that if the allowable load is honored the anchor system will not fail. This test series, same as the control test series, only contained five samples and the statistical power of this data is roughly 0.5. From the data collected it is obvious that the addition of water to the HIT HY 150 MAX significantly lowers its bond capacity.

The following test we used the same anchors and adhesive system but the holes were contaminated with water before installing the anchors. The average ultimate load for this test came to 6 kips with a standard deviation of 1 kip and all five anchors pulled out of the concrete at failure. The large standard deviation came from one of the five samples yielding a significantly lower value for loading at failure. The actual diameter rod was measured to be 3/10 inch. The stress in the rod averaged 85.6 ksi and did not fail. Using the surface area of the side walls of the drill hole, the same method as the control test, the average bond strength is calculated to be 1304 psi with a standard deviation of 211 psi. The results calculated show a loading of roughly 67% the ultimate capacity of the control group and roughly 53% the target ultimate capacity but still surpasses the allowable capacity in the HILTI manual by a factor of 2. Therefore it is a reasonable assumption that if the allowable load is honored the anchor system will not fail. This test series only contained five samples and the statistical power of this data is roughly 0.5. From the data collected it is obvious that the addition of water to the HIT HY 150 MAX significantly lowers its bond capacity.

In the last test, we used the same anchors and adhesive system contaminated with water except the test samples were rectangular blocks. The blocks were made from the same batch of concrete as the other samples. Each of the two blocks were 30” x 6” x 6” and contained three anchors. Due to the dimensions of the block an edge factor of 0.76 is needed for comparison to the listed data in the HILTI manual. The average ultimate load for this test came to 5.8 kips with a standard deviation of 0.8 kips. Samples 1, 4, and 5 failed with anchor pull out, which is shown in Figure 41, while samples 2, 3, and 6 split the sample apart at failure shown in Figure 42. The large standard deviation comes from the wide range of values and this most likely due to the different levels of contamination due to water during installation. Using the actual diameter of

3/10 inch, the stress in the rod averaged 82.7 ksi and did not fail. Using the surface area of the side walls of the drill hole, the same method as the control test, the average bond strength is calculated to be 276psi with a standard deviation of 38 psi. The results calculated a loading of roughly 62% the ultimate capacity, keeping in mind the ultimate capacity is now multiplied by 0.76 because of the edge distance factor, and roughly 64% of the ultimate capacity of the control group. Although the rods failed to reach the ultimate capacity they still surpass the allowable capacity in the HILTI manual by a factor of 2.5. Therefore, it is a reasonable assumption that if the allowable load is honored the anchor system will not fail even with drill holes between 7/16 inches and 1 inch. These stress values may not be accurate because the tests had two different modes of failure. On average the lower failures were due to anchor pull out, therefore we will assume that the values for bond strength are reasonable since low bond strengths were observed for three of the tests.

Figure 41: HIT HY 150 Max, Oversized, Wet Pull Out

Comparing this test to the other HIT HY 150 MAX test contaminated with water we see very little change in load capacity with the increase in surface area for the epoxy to bond with. With the increase in hole diameter the volume of water in the holes increased from roughly 0.5 cubic inches to 0.9 cubic inches. The bond strength for the two different tests decreased from 1,304 psi to 276 psi respectively. From this we can assume with a greater volume of water in the drill holes the greater chance it will have an adverse affect on the epoxy. This test series only contained six samples and the statistical power of this data is roughly 0.6. From the data collected it is obvious that the addition of water in oversized holes to the HIT HY 150 MAX lowers its bond capacity more than the specified drill hole size.

Figure 42: Split Sample

The three tests conducted with the HIT HY 150 MAX adhesive system with 3/8 inch HAS-E rods yielded results pointing to the significant decline of load resistance with the contamination of water. Although all the results did pass the allowable bond/concrete capacity, each test had a different factor of safety. The allowable loads are determined using a factor of safety in order to compensate for unintentional flaws in materials and/or human error that may result in improper installation. Since the HIT HY 150 MAX adhesive is not resistant to water it would be wise to use an adhesive system that is not affected. Therefore in order for the loads applied to have a large factor of safety, a proper adhesive system is required and/or contaminates must not be present during installation. Also the installation requirements such as hole size and edge distance must be honored to ensure the safety of the project.

Appendix A: Definitions

All definitions are taken from the HILTI 2006 North American Product Technical Guide.

Adhesive Anchor: A device for transferring tension and shear loads to structural concrete, consisting of an anchor element embedded with an adhesive compound in a cylindrical hole drilled in hardened concrete.

Anchor Category: An assigned rating that corresponds to a specific strength reduction factor for concrete failure modes associated with anchors in tension. The anchor category is established based on the performance of the anchor in installation safety tests.

Anchor Group: A group of anchors of approximately equal embedment and stiffness where the maximum anchor spacing is less than $3h_{ef.}$

Anchor Spacing: Centerline to centerline distance between adjacent loaded anchors.

Attachment: The structural assembly, external to the surface of the concrete, that transmits loads to or receives loads from the base material.

Characteristic Capacity: 5% fractile of the anchor capacity, defined as that value that will be exceeded by 95% of the population with a 90% confidence.

Concrete Breakout: Failure of the anchor characterized by the formation of a conical fracture surface originating at or near the embedded end of the anchor element and projecting to the surface of the base material.

Cracked Concrete: Condition of concrete in which the anchor is installed; concrete is assumed to be cracked for anchor design purposes if cracks could form in the concrete at or near the anchor location over the service life of the anchor.

Critical Spacing: Required edge distance between adjacent loaded anchors to achieve full capacity.

Critical Edge Distance: Required edge distance to achieve full capacity.

Cure Time: The elapsed time after mixing of the adhesive material components to achieve a state of hardening of the adhesive material in the drilled hole corresponding to the design mechanical properties and resistances.

Displacement Controlled Expansion Anchor: An expansion anchor designed to expand in response to driving a plug into the anchor body.

Ductile Steel Element: An element with a tensile test elongation of at least 14% and corresponding reduction of area of at least 30% at failure.

Gel Time: The elapsed time after mixing of the adhesive material components to onset significant chemical reaction as characterized by an increase in viscosity.

Edge Distance: Distance from centerline of anchor to free edge of base material in which the anchor is installed.

Effective Embedment Depth: Effective anchor embedment equal to distance from surface of base material, for expansion anchors taken as distance from surface of base material to tip of expansion element(s).

Minimum Edge Distance: Minimum edge distance to preclude splitting of the base material during anchor installation.

Minimum Spacing: Minimum spacing between adjacent loaded anchors to preclude splitting of the base material during anchor installation.

Minimum Member Thickness: Required thickness of member in which anchor is embedded to prevent splitting of the base material.

Projected Area: The area on the surface of the concrete member that is used to represent the base of the assumed rectilinear failure surface.

Side Face Blowout: Failure mode characterized by blowout of side cover of an anchor loaded in tension.

Supplementary Reinforcement: Reinforcement that is proportioned and positioned to tie the concrete breakout surface into the structural member.

Torque Controlled Expansion Anchor: An expansion anchor designed to expand with the application of torque to the anchor bolt or nut.

Torque Controlled Adhesive Anchor: An adhesive anchor employing an anchor element designed to generate expansion forces in response to tension loading.

Undercut Anchor: A mechanical anchor designed to interlock with drilled deformations (undercuts) in the base material.

Appendix B: Equations

Allowable Load = $0.33*A_{nom}*F_u*f_{es}$

Ultimate Load = $0.75*A_{nom}*F_u*f_{es}$

σ = Load/Area

$\epsilon = \Delta L/Lo$

$E = \sigma/\epsilon$

FS = (Ultimate Load)/(Allowable Load)

$$s = \sqrt{\frac{1}{n-1}\sum_{1}^{n}(x_i - \bar{x})^2}$$

(95%) Confidence Interval:

AVE±1.96*sqrt(SD/sqrt(n))

A_{nom} = nominal area

F_u = Ultimate Strength of Steel

f_{es} = edge and/or spacing factor

σ = Stress

ϵ = Strain

E = Modulus of Elasticity

FS = Factor of Safety

SD = Standard Deviation

AVE = Average

n = Number of Samples

sqrt = Square Root

Appendix C: References

"ACI Manual of Concrete Practice. Variant Title: Manual of Concrete Practice. American Concrete Institute Manual of Concrete Practice Primary Material: Periodical Subject(s): Concrete--Handbooks, Manuals, etc.--Periodicals. Concrete Construction--Handbooks, Manuals, etc. --Periodicals." .

American Society for Testing, and Materials. "Annual Book of ASTM Standards. Variant Title: Annual Book of A.S.T.M. Standards Annual A.S.T.M. Standards Annual ASTM Standards Annual Book of American Society for Testing and Materials Standards Primary Material: Periodical Subject(s): Materials--Standards--United States--Periodicals. Materials--Testing--Standards--United States--Periodicals." .

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Appendix D: Test Data Sheets

Attached PDF File