Tensile Behavior of Large
Powder-Driven Fasteners in Concrete

by

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Thesis

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SUPERVISING COMMITTEE:

For the unlimited support given to me over the past two years,

this thesis is dedicated to

my family.

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ABSTRACT

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The tensile behavior, in concrete, of a powder-driven nail, developed by the Hilti Corporation, was studied through the use of simple pull-out tests. A likely application of the nails is to provide tensile restraint across an interface between two layers of concrete so that a shear transfer mechanism can develop. Shear transfer capacity can be determined using the shear-friction model which depends on tension in dowels or fasteners crossing the interface. Therefore, tensile pull-out tests are fundamental to understanding the behavior of the nails and to give an indication of their performance for design purposes.

Many of the variables considered to affect the nail's performance were studied. The most important ones were concrete strength, proximity of the nail to an edge of the slab, and proximity of the nail to a crack in the slab. The results show that nails driven into weaker concretes have a lower pull-out strength. They also show that proximity to an edge or a crack reduces the pull-out capacity of the nail.

A data base of 366 simple pull-out tests that were conducted at Ferguson Structural Engineering Lab at the University of Texas at Austin was used to assess the performance of the nails and to develop recommendations for their use in the design of projects involving interface shear transfer. The rapid installation of the nails, which will save time and costs in a construction project, was demonstrated by the large number of tests performed in a short time.

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English to SI Conversions

1 inch = 25.4 mm

1 kip = 4.448 kN

1 psi = .0069 MPa

SI to English Conversions

1 mm = .039 inch

1 kN = .2248 kip

1 MPa = 145.0 psi

Chapter 1: Introduction

1.1 Objective

When a highway pavement or bridge deck reaches the end of its useful life due to deterioration or increased traffic load, two options are generally considered to return them to service: reconstruction or rehabilitation. Reconstruction may be very costly due to the time required for completion and inconvenience to the user when the roadway is taken out of service. Rehabilitation requires less material and produces less disruption to traffic than reconstruction, however, there is often a reluctance to rehabilitate because the performance of such techniques is not well known. In the U.S., roadway rehabilitation usually takes the form of asphalt overlays which can be constructed rapidly and provide a smooth surface, but have a limited service life. Concrete overlays provide a much stronger and potentially longer service life, but have not been widely used in the U.S. The main reason is the longer construction time, compared with asphalt overlays, and the lack of information regarding their long term performance. There are three kinds of concrete overlays.

An *unbonded overlay* is similar to reconstruction in that the overlay is expected to act independently of the original roadway in carrying traffic loads. It has the advantage that cracks in the original roadway surface will not reflect into the new overlay. However, the necessity of an extra bond breaker can be expensive and the relatively thick layer of concrete increases material costs and could pose potential clearance problems at overpasses (11).

In a *partially bonded overlay*, some bond is expected between the original concrete and the overlay; however, it is not ensured. Partial bonding allows for a slightly thinner overlay than in the unbonded case and the expense of thorough surface preparation is reduced. However, the performance of a partially bonded overlay is less predictable than that of an unbonded overlay and reflection cracking will take place (11).

In the past ten years, *bonded overlays* have received increasing attention (14). By providing adequate bond between the original concrete and the overlay, the remaining strength of the original concrete can be utilized, resulting in a much thinner overlay (7). With a bonded overlay, a monolithic pavement is created. Achieving this monolithic behavior is important for obtaining the proper stress distribution and maximum fatigue life. Reflection cracking is a problem, as with the partially bonded overlay, however, the savings in material costs and increased performance resulting from monolithic action justify the use of bonded concrete overlays for rehabilitation projects (11). The most important concern with bonded overlays is the problem of delamination. If the overlay delaminates, or de-bonds, from the base concrete, it cannot be relied upon to behave monolithically, and the overlay will not respond as needed for successful rehabilitation.

The objective of this study is to examine the behavior of powder-driven nails, developed by the Hilti Corporation and proposed for use in concrete overlays, bridge decks, and other concrete rehabilitation projects which are based on achieving monolithic behavior between an overlay and base after fresh concrete is placed against existing concrete.

1.2 The Problem of Delamination

In order for a bonded concrete overlay to perform properly, adequate bond must be maintained between the overlay and the base concrete. If delamination occurs, the assumption of monolithic behavior, and associated stress distributions, will no longer be valid.

The bond strength that develops at the interface of a well prepared overlay is usually three to four times the shear stress caused by traffic loads (1, 5). It would seem, therefore, that delamination would not be a problem. However, a five-year-old overlay project in Louisiana delaminated at approximately 36% of the joints, and a California overlay delaminated over 90% of a one-and-a-half mile section and required replacement (7). Many overlay test sections have been evaluated on IH610 in Houston, Texas. Although the delamination was not as widespread as in the projects in Louisiana and

California, it still occurred at joints, cracks, and near the edges of the slab (5). The extent of delamination on the IH610 project was reduced through the use of improved construction techniques which will be discussed later. The exact consequence of partial delamination of an overlay is uncertain; however, it is believed that any delamination will reduce the service life of the system (7, 14).

It is also believed that early-age failures in bonded concrete overlays are the result of delamination (7). Delamination is often an early-age problem caused by volume changes in the concrete, due to temperature changes and shrinkage, which occur when the bond strength is still low (1, 7). Delamination may occur within the first 24 hours after placement and may increase progressively for about a month. Field observations indicate that, after this time, delamination is no longer spreading (14).

There are many construction variables which will influence the onset of delamination. The condition of the surface of the base concrete is critical. Since bond exists at the interface, clean, sound concrete is necessary (11). Bonding agents have also been used to improve bond and will be discussed later. The ambient temperature and humidity at the time of placement affect the evaporation rate and degree of shrinkage of the overlay which creates the shear stresses at the interface (1, 13). Temperature changes have a similar affect. The moisture level of the pavement seems to impact bond characteristics at the interface (11). A dry surface is preferred to a wet surface, but is often beyond control (11). Delamination is more common along the edges and corners of the slab than it is in the interior. This is most likely due to the fact that the edges and corners may suffer from lack of proper vibration and experience the largest stresses due to volume changes (2, 11, 12).

1.3 Current Remedies

If proper construction techniques are used, the extent of delamination can be greatly reduced, as in the IH610 project in Houston. Proper techniques involve preparing or modifying the surface of the concrete prior to placement of the overlay.

As mentioned before, it is imperative that the surface of the concrete be clean and sound. Typical procedures involve scarifying the surface with a rotomill or shot-blasting to produce a rough interface. This process not only removes damaged concrete, debris, oil, and grease, but also increases the surface area to which the overlay can bond and allows the aggregate to interlock for shear resistance (11). The scarifying process is performed in most overlay projects. In some cases, it is the only form of surface preparation used. In others, a bonding agent is also applied.

There are two types of bonding agents generally considered: portland cement grouts and epoxy resins (1). The grouts can be either water-cement-sand or simply water-cement. Epoxies come in many variations. The two common characteristics between the grouts and epoxies are that they are both used with the intent to improve the interface bond and both increase construction costs.

One study has shown that grout can improve the bond characteristics of a wet pavement, but not a dry one (11). Also, bond can actually be prevented if the grout dries before the overlay is placed (1, 11). Therefore, the application of grout is highly dependent on environmental conditions and construction schedule, both of which may be beyond the control of the design engineer.

Like grout, epoxy is spread over the surface of the concrete before the overlay is placed. Epoxies, however, have even more restrictions than grout depending on the manufacturer. Epoxies have a limited pot life which ranges from one-half hour to two hours, during which time the epoxy needs to be mixed, spread and overlaid. The performance of the epoxies is also highly dependent on the ambient temperature and humidity, which will not necessarily remain constant throughout an overlay project, and many epoxies are not compatible with a wet surface. Epoxies are toxic materials which may pose a hazard to workers and the environment (3).

Although scarification and bonding agents have a history of successful applications, the fact that adequate bond cannot be guaranteed over a large range of situations makes them less than ideal remedies for the delamination problem. Another solution would be to provide a mechanical transfer of forces across the interface, as opposed to a chemical transfer such as would be provided by the bonding agents. This mechanical transfer would take the form of dowels set normal to the surface of the interface. In essence, the interface bond would be assumed not to exist and monolithic behavior would be achieved through transverse reinforcement.

Such mechanical transfer is required by AASHTO in bridge decks. The amount of transverse reinforcement used is described as a ratio of the cross-sectional area of dowels crossing the interface to the area of concrete being overlaid. AASHTO specifies a reinforcement ratio of 0.08%, but studies have shown that this amount of reinforcement is not adequate in maintaining monolithic behavior after the bond is broken. Instead, a reinforcement ratio of 0.28% is suggested (9). The cost of placing these dowels can be as much as 15 to 20% of the total rehabilitation cost (10). Another study indicated that a reinforcement ratio of more than 0.1% would be uneconomical, but that much smaller ratios could be used if the surface of the interface is scarified prior to placing the overlay (8).

The reason for the high cost of using transverse reinforcement is that installing dowels is a very slow, tedious, labor intensive process. Dowels are short lengths of epoxy-grouted bars in pre-drilled holes. After the holes are drilled, they must be carefully cleaned of all dust, otherwise the epoxy will not bond well to the walls of the drill hole (3). Adequate cleaning requires that the hole be scrubbed with a stiff brush and vacuumed. Compressed air alone is not sufficient in removing all the dust and may contaminate the hole with oil (6). The hole is then filled with epoxy and the dowel is set. The limited pot life of the epoxy slows the placement of the dowels since it must be mixed in small batches; the epoxy, again, poses hazards to workers and the environment; and all tools must be thoroughly cleaned before the epoxy hardens. Most importantly, the dowels must stand undisturbed until the epoxy is cured, which can take from 2 to 20 days depending on the manufacturer and ambient temperature (3). This, of course, slows the placement of the concrete.

Although the use of transverse reinforcement is a slow and expensive procedure, bond at the interface is not required to develop interface shear.

Therefore, the design engineer can take a more active role in ensuring that the overlay behaves as intended. If setting the reinforcement were not so labor intensive, it would be much more economical to use, even for highway overlays.

1.4 The Proposed Hilti Fastener

In 1990, the Hilti Corporation began research on a mechanical fastening element for the shear transfer between two layers of concrete. The result was a large nail referred to as a Jumbo Nail (Figure 1.1). The concept is similar to that of the epoxy-bonded dowels; however, to expedite the installation, this nail is driven into the concrete with a special driving tool which makes use of an explosive charge (Figure 1.2).

A series of pull-out tests was performed by Hilti in order to determine the optimum geometry of the nail. The factors considered were the diameter of the shank, the diameter of the nail head, the embedment depth, and the surface profile of the shank. Two shank diameters studied were nominally 8 and 10 mm. Three nail head diameters studied were nominally 15, 17.5, and 20 mm. Two embedment depths studied were 50 and 60 mm. The surface profile includes creating a raised surface on the upper half of the shank to resemble the deformations of reinforcing bars and a smooth shank. The optimum nail geometry would be such that the pull-out strength of the lower half of the nail, which is driven into the hardened concrete, is the same as the pull-out strength of the upper half, which will have fresh concrete cast around it.

These tests showed that the 20-mm nail head diameter produced the best results. The surface profile had little influence on the nails with a 20-mm head diameter, but had a significant influence on those nails with a 15-mm head diameter. Although a 20-mm head diameter was ultimately chosen for the final design, a surface profile was also chosen. This was done in order to improve the bond between the upper half of the nail and the fresh concrete in case of poor compaction during placement. It also produces a likeness to the well known surface deformations of rebar.

The final design produced a nail 120.65 mm (4.75 in.) long and 10.65 mm (0.419 in.) in diameter. The nail head diameter is 19.15 mm (0.75 in.), and 38.1

mm (1.5 in.) of the shank below the head is profiled. The nail is made from high strength steel (600 MPa = 87 ksi yield strength) with a galvanized finish.

The nail is driven into a pre-drilled hole such that only the leading half penetrates the base concrete. The top half (approximately 2.25 in.) protrudes above the surface of the concrete to act as a shear stud for the transfer of forces once the overlay is placed.

The drill hole into which the nail is driven is 60 mm (2.36 in.) deep. The drill bit used is 10.3 mm (0.406 in.) in diameter, 0.3 mm (0.014 in.) smaller than the nail itself. The impact of the driving process created shallow, hairline cracks which radiated from the nail on the surface of the concrete. In order to reduce the occurrence of the surface cracks, Hilti modified the drill bit to produce a stepped bore hole (Figure 1.3). The top 15 mm (0.591 in.) of the drill hole is 12.3 mm (0.484 in.) in diameter and, therefore, makes no contact with the nail (Figure 1.4). With the first point of contact between the nail and the concrete below the surface of the concrete, the amount of surface cracking is reduced.

Hilti found that removing the drill dust from the hole prior to driving the nail reduces the variation in the nails' performance. Use of a hand pump is sufficient in removing this dust; however, compressed air will expedite the process.

There are two mechanisms which provide the pull-out capacity of the nails. The first is friction related to a clamping force created by driving the nail into a hole of smaller diameter. The second is sintering which is the fusing of concrete to the tip of the nail under the great pressure of the driving action. This sintering is usually associated with the tip of the nail, but not exclusively (Figure 1.4).

Hilti performed several pull-out tests in order to isolate the effects of clamping and sintering. Since sintering generally occurs at the tip of the nail only, some nails were machined to have a flat tip (Figure 1.5). Therefore, the working mechanism for these nails would be limited to clamping. Other nails were machined so that the shank above the tip had a smaller diameter than the drill hole (Figure 1.6). Since clamping action could not exist on these nails, the effect of sintering was isolated. When compared with a standard nail (one on which both clamping and sintering existed), clamping was responsible for approximately 70% of the total pull-out capacity, while sintering was responsible for the other 30%.

The base concrete into which the nail is driven could be prepared in much the same way as for epoxy-grouted dowels. The surface can be roughened by rotomilling and/or shot blasting, holes drilled and cleaned, and the nails driven. The difference is that driving the nail is much less labor intensive than setting the grouted dowels. The holes do not have to be cleaned nearly as well; there is no epoxy to mix; and, most importantly, there is no time lost waiting for the epoxy to cure. The load carrying capacity of the nail develops immediately and is available for service as soon as the installation is completed. The overlay can be placed soon after the nails are driven.

In the laboratory, the process of drilling a hole, cleaning it, and driving the nail took approximately 60 seconds. At that rate, reinforcement ratios as high as 0.28% can be provided economically. Therefore, the nails can be used to replace grouted dowels without the high labor costs.

Since the nails can be tested readily, their behavior can be determined under a variety of service situations with confidence. Therefore, an engineer can specify proper use of the nail in a design. Because of the simplicity of their installation, the nails could be used to improve highway overlay projects where interface reinforcement is not currently used because of the high cost. The overlay should be more reliable if a mechanical transfer of forces were provided, instead of relying solely on surface preparation, and the overlay should not be dependent on environmental factors or construction scheduling.

In this study, the tensile performance of Hilti's powder-driven "jumbo" nails in concrete is investigated. Pull-out tests of single nails were conducted. The factors which influence their behavior will be determined considering a variety of possible installation conditions.

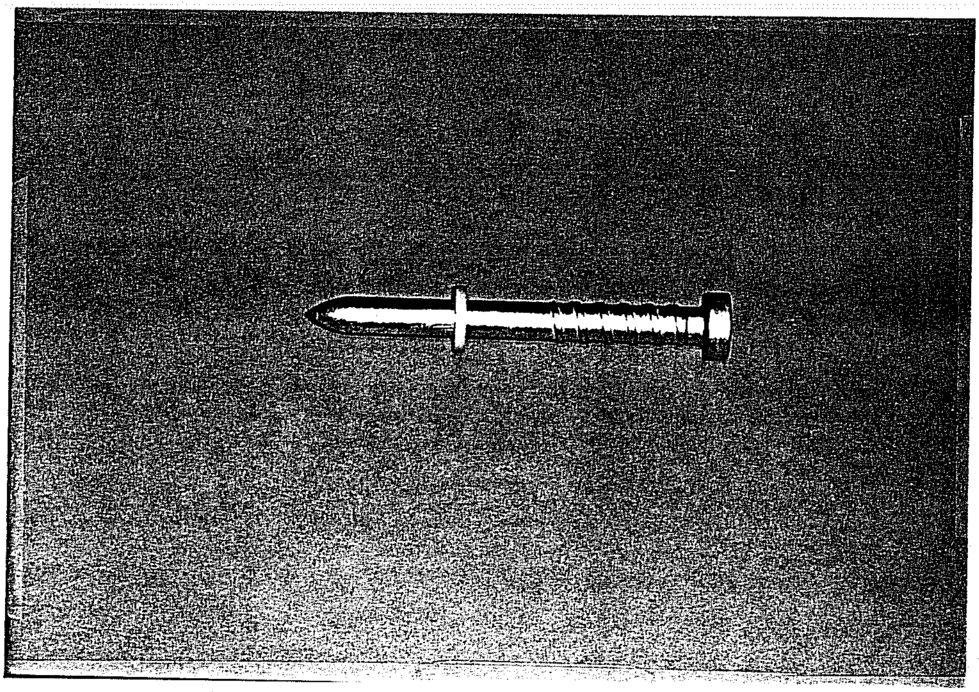


Figure 1.1 The Hilti Jumbo Nail

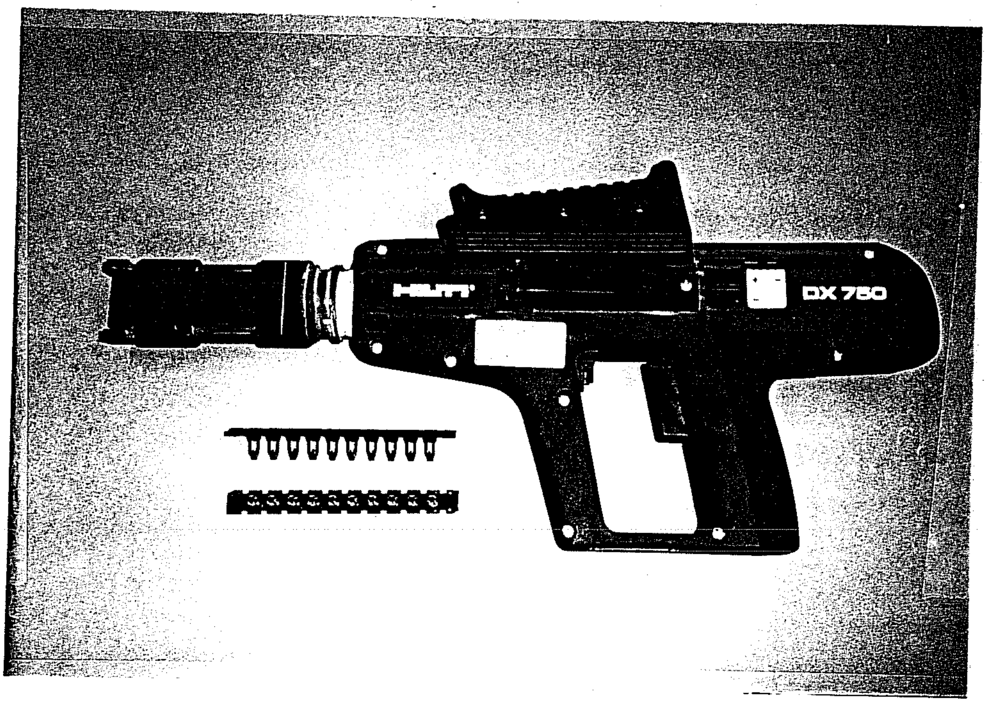


Figure 1.2 Driving Tool and Charges

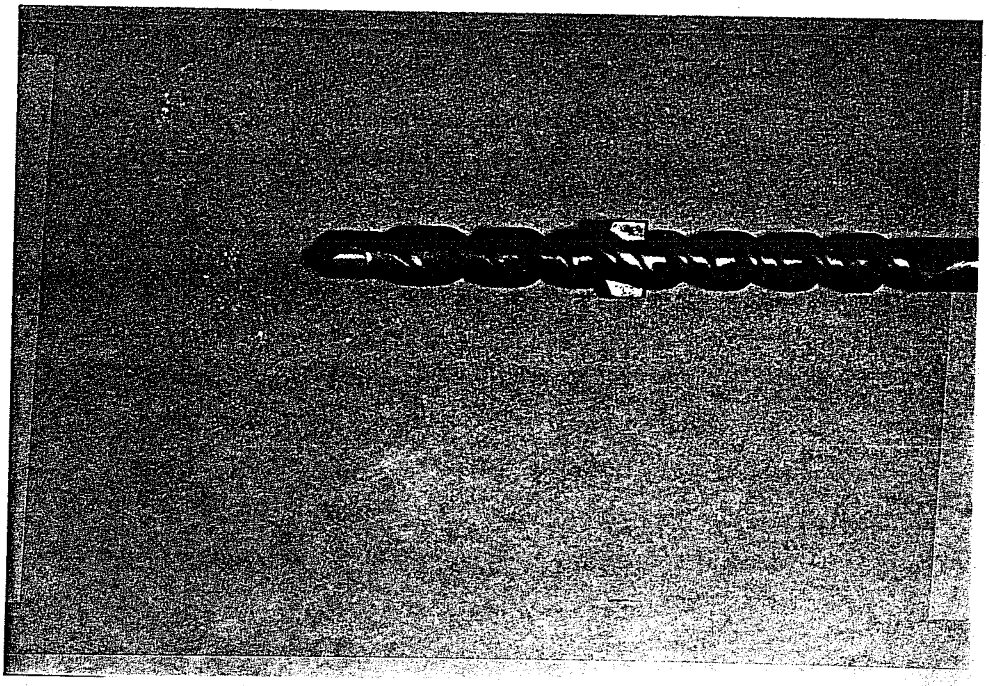


Figure 1.3 Modified Drill Bit to Produce Stepped Bore Hole

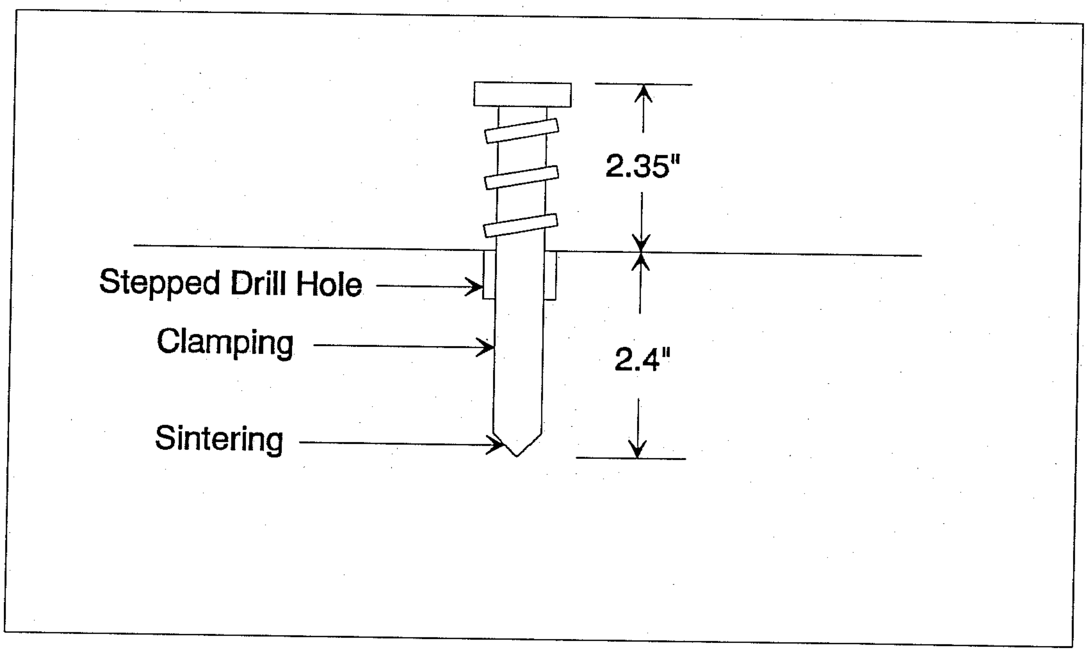


Figure 1.4 Schematic of Installed Nail

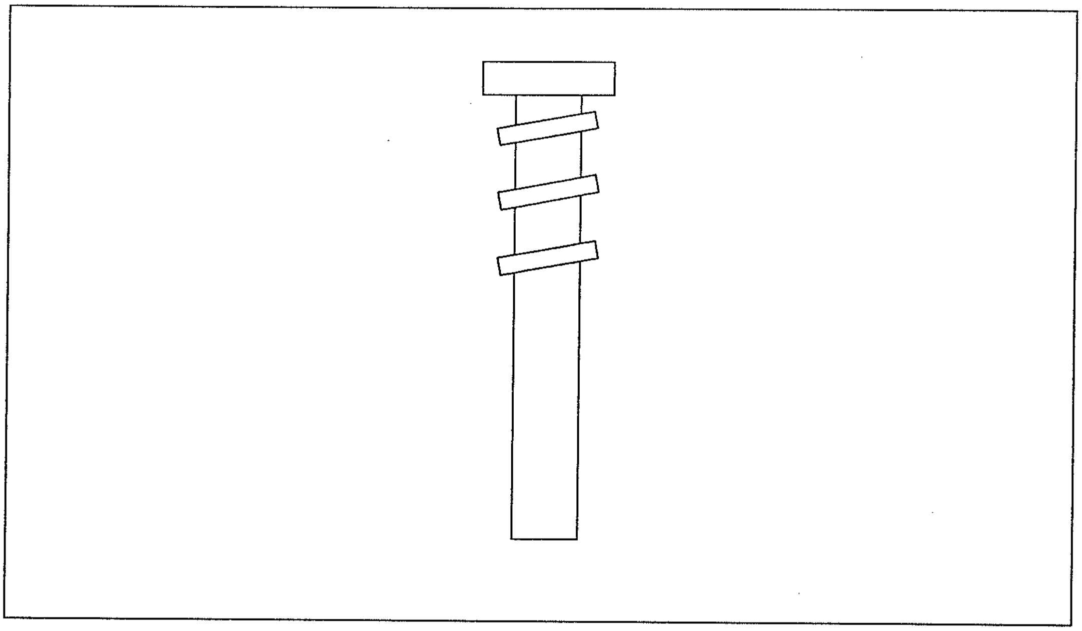


Figure 1.5 Nail Modified to Isolate Clamping

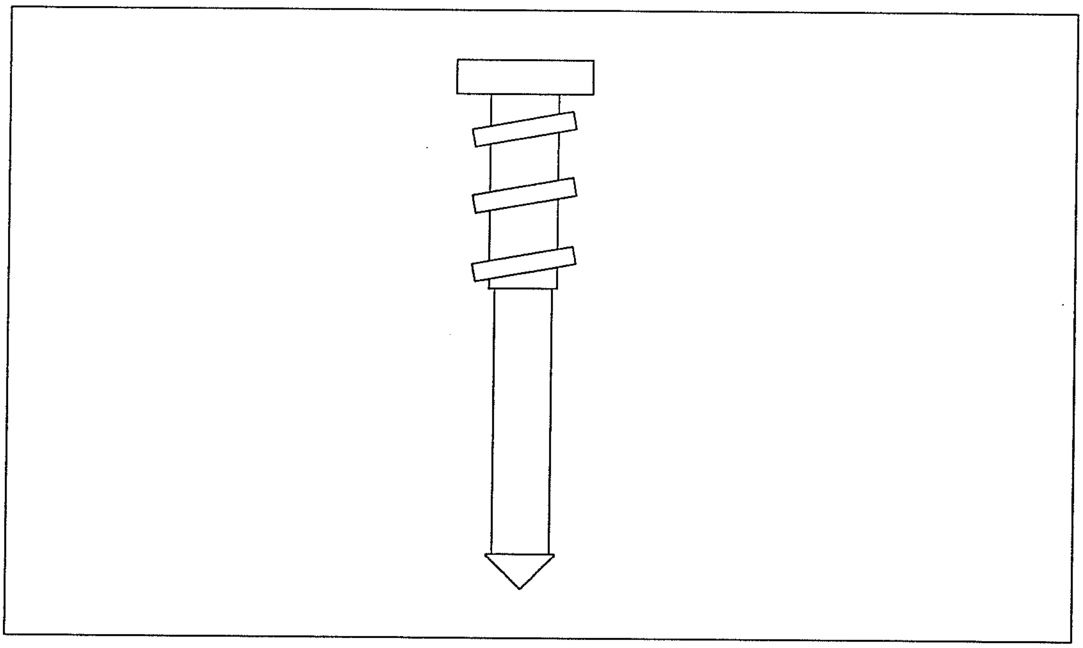


Figure 1.6 Nail Modified to Isolate Sintering

Chapter 2: Pull-Out Test Program

2.1 Introduction

In order for a thin concrete overlay to work effectively, the overlay must act monolithically with the base concrete on which it is placed. Therefore, any shear stresses that develop must be transferrable between the two layers of concrete. In the absence of adequate bond at the interface, the transfer of shear is accomplished only through the use of transverse reinforcement.

If the interface were perfectly smooth, shear stresses would be transferred by dowel action of the reinforcement (Figure 2.1). However, the surface of the base concrete is often roughened prior to placement of the overlay. This not only changes the bond characteristics at the interface, but also changes the role of the transverse reinforcement.

The shear-friction model demonstrates how shear forces at the interface induce tensile forces in the reinforcement (Figure 2.2). That is, in order for the overlay to displace horizontally relative to the base, it must necessarily displace vertically. Vertical displacement mobilizes a tensile force in the transverse reinforcement.

In addition to the importance of understanding the behavior of the transverse reinforcement in tension, the pull-out tests have the advantage of being performed quickly. In this program, a large data base was created with replicates of many test groups. In this way, the important factors which effect the reinforcement's behavior were determined and could be implemented in future tests.

2.2 Test Apparatus

Shortly after it was driven, a tensile load was applied to the nail until failure occurred with it pulling out of the concrete. The load was applied with a hydraulic ram resting on a reaction ring. The reaction ring was a ten-inch-diameter pipe approximately 20 inches tall (Figure 2.3). A ten-inch diameter was felt to provide adequate space around the nail so as not to affect its performance by restraining the concrete in its proximity. Access to the nail inside the reaction ring was provided by openings cut in the wall of the pipe. A special collar was fabricated to fit below the head of the nail such that displacement readings could be taken directly from the nail head during the loading process (Figure 2.4).

Displacement readings were taken by a linear potentiometer attached to an arm which extended from outside the loading ring (Figure 2.5). The applied load was measured with a pressure transducer. Signals from the linear pot and pressure transducer were recorded continuously. Load was applied slowly for 60 seconds with failure occurring at approximately 40 seconds. This allowed for post-failure behavior to be recorded.

2.3 Variables Tested

The test program was developed to simulate field conditions as closely as possible. Variables, such as the presence of cracks in the concrete, that would normally be encountered during the application of the nails, as well as subtle variations from the recommended installation procedure, were studied.

Concrete Strength: As with most studies in concrete, the strength is perhaps the most important factor to be considered. A great deal of the tensile capacity of the nail comes from the clamping action provided by driving the nail into a hole of slightly smaller diameter. The magnitude of this clamping force is related to the modulus of the concrete, which is, of course, related to its strength. Four slabs with different concrete strength were cast. The first slab had a compressive strength of approximately 4650 psi at the time of testing. Similarly, slab two had a strength of 2710 psi; slab three had a strength of 4090 psi; and slab four had a strength of 7440 psi. These four strengths cover, approximately, the range of concrete strengths typically found in roadway construction.

Aggregate Type: In order to determine whether concrete materials influence the performance of the nails, three different aggregates were used in the slab designs. Slab one was cast with river gravel, slabs two and four with soft limestone, and slab three with hard limestone. Slabs one and three, which have similar strengths, have different aggregate types, while slabs two and four, which have the same aggregate, have very different strengths. With these pairings, the effects of aggregate type on nail behavior can be separated from the effects of concrete strength.

Power level: The driving tool used to install the nail was equipped with a dial that allowed the user to adjust the amount of the charge that was directed towards driving the nail. The dial was demarcated one through four with intervals of one-half. In order to study the effects of the charge on the behavior of the nail, tests were performed at power levels 1, 2, 3, and 4.

Location of nail on slab: Three main characteristics related to the condition of the slab, other than the concrete strength, were proximity of the nail to the edge of the slab, proximity of the nail to a crack in the slab, and a standard condition where the nail was driven near neither a crack nor an edge. Since many variables were expected to influence the behavior of the nail, it was important to separate their effects as much as possible. Therefore, the standard tests, performed away from an edge or a crack, were taken as a reference against which the other tests could be compared.

Distance from edge of slab: Considering that most delaminations occur along the edges of pavements, or at cracks, it is likely that the nails will be used more frequently at these locations. The effect of the edge of the slab on the pull-out behavior of the nail was studied by driving them at various distances from an edge. During a preliminary test, a nail was driven close enough to an edge to cause a cone of concrete to spall off. It was therefore determined that a limit had to placed on the proximity of a nail to an edge in order for the nail to be effective. Nails were driven from four to six inches from the edge of the slabs in one-half-inch or one-inch increments.

Presence of a crack: Quite often, cracks will exist in the pavement on which the nails are to be applied. It is likely, therefore, that some nails will be driven in or near an existing crack. It is also common for delaminations to take place at the locations of cracked pavement. Several series of tests were performed in cracked slabs.

The slabs were cracked and loaded by creating a constant moment region in the center section of the slab. Pin supports were provided 48 in. from either end of the slab and hydraulic rams tied to the strong floor provided the necessary load. The distance from the support to the load point was 42 in. (Figure 2.6)

Many variations of the cracked-slab tests were performed. The simplest, series B, was to drive the nail directly into a crack and pull it out immediately (Figure 2.7). Series A involved driving the nail into an existing flexural crack and then loading the slab in flexure such that the crack began to dilate (Figure 2.8). The nail was tested after loading the slab. Series C was similar to series A except that the slab was loaded to only half the level as in series A (Figure 2.8). A battery of tests in series D was performed with the nail driven near a crack, rather than directly in it, and tested immediately (Figure 2.9). Here, the proximity of the nail to the crack was the variable. Distances of one, two, and three inches were used. During some preliminary tests, cracks developed between nails that were driven close to each other. The next two series of tests involved driving a line of nails across the width of the slab at eight-inch intervals. This produced a hairline crack, approximately 0.002 in. in width, between the nails. The slab was then loaded in flexure until the crack began to widen. In series F, the nails were pulled immediately after loading (Figure 2.10). Series G followed the same procedure as series F, except the slab was unloaded before the nails were tested (Figure 2.11).

Results from the standard tests, performed prior to the cracked-slab tests, showed that the pull-out strength of the nails was independent of power level. Therefore, it was not necessary to have replicates of each series under every power level. The limited space on each slab was also unable to accommodate tests at several power levels. In all cracked-slab tests, the nails were driven at power-level two.

2.4 Sensitivity to Drilling Procedure

Technical recommendations for the drilling procedure were provided by Hilti. These recommendations included the depth and angle of the drill hole.

Although variations from the recommended procedure were not intentional, it was found that they were inevitable. By recording the drill-hole depth and angle, the effects of deviations in the recommended values on the nail's performance could be studied.

Depth of drill hole: Recommendations by Hilti called for the hole for the installation of the nail to be 2.36 in. (60 mm) deep. During preliminary testing, it was found that obtaining the 2.36-in. depth exactly was very difficult given the variation in surface roughness and the accuracy of the depth gage on the drill. Therefore, after the hole was carefully drilled and cleaned, its exact depth was measured using a depth gage micrometer (Figure 2.12). Two or three separate readings were taken to ensure consistency. The hole was used regardless of the depth.

Angle of drill hole: It was also recommended that the hole be drilled perpendicular to the surface of the concrete. The hole was drilled as plumb as possible with a hand drill, and then cleaned. A dowel was placed in the hole and a protractor was used to measure the angle of the hole with the surface of the concrete (Figure 2.13). The angle was measured in two orthogonal directions so that the resultant angle could be determined. The hole was used even if it were drilled several degrees out of plumb.

2.5 Other Factors Studied

Observations characteristic of the nail's performance were recorded. These were surface crack lengths, type of failure, and degree of sintering.

Surface cracks: Although the stepped hole created by the modified drill bit was intended to reduce the damage caused during installation, it was found that driving the nail still produced hairline cracks, 0.002 in. wide, that radiated from the nail. These cracks extended further for some nails than for others. The cumulative lengths of all the cracks produced at a nail were recorded in order to determine if they had any influence on performance (Figure 2.14).

Failure Cones: There were two basic modes of failure for the nails. Most pulled cleanly out of the concrete. On several occasions, however, the nail pulled a cone of concrete from the slab (Figures 2.15a and 2.15b). Some of the cones were almost as large as the reaction ring in diameter and nearly as deep as the nail. Others were smaller in diameter and shallow. The presence and size of these cones were recorded.

Sintering: There are two mechanisms which provide the pull-out capacity of the nails. The first is a clamping force produced by driving the nail into a hole of smaller diameter than itself. The second is sintering which is the fusion of concrete to the sides and tip of the nail. The amount of sintering that took place varied from negligible to large pieces of mortar, and even aggregate, attached to the nail. After the nail was pulled out, the degree of sintering was noted as low, medium or high (Figures 2.16a, 2.16b, 2.16c).

2.6 Procedure and Data Collection

The test program began by casting the four slabs required to perform the necessary tests. The slabs were 13 ft. long, 4.5 ft. wide, and 8 in. deep. Reinforcement consisted of number 6 bars spaced 10 in. in both directions at mid-depth. This provided 0.5% reinforcement which is common in roadway pavements. It also allowed for both sides of the slab to be used for test space. (This proved not to be necessary, as all tests in this program fit on a single side of each slab.) Slabs were cast in pairs on four separate dates. The first of each set of slabs was used for the pull-out tests. The second of each set was reserved for future use. Testing began after the slabs were cured for at least 28 days.

After the hole was drilled, a small hand pump or compressed air was used to remove dust from the hole. The depth and angle of the drill hole was then measured and recorded.

The power level on the driving tool was set to the level desired and the nail was driven. The surface of the concrete around the nails was inspected for hairline cracks and their cumulative lengths recorded.

For those tests in which the presence of a crack played a role, the crack width was measured using a template. For series A, B, C and D, the crack width was measured before and after driving the nail. For series A and C, the crack width was also measured after the slab was loaded in flexure. For series F and G, a hairline crack formed between the nails shortly after being driven. The widths of these cracks were 0.002 in. or smaller. The crack width was measured after the slab was loaded, and again after being unloaded for series G.

The loading sequence for the pull-out tests consisted of first placing the reaction ring over the nail such that it was nearly centered over the nail. The split-collar fixture was placed over the head of the nail and attached to the hydraulic ram. A linear potentiometer was set in place on the center of the head of the nail to measure the displacement of the nail directly. A pressure transducer was used to measure the pressure in the hydraulic line leading to the ram. The linear pot and transducer were linked to a data logging X-Y plotter which stored 1000 readings of each channel during a 60 second test period. Pressure in the ram was controlled with a hand pump. The loading rate was controlled to reach failure in approximately 40 seconds. At this rate some post-failure data were recorded.

To expedite the test procedure, a group of nails was driven at the same time and tested in sets. Testing time, from the preparation of drill hole and cracking of the slab to inspection of the sintering level, took between 6 and 12 minutes per nail.

After the nail was pulled out, the size of the failure cone, if any, and the level of sintering could be determined. A shallow cone, six inches in diameter or smaller, was taken as a medium cone. A full cone was larger than six inches in diameter and generally extended down the length of the nail (Figures 2.15a and 2.15b). The level of sintering was a fairly subjective measurement based on the amount of cement paste or mortar fused to the nail. Figures 2.16a, 2.16b, and 2.16c show typical examples of low, medium, and high levels of sintering, respectively.

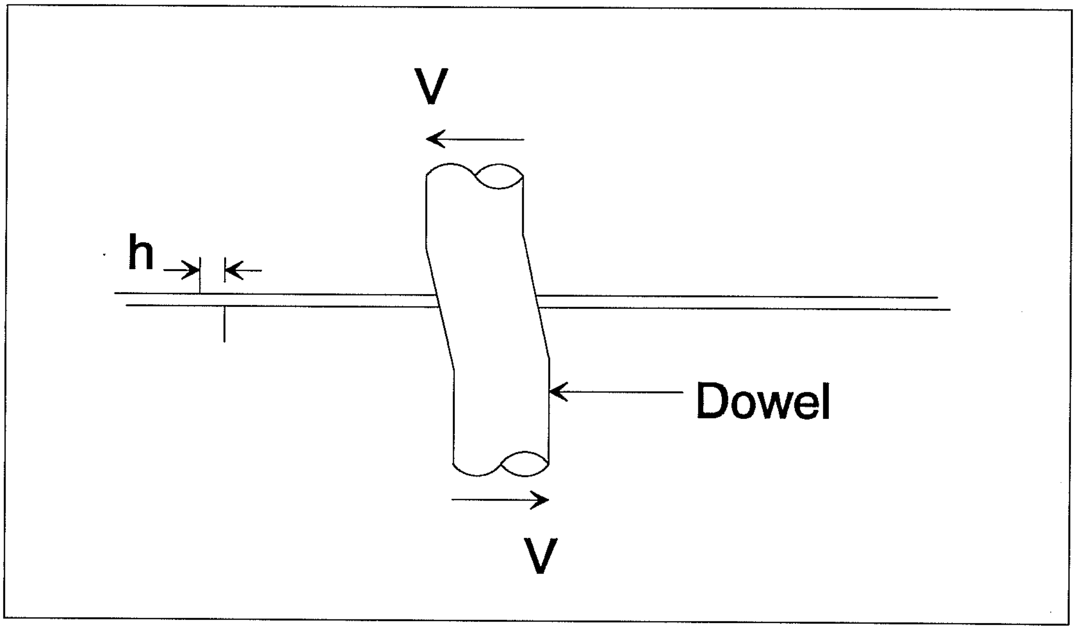


Figure 2.1 Shear Transfer by Dowel Action

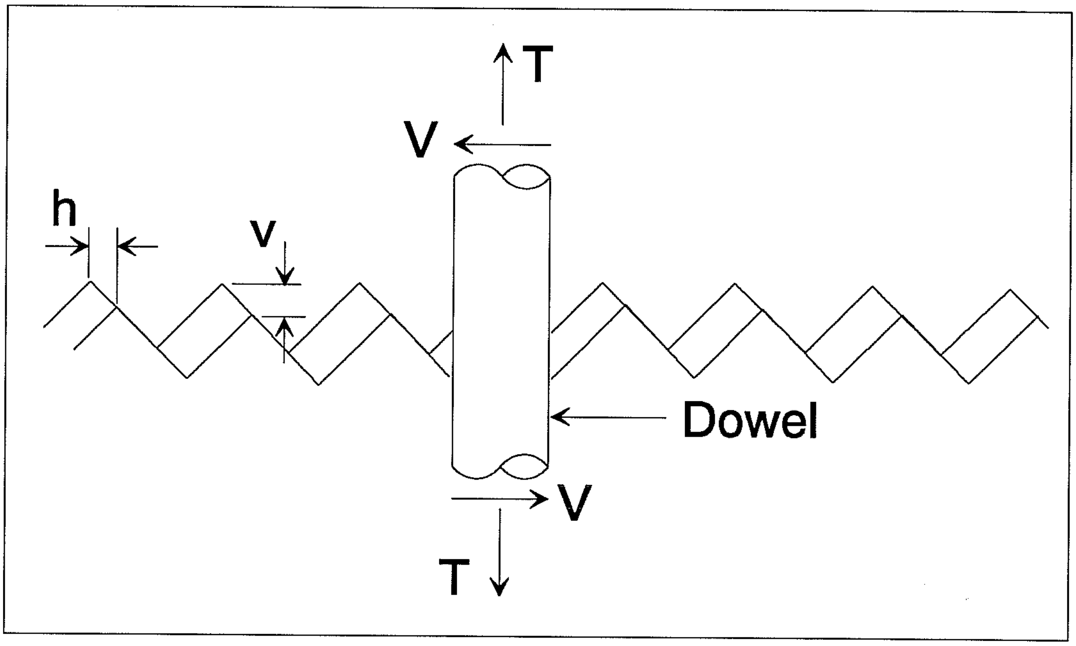


Figure 2.2 The Shear-Friction Model

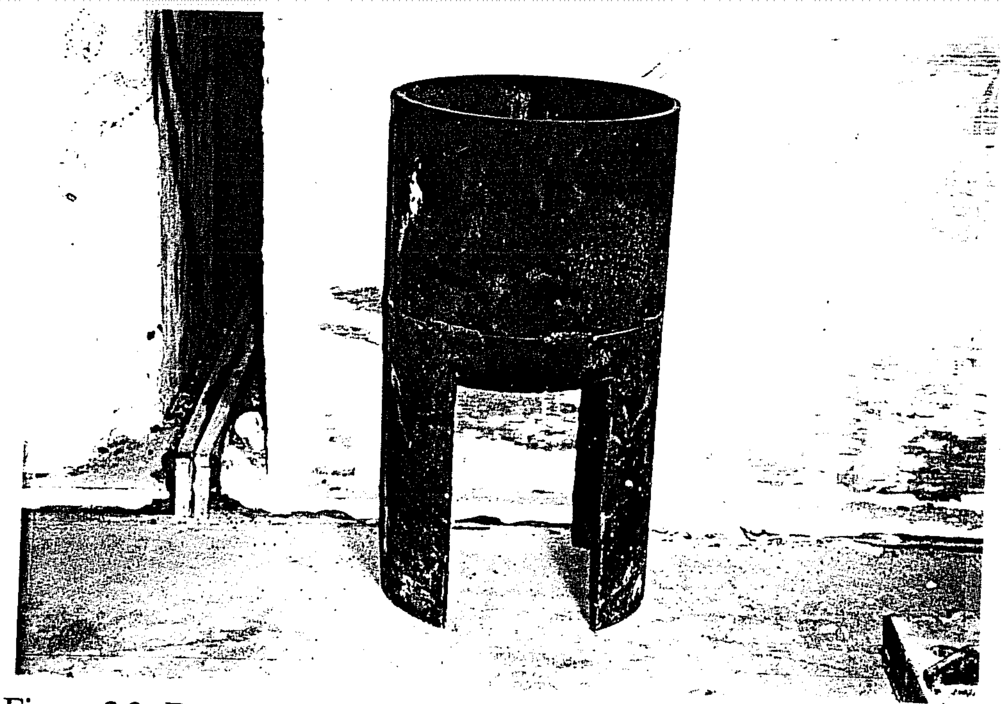


Figure 2.3 Reaction Ring

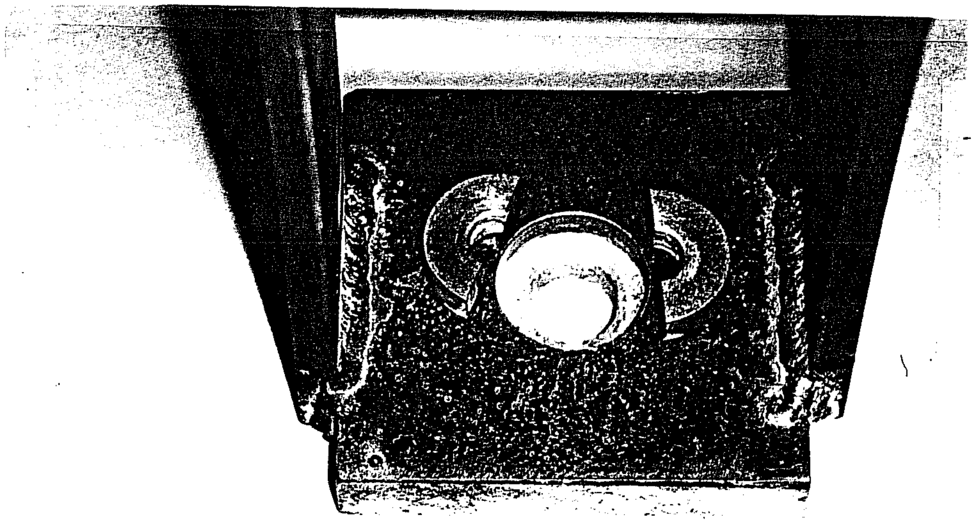


Figure 2.4 Split Collar to Facilitate Displacement Readings

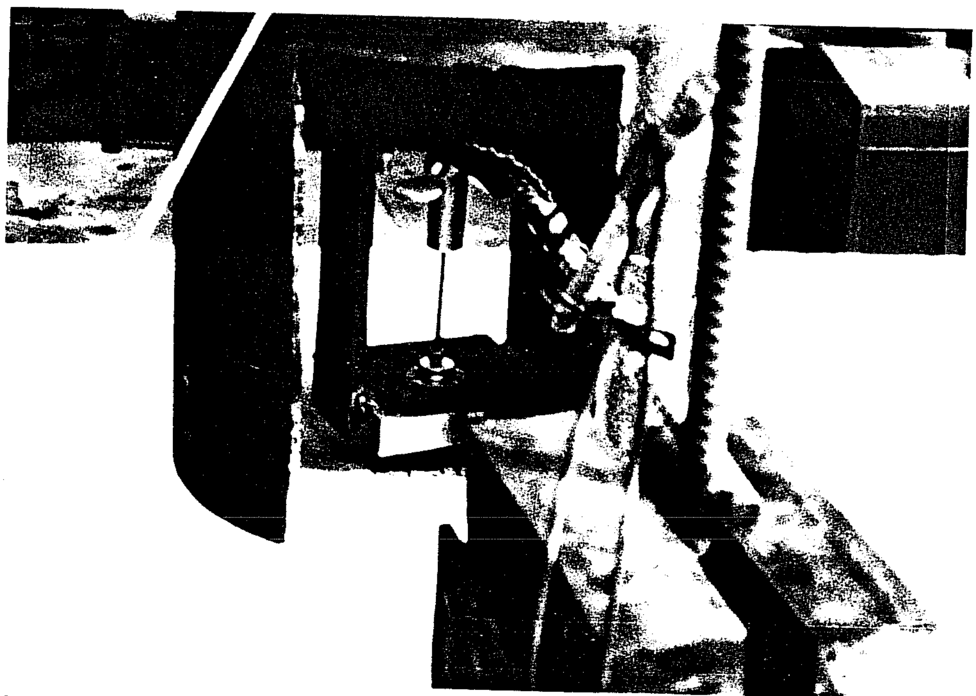


Figure 2.5 Linear Potentiometer for Displacement Readings

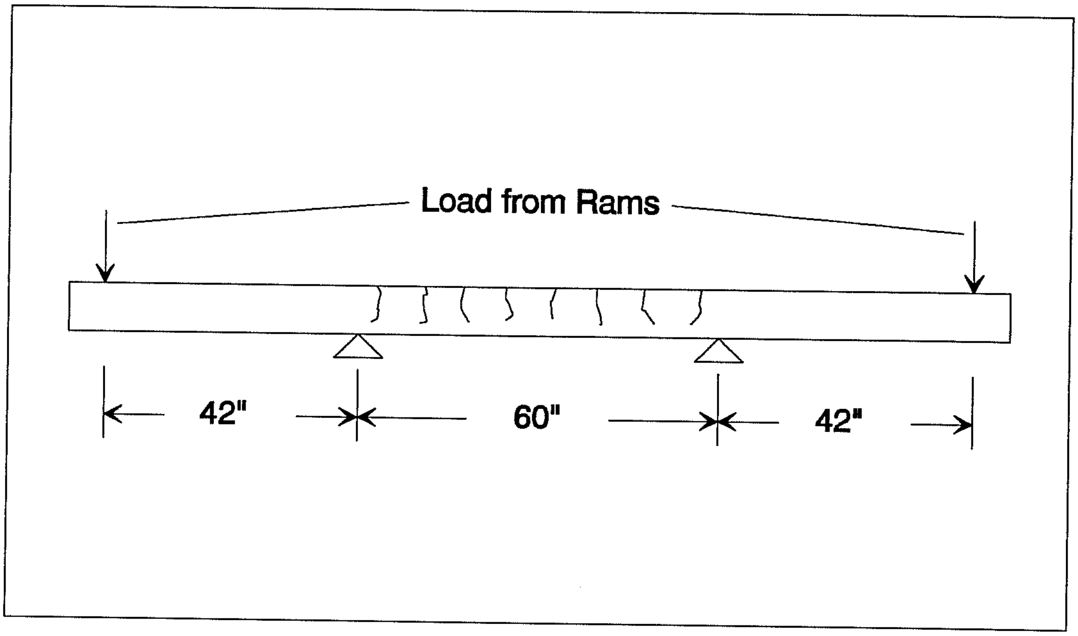


Figure 2.6 Cracks in Slabs Created by a Constant Moment Region

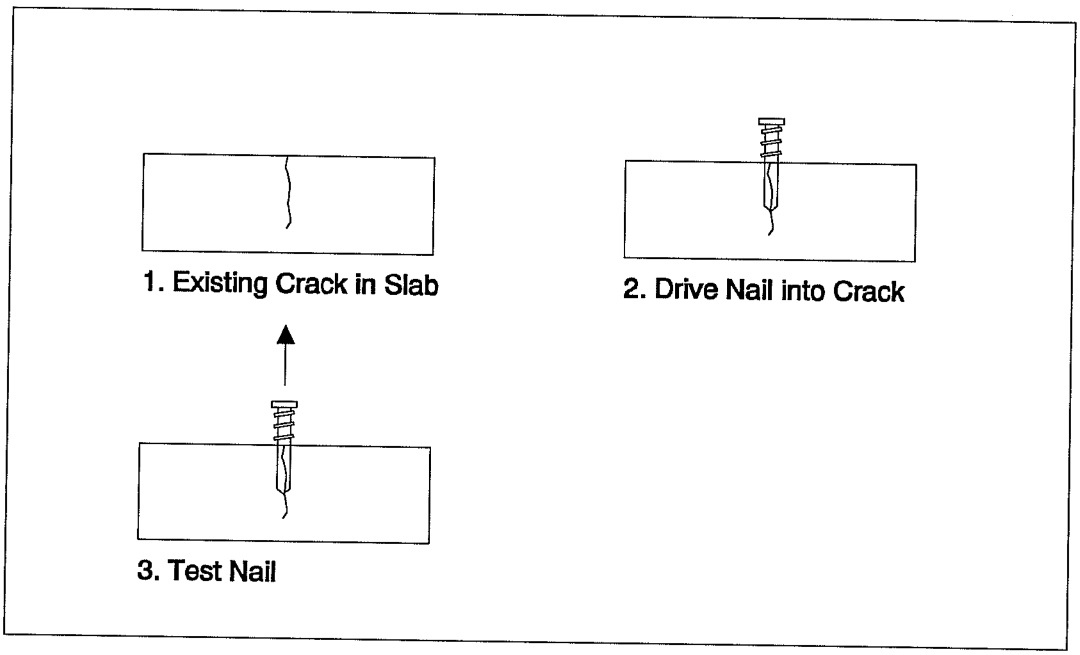


Figure 2.7 Schematic of Series B Tests

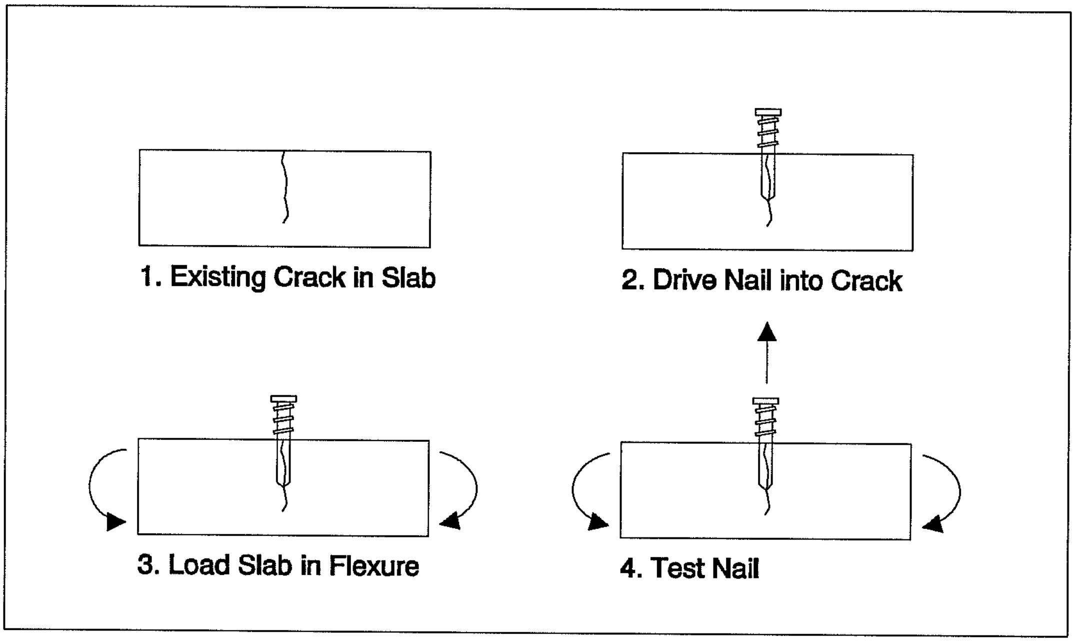


Figure 2.8 Schematic of Series A and Series C Tests

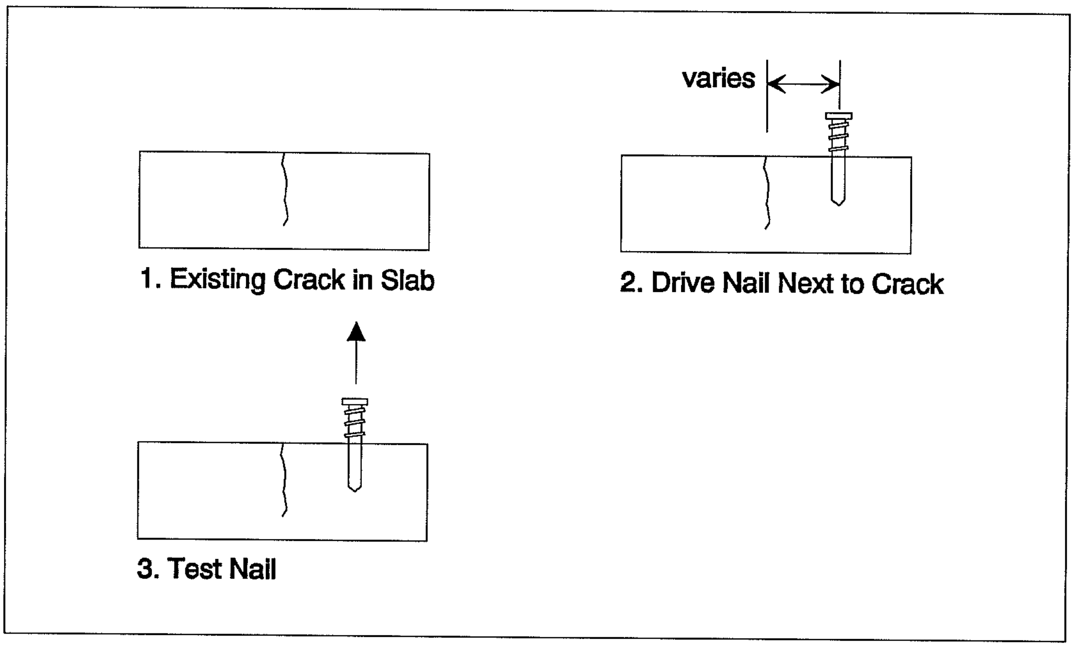


Figure 2.9 Schematic of Series D Tests

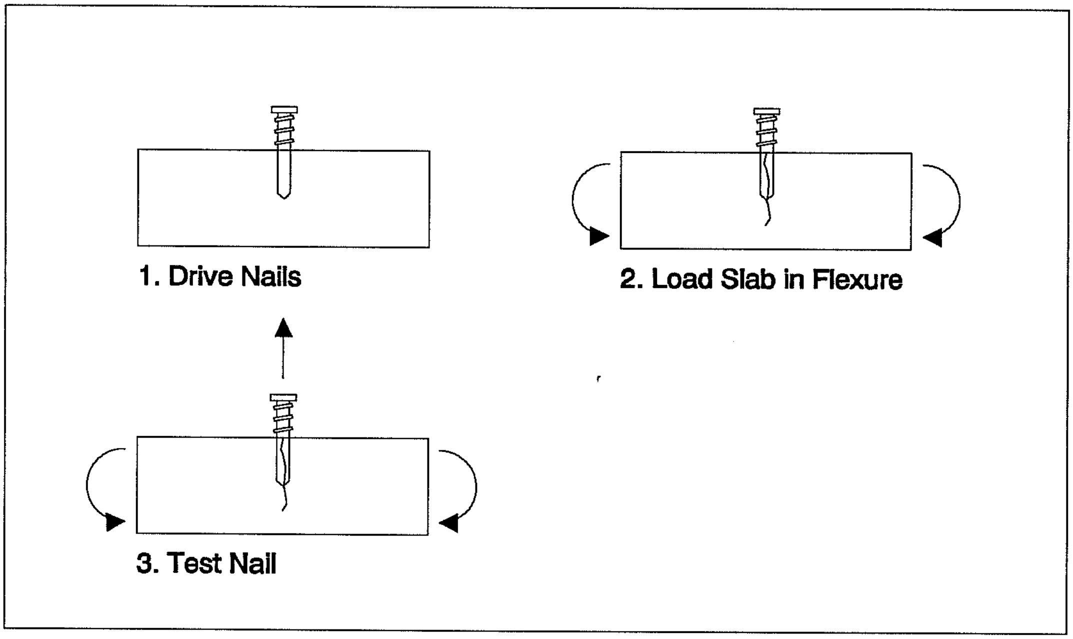


Figure 2.10 Schematic of Series F Tests

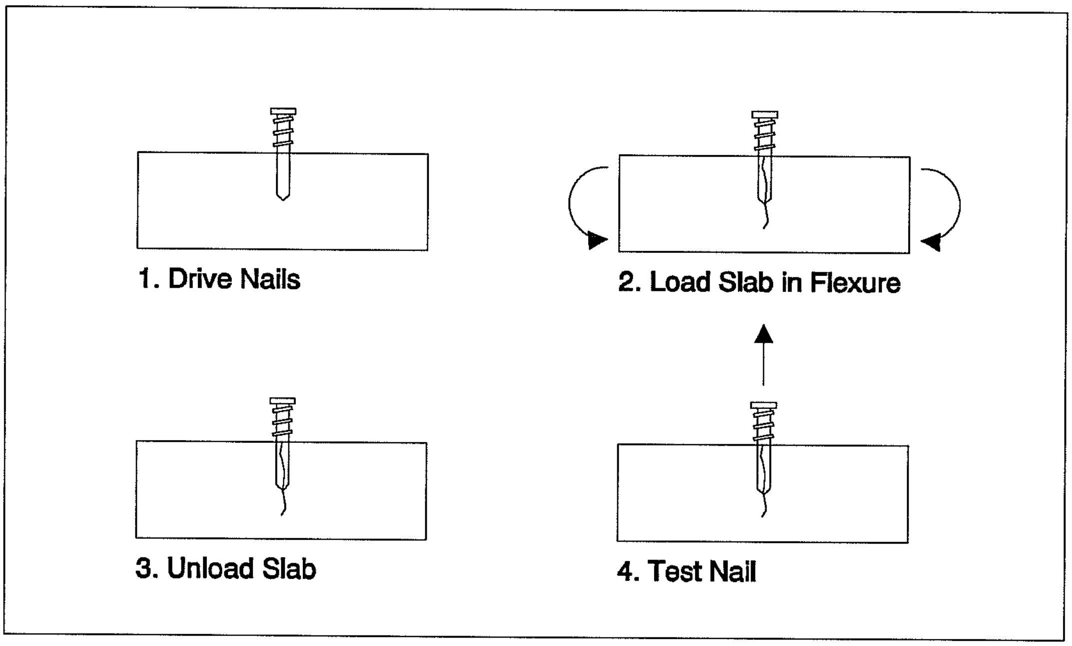


Figure 2.11 Schematic of Series G Tests

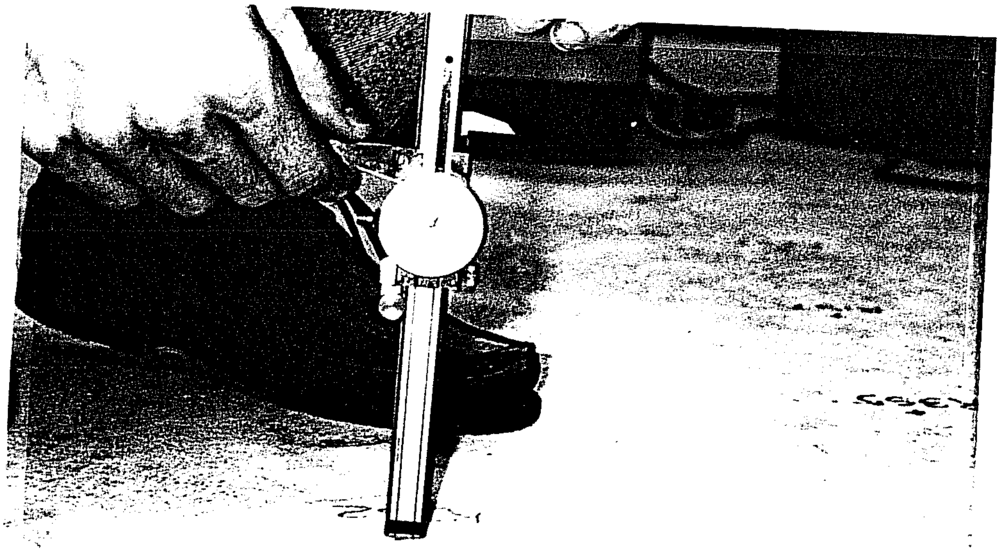


Figure 2.12 Measuring the Depth of the Drill Hole

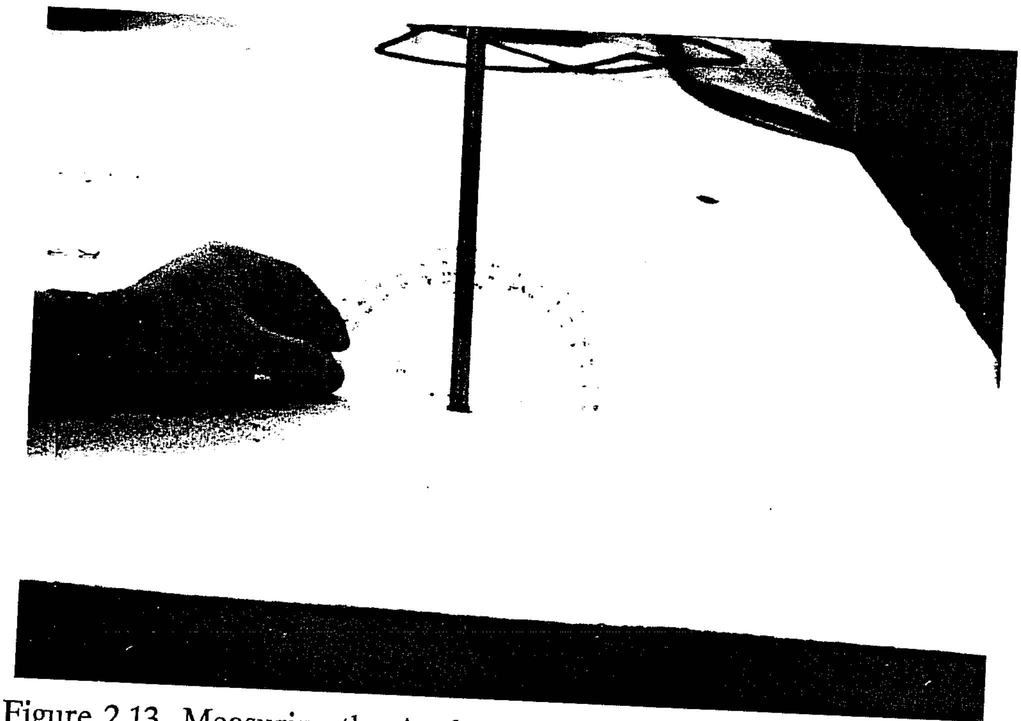


Figure 2.13 Measuring the Angle of the Drill Hole

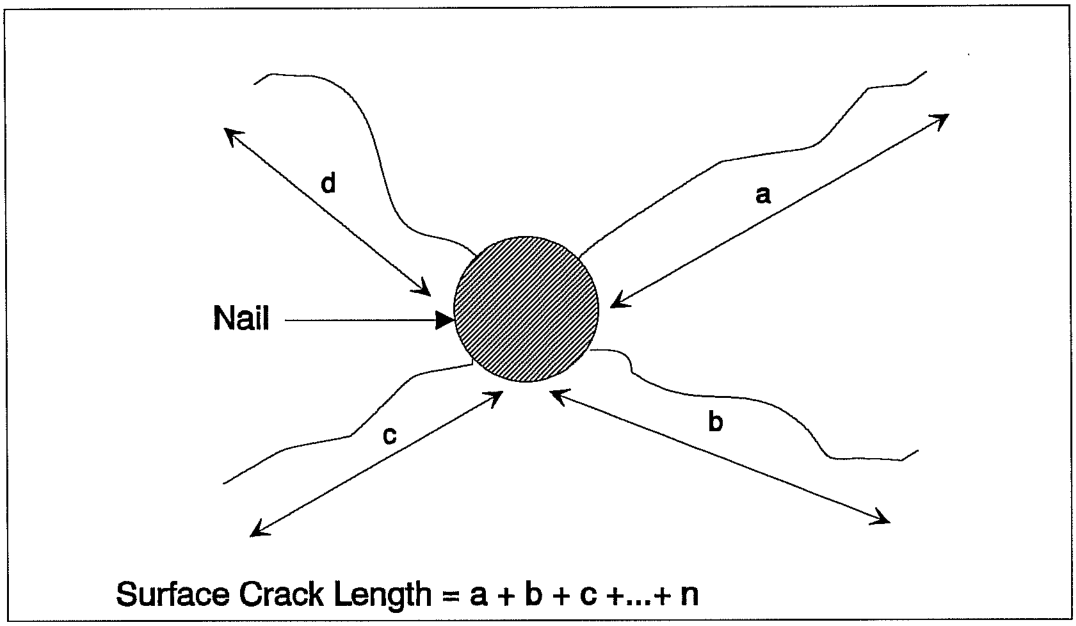


Figure 2.14 Cumulative Length of Surface Cracks

Figure 2.15a Cone-Type Failure

Figure 2.15b Cone-Type Failure

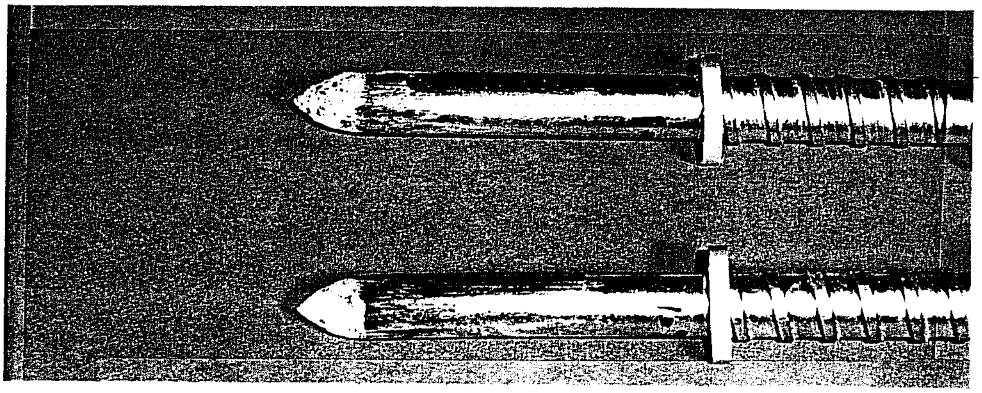


Figure 2.16a Low Level Sintering

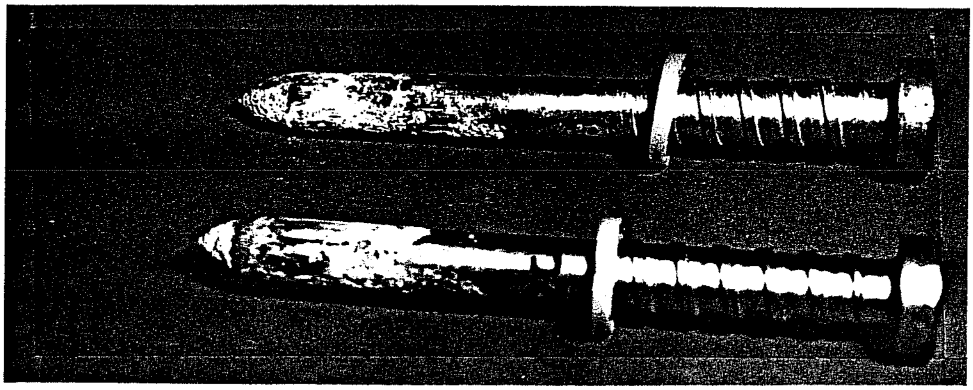


Figure 2.16b Medium Level Sintering

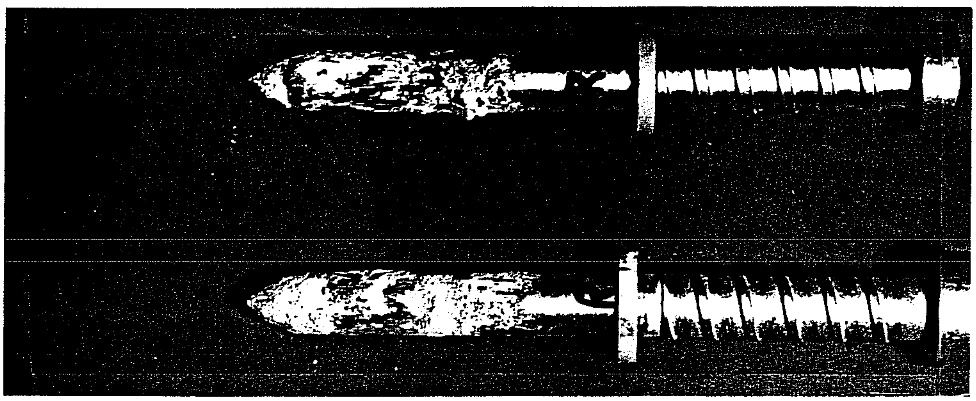


Figure 2.16c High Level Sintering

Chapter 3: Results and Discussion

3.1 General Behavior

The collection of pressure transducer and linear potentiometer readings allowed for the development of load-displacement plots for each nail tested. A typical load-displacement plot can be seen in Figure 3.1. All other plots can be found in the Appendix.

The peak load for every nail was easily obtained from the plot and is recorded in the Appendix. Failure, which is accompanied by a sudden drop in load carrying capacity, occurs shortly after the peak load is reached. The displacement corresponding with the peak load is between 0.01 and 0.02 in. for almost all the tests performed. After failure, the displacements increased more quickly. Although the nail could not maintain the peak load through large displacements, Figure 3.1 shows that it could maintain approximately 50% to 70% of its peak load.

Judging from the tests performed by Hilti, which showed that clamping was responsible for about 70% of the total capacity, it would seem reasonable to assume that the sudden drop in load was due to the failure of the sintering on the nail. Once this bond between the nail and concrete was overcome, the only load-carrying mechanism which remained was clamping.

The vast majority of the nails pulled out cleanly from the concrete leaving no marks on the surface except for the drill holes. Some of the nails, however, pulled out a cone of concrete from the slab. The cones were of various sizes. The largest ones had a diameter of up to 10 in. (the size of the reaction ring) and extended nearly to the tip of the nail. Figures 2.15a and 2.15b show a typical large-cone failure. Other cones were both smaller in diameter and depth. About 6% of the 366 nails tested failed by pulling out a cone.

Nails that pulled out with a cone-type failure showed little difference in strength from nails that pulled cleanly from the concrete. The only difference between the two was the post-failure behavior. Figure 3.2 shows the load versus displacement plots for two nails that failed with cone-type failure (R4S2 and H3S3) and, for comparison, two nails that failed by pulling cleanly from the concrete (R4S1 and H3S2). Whereas nails that pulled cleanly from the concrete could sustain 50 to 70% of their peak load for large displacements after failure, the load carrying capacity of the nails that failed by pulling a cone dropped immediately after failure. There was no ductility at all associated with the cone-type failures. This sudden reduction in pull-out load is represented by the dashed lines in the plots of nails R4S2 and H3S3. The actual path of unloading for the nails at these points is unknown since the data acquisition system had a finite scan rate.

3.2 Number of Nails Tested

In a five month period, 366 nails were tested. This rate of testing demonstrates the nails' short installation time. Table 3.1 shows the distribution of the nails tested among the test types. The 366 nails were divided almost equally between the standard, edge, and cracked-slab tests.

At first, it was desired to produce as many replicates of each test as the slab would allow. The standard tests and edge tests on slabs 1 and 2 were the first to be performed. Eight and nine replicates, respectively, of each test under four power-level conditions were taken. The results showed very little scatter. It was felt, therefore, that fewer replicates of each test could be made while still maintaining confidence in the results. For slabs 3 and 4, only six replicates of each test type were taken.

For the standard tests on slabs 1 and 2, eight replicates per power-level for a total of 32 tests per slab were conducted. Reducing the number of replicates to six for slabs 3 and 4 resulted in a total of 24 tests per slab.

The edge tests on slabs 1 and 2 involved edge distances from 4 in. to 6 in. with half-inch increments. Two replicates of each distance from 4 in. to 5.5 in. and a single test at 6 in. were taken. These nine tests over the four power-levels gave a total of 36 tests for each of these two slabs. The edge distances for slabs 3 and 4 were also 4 in. to 6 in., with one-inch increments, however.

Two replicates at each distance over four power-levels totalled 24 tests for each of these two slabs.

The cracked-slab tests consisted of six different series. The most important were series B and D since they represented, most closely, conditions that would be expected in the field. These series involved driving the nail into or near an existing crack and pulling it out (refer to Figures 2.7 and 2.9). For series B, as many replicates as the cracks in the slab would allow were performed. This varied from eight to twelve. In series D (nails near a crack), three replicates were tested for each of three distances from the crack. A total of nine tests per slab was performed. Series A, C, F, and G were performed primarily for understanding nail behavior rather than to simulate any specific field condition (refer to Figures 2.8, 2.10, and 2.11). Since the slab was loaded in flexure after driving the nail and, in the case of series G, unloading, only a few replicates of each nail geometry were performed.

3.3 Pull-Out Strength Summary

Table 3.2 contains a summary of the average pull-out strength, in kips, for the nails tested in the standard tests. The average pull-out strength for these 112 nails was 7.52 kips, with a range of 3.14 kips (slab 2, nail S1S7) to 11.33 kips (slab 4, nail T4S6). The main difference between the four slabs was the concrete strengths, which, at time of testing, were 4650 psi for slab 1, 2710 psi for slab 2, 4090 psi for slab 3, and 7440 psi for slab 4.

Effect of Concrete Strength: Table 3.2, along with Figure 3.3, shows a clear trend between concrete strength and average pull-out strength. Higher strength concrete produced higher pull-out strengths. It seems that the higher strength concrete provided greater clamping force on the nail. The process of driving a nail into a hole of slightly smaller diameter introduced a radial strain in the surrounding concrete. The stress associated with this strain was related to the modulus of elasticity of the concrete, which, in turn, was related to the concrete strength. As the concrete strength increased, so did the modulus. Therefore, for the given strain that the nail imposed on the concrete, the higher strength (stiffer) concrete reacted with a greater clamping stress. Since clamping was responsible for 70% of the pull-out capacity of the nail (and sintering the other 30%), any factor which influences the clamping action will influence the pull-out strength as well.

Effect of Power Level: Table 3.2, along with Figure 3.4, shows a slight increase in pull-out capacity when higher power levels were used to drive the nail. Higher power levels, however, also have negative impacts on the amount of surface cracking created. Since the power level does not have a significant influence on the pull-out capacity, all further tests were performed at power-level two, which was considered to be a good compromise between pull-out strength and surface cracking. Figure 3.4, therefore, shows the pull-out strength normalized with respect to power-level two.

Edge Effects: Table 3.3 shows the average pull-out strength, in kips, for nails tested near the edge of the slab. For comparison, the pull-out strength is also shown as a percentage of the standard pull-out strength for nails driven in the same slab. As might have been expected, driving a nail close to an edge had an adverse effect on its performance. Overall, only 87% of the standard-test pull-out strength could be expected, and in some cases, even less. The radial stresses which develop as the nail is driven into the concrete are not as high when the nail is near an edge. In essence, the concrete surrounding the nail is more flexible and the reduction in confinement relaxes the clamping force on the nail which is critical for its proper performance. Figure 3.5 shows, qualitatively, how the radial stresses around the nail are reduced when it is driven near an edge. Since stresses cannot exist on the edge of the slab (stress-free surface), the radial stresses must drop to zero there.

An important trend that can be seen in Table 3.3, along with Figures 3.6a and 3.6b, was the effect of edge distance (perpendicular distance from the edge of the slab to the nail) on pull-out strength. As the edge distance increased, so did the pull-out strength. This increase was most evident in slab 4 (7440 psi) which was most affected by the influence of the edge condition. The edge distance at which edge effects no longer had an impact on the nails' performance depended on the concrete strength. For example, the low-strength concrete (slab 2; 2710) seemed not to be effected at all by the edge, even at edge distances as close as 4 in.; the high strength concrete (slab 4; 7440 psi) could achieve only 83% of the standard pull-out strength even when driven 6 in. away from the edge.

It is quite possible that at edge distances smaller than 4 in. the edge effect would be more dramatic. However, during some preliminary tests, nails driven less than 4 in. from an edge developed extensive cracking in the concrete and even caused the edge to spall off. To reduce the risk of losing data during a test, the smallest edge distance was taken to be 4 in.

An interesting trend that can be seen in Table 3.3 was the influence of concrete strength on the pull-out performance of nails near an edge. In the standard tests, higher concrete strengths lead to higher pull-out strengths; in the edge tests, the opposite seemed to be true. Nails in the high-strength slab (slab 4; 7440 psi) achieved only 66% of the strength of those in the simple tests, while nails in the low-strength slab (slab 2; 2710 psi) achieved 107% of the strength of those in the simple tests. The performance of the nails in the two medium-strength slabs fell between those in slabs 2 and 4. The higher strength concretes lost more of their confining stresses through the introduction of an additional stress-free surface at the edge of the slab. There was no reason to believe, however, that the nail's proximity to an edge could have a beneficial effect (as is the case in slab 2). The results for slab 2 were most likely attributable to scatter in the data.

Nails Near Cracks: Table 3.4 contains a summary of pull-out strengths (in kips) of nails tested on a cracked slab. Also shown is the pull-out strength as a percentage of the standard pull-out strength. The presence of cracks in the slab is a detrimental factor influencing the nail's performance. The average pull-out strength for the 134 nails tested in or near cracks was only 57% of the strength of those nails in the standard tests.

The six series of tests performed on cracked slabs can be grouped for comparison. Series A, B, and C were all similar in that the nails were driven into an existing crack. The difference between these three series is the magnitude of flexural loading on the slab prior to testing the nail (refer to Figures 2.7 and 2.8). For series A the slabs were loaded to produce a moment of approximately 275 k-in. which corresponded to the moment at which the crack began to dilate. The actual load required to increase the crack width varied from slab to slab and was monitored by an analog pressure gage on the hydraulic line leading to the rams. For series B the slabs were not loaded. For series C the slabs were loaded to approximately 145 k-in. This corresponded to half the load used for series A and, again, was monitored by a pressure gage on the hydraulic line. The loads applied for each series are listed in the Appendix.

As would be expected, and seen in the values in Table 3.4, the nails in series C, with half the moment level applied in series A, had about twice the pull-out strength. The nails in series B, with no loading, achieved more than 250% of the strength of those in series A.

As can be seen in Table 3.4, there were no tests in series A or C performed on slab 3, because the cracks produced on slab 3 during prior tests were quite large. It was felt that little useful information could be retrieved from series A or C tests since further loading would only dilate the crack to an unreasonable width.

Series F and G were similar in that they were not driven into existing cracks, but, were driven such that a hairline crack would develop between them. The slabs were then loaded in flexure to produce a moment of approximately 325 k-in in order to widen the hairline crack (refer to Figures 2.10 and 2.11). The load required to do this varied among the slabs and actual values can be found in the Appendix. The difference between these two series was that in series F the nails were tested while the slab was loaded, while in series G the nails were tested after the slab was unloaded. The nails in series G developed approximately 150% of the strengths of the nails in series F. This difference in strength would be expected.

In series D, the nails were not driven into cracks, but beside the crack at various distances (perpendicular distance from the crack to the nail). In this respect, series D was quite similar to the edge tests. The crack distances, however, were much smaller: 1 in., 2 in., and 3 in. (as opposed to the 4- to 6-in. edge distances). The performance of the nails with respect to these distances was also more dramatic and can be seen in Table 3.5 and Figure 3.7. As the crack distance increased so did the pull-out strength. In fact, Figure 3.7 seems to be an extension of the plot of edge distance versus pull-out strength (Figure 3.6b). At 4 in. from an edge, the pull-out strength was about 81% of the simple-test pull-out strength; at 3 in. from a crack, the pull-out strength was about 76% of the simple-test pull-out strength and dropped quickly to 53% at 1 in. from a crack. In Figure 3.8, the crack-distance and edge-distance results are superimposed to show the continuity between them.

Once again, it was expected that the loss in strength was due to a loss in the confinement stress which assisted the clamping action. The nails were driven on the tension face of the slabs. Therefore, the clamping stresses on the nail would be reduced by tension due to flexural loading. This would help explain why the pull-out strengths of the nails in series A were less than those in series C which were less than those in series B; and similarly, why the strengths in series F were less than those in series G. If a crack face is considered to be similar to an edge, in the sense that it is a stress-free surface, then the 1 in. crack distance provided less confinement than the 3 in. crack distance. The effects of loss of confinement become more apparent after studying pull-out strength versus crack width and, more importantly, crack width changes.

The presence of cracks in the concrete adversely affected the performance of the nails and was summarized in Table 3.4. Cracking in concrete is often associated with a loss of stiffness. It was believed that the reduction in pull-out strength was due to a relaxation of the clamping force. The widths of the cracks used for the cracked-slab tests were recorded. Figures 3.9 to 3.14 show how the pull-out strengths of the cracked-slab tests were influenced by the crack width and, more importantly, changes in the crack width throughout the test. The pull-out strengths are represented as a percentage of the standard strengths.

The series A tests are shown in Figure 3.9. Plotted are the pull-out strengths versus original crack width and the change in crack width. The original crack width was the width measured prior to driving the nail into the crack (noted as "Original" in Figure 3.9). The crack width was measured again after the nail was driven and once more after the slab was loaded. The difference in the last two measurements was the change in crack width. That is, the change in crack width was the dilation of the crack due to loading the slab in flexure (noted as "Change" in Figure 3.9). There was no strong trend between original crack width and pull-out strength. A clearer trend exists between the pull-out strength and the change in crack width. As the change in width (i.e.: dilation of crack due to flexure in slab) increased the pull-out strength decreased. Since the nails were driven on the tension side of the slab, loading it in flexure would reduce the compressive stresses responsible for clamping. The change in crack width can be considered a physical indication of the presence of tension across the crack. It would, therefore, be reasonable to expect the capacity of the nail to decrease as the crack widened (reducing the clamping force).

The series B tests are shown in Figure 3.10. Plotted are the pull-out strengths versus original crack width and the change in crack width. The original crack width was that width measured prior to driving the nail into the crack (noted as "Original" in Figure 3.10). The change in crack width represents the dilation in the crack caused by driving the nail (noted as "Change" in Figure 3.10). Figure 3.10 clearly shows a decreasing trend in pull-out strength with increasing original crack width. There was no clear trend, however, with the change in width.

The series C tests are shown in Figure 3.11. The data acquisition for these tests was identical to that for series A, and the plot presents the same information: pull-out strength versus original crack width and change in crack width. The trends for both sets of data were quite clear here. The wider the existing crack the nail was driven into, the lower the pull-out strength for the nail. Also, the more the crack width dilated because of the loading, the lower the pull-out strength. The rationale behind this decreasing trend was the same as for series A, that is, a reduction in clamping force. Although both series A and C showed this decreasing trend, series C had the larger magnitude of pull-out strength.

The series D tests are shown in Figure 3.12. Once again, the crack width prior to driving the nail was measured and was plotted as the original crack width (noted as "Original" in Figure 3.12). In most cases, the crack closed slightly after the nail was driven beside it. The amount of crack closure after driving the nail was plotted as the change in crack width (noted as "Change" in Figure 3.12). The pull-out strengths of the nails were plotted against both the original crack width and the change in crack width. In both cases there was a decreasing trend in the nail's capacity as the crack width, and change in crack width, increased. In the former case, the larger cracks can be assumed to approach, more closely, the stress-free-surface condition of the edge of the slab which relaxes some of the confining stresses. In the latter case, the larger change in width corresponds to more crack closure. This was a visual indication of a lack in the concrete's ability to confine the nail and provide a clamping force. Again, the greater the reduction in the clamping force, the greater the reduction in pull-out strength.

The series F tests are shown in Figure 3.13. All the cracks in the series F tests began as hairline cracks with a 0.002 in. width. The loading process widened the crack and, naturally, reduced the clamping force on the nail. This is evident in Figure 3.13 which shows the pull-out strength versus the final crack width after loading the slab. The strength decreased with increasing crack width.

The series G tests are shown in Figure 3.14. As with series F, all cracks began as hairline cracks with a 0.002 in. width. Loading the slab in flexure widened the crack. Subsequent unloading of the slab allowed the cracks to close slightly. The pull-out strength was plotted against the crack width after loading and also against the crack width after unloading. The former case was very similar to the series F tests except that the magnitude of the pull-out strength was greater for series G. This was because a portion of the clamping force which was lost in the loading process was restored in the unloading process as the crack closed.

3.4 Other Factors Affecting Pull-Out Strength

Drill Hole Depth: The effect of the drill hole depth on the pull-out strength can be seen in Figure 3.15. Although it would seem reasonable to assume that deeper drill holes would allow more of the nail to make contact with the concrete and therefore produce higher strengths, this was not observed from the data. The drill bit produced a stepped hole (Figures 1.3 and 1.4) and the length of nail in contact with the concrete remained constant regardless of drill hole depth. As expected, the strength showed very little variation with depth.

Drill Hole Angle: The effect of the drill hole angle on the pull-out strength can be seen in Figure 3.16. A very slight increase in strength was noticed with increasing drill hole angle. The increase could have been due to the fact that the testing apparatus applied load normal to the concrete surface and not along the axis of the nail. The larger the drill hole angle, the more out-of-plumb the nail was relative to a line normal to the surface. Loading introduced bending of the nail and bearing on the concrete which could alter the behavior of the nail. The increase in pull-out strength with drill hole angle was very slight, however, and can be ignored in estimating the strength of the nail.

Surface Cracking: The effect of surface cracking on pull-out strength can be seen in Figure 3.17. No strong trends can be seen in the plot, primarily because surface cracking on the standard tests was effectively reduced through the use of the a stepped drill hole. Slab 4 was the only exception. At first, it was expected that surface cracks existed only on the surface of the concrete. However, the actual depth to which the cracks extended was difficult to determine. Regardless of their depth, the presence of surface cracks may have an impact on the nails' performance. This was evidenced in the series F and G tests on the cracked slabs. The cracks in these two series began as, what appeared to be, simply surface hairline cracks. The fact that, upon loading the slab, these hairline cracks widened while no other new cracks formed could imply that the surface cracking was more influential than previously thought.

3.5 Factors Affecting Surface Cracking

Concrete Strength: Figure 3.18 shows the relationship between concrete strength and cumulative length of surface cracking at a nail created by the driving process. It shows that the slabs with the low and medium strength concrete (2710 to 4650 psi) had a relatively constant length of surface cracking at approximately 1 in. per nail. The slab with higher strength concrete (7440 psi) had much more surface cracking with approximately 7 in. per nail. An increase in strength usually results in a more brittle material, and is likely the main reason for the increase in surface cracking.

Power Level: It was suspected that the power-level with which the nail was driven could affect the degree of surface cracking. Figure 3.19 shows the relationship between cumulative surface crack length and power-level. The slight increasing trend in surface crack length with power-level was most apparent in the slab with higher strength concrete (slab 4; 7440 psi). Higher power-levels direct more of the force from the explosive charge to the nail. The higher impact of the nail on the concrete can result in more disruption to the concrete matrix. Although slightly longer surface cracks could be expected from higher power-levels, so could higher pull-out strengths (see Figure 3.4). It was felt that a good compromise between pull-out strength and surface cracking could be reached at power-level 2. For this reason, power-level 2 was chosen for the cracked-slab tests which could not facilitate the testing of all four power-levels.

Edge Effects: The most detrimental factor affecting the formation of surface cracks was the nail's proximity to the edge of the slab. Much longer surface cracks were produced in the edge tests than in the standard tests (200% to 1100% of the standard test lengths). Figures 3.20a and 3.20b show the length of surface cracking (in inches and as a percentage of the surface crack length in the standard-type tests, respectively) versus edge distance. Most of these cracks propagated parallel to the edge. The inability of the concrete near the edge to provide adequate clamping forces indicates that the strains perpendicular to the edge were greater than the strains parallel to the edge and were large enough to develop cracks parallel to the edge.

As the distance from the edge increased, the conditions of the standard tests were approached. Therefore, less surface cracking would be expected as the edge distance became larger. This can be seen in Figures 3.20a and 3.20b which show a decreasing surface-crack length with edge distance. In slab 1 and 2 nails 6 in. from the edge were driven at the corners of the slabs, therefore, 6 in. away from two perpendicular edges. More exposure to edges resulted in longer surface cracks.

3.6 Cone-Type Failures and Sintering

Of the 366 nails tested, 22 failed by pulling out a cone of concrete. Eighteen cones formed on slab 1, one on slab 3, three on slab 4, and none on slab 2. The concrete strength in slab 3 was nearly the same as in slab 1, but only one cone-type failure was observed. The difference in the slabs was in the coarse aggregate used in the mix design. Slab 1 was cast with river gravel; all other slabs were cast with either soft or hard limestone. The aggregate may be responsible for the differences in frequency of cone-type failures, but the reason for this behavior is not known and too few data exist to draw any definite conclusions.

The only aspect of nail behavior that correlated well with the occurrence of cone-type failures was the degree of sintering. In most cases, sintering was limited to the tip of the nail. However, in some cases sintering extended along the sides of the nail. The sintering usually consisted of a thin layer of concrete paste. Sometimes, thicker patches of mortar and even small pieces of aggregate fused to the nail.

Determining the degree of sintering was fairly subjective. If no paste was attached to the side of the nail and only a thin layer fused to the tip, it was considered low sintering. If some paste fused to the side of the nail or a thicker layer of mortar was found on the tip of the nail, it was considered medium sintering. If pieces of aggregate pulled up with the nail or if a large portion of it was covered with paste, it was considered high sintering. Examples of nails with low, medium, and high levels of sintering can be found in Figures 2.16a, 2.16b, and 2.16c, respectively.

As was mentioned earlier, the level of sintering correlated well with the type of cone failure. A clean pull-out was usually accompanied by low sintering. A medium cone (up to 6 in. in diameter and shallow) was always accompanied by medium or high sintering. A full cone (up to 10 in. in diameter and deeper) was always accompanied by a high level of sintering.

Tests performed on epoxy bonded dowels and anchor bolts often develop cone-type failures which are usually attributed to excellent bond between the concrete and dowel or bolt. Sintering on the nails undoubtedly indicates better adhesion and stronger bond between the nail and the concrete and may explain why higher levels of sintering accompanied the cone-type failures. However, the reason for the higher levels of sintering cannot be determined from these tests.

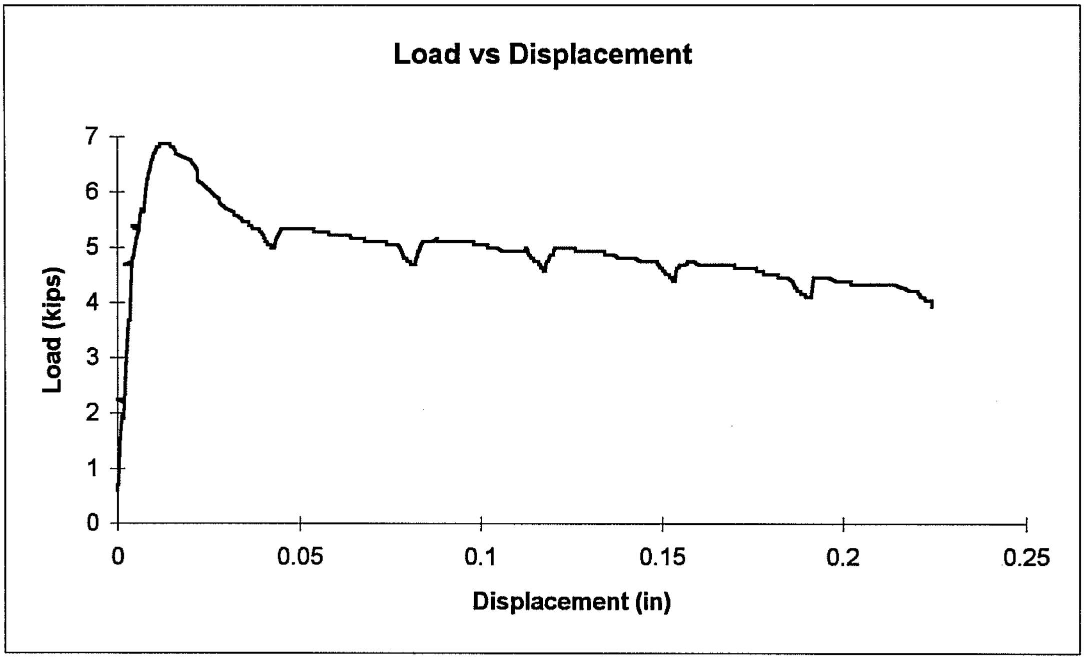


Figure 3.1 Typical Load-Displacement Plot
Considerable Load Carrying Capacity After Failure

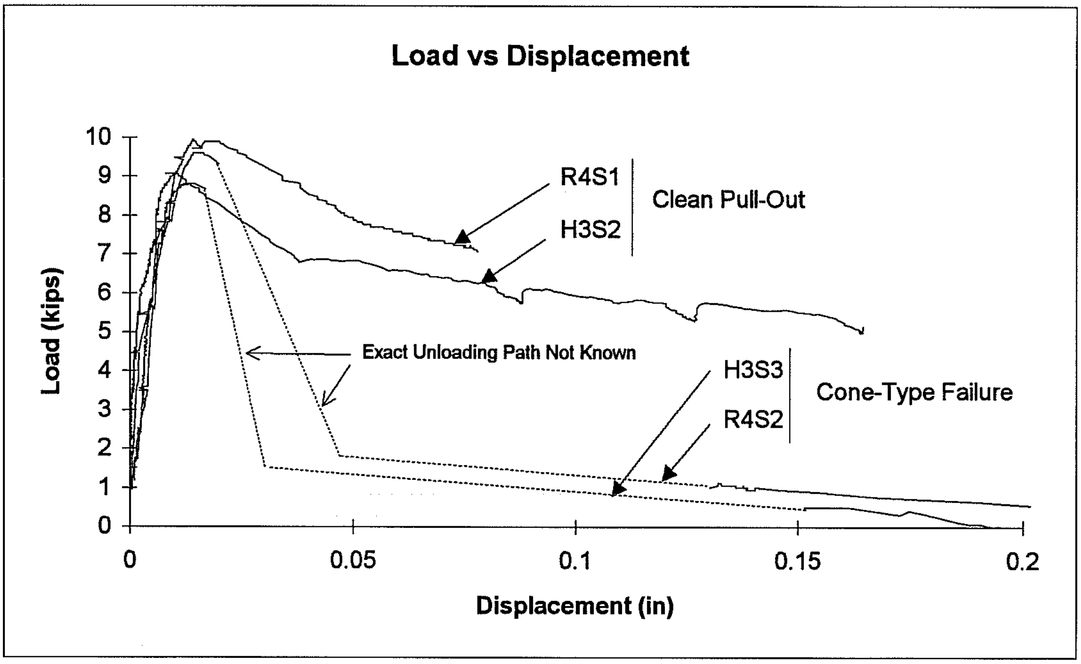


Figure 3.2 Comparison of Clean Pull-Out and Cone Failure Behavior

TABLE 3.1 : Number of Nails Tested									
	Test Type								Total
	Standard*	Edge	Crack A	Crack B	Crack C	Crack D	Crack F	Crack G	
Slab 1	32	36	4	12	4	9	6	3	106
Slab 2	32	36	4	8	4	9	4	4	101
Slab 3	24	24	0	10	0	9	6	4	77
Slab 4	24	24	3	9	3	9	6	4	82
Total	112	120	11	39	11	36	22	15	366

(* No edge or crack in vicinity of nail.)

TABLE 3.2 : Pull-Out Strength Summary						
Test Type : Standard						
		Power Level				Average
	f'c	1	2	3	4	
Slab 1	4650	8.14	8.24	8.71	8.93	8.51
Slab 2	2710	3.88	4.53	4.28	4.96	4.41
Slab 3	4090	7.61	8.06	8.48	8.18	8.08
Slab 4	7440	10.08	9.21	9.55	10.37	9.80

TABLE 3.3 : Pull-Out Strength Summary						
Test Type : Edge, All Power Levels						
	Distance from Edge					Average
	4	4.5	5	5.5	6	
Slab 1	7.75	8.37	7.86	8.66	8.66	8.22
	91.1	*98.4*	*92.3*	*101.8*	*101.8*	*96.6*
Slab 2	4.77	4.34	4.84	4.86	4.96	4.73
	108.1	*98.2*	*109.6*	*110.0*	*112.4*	*107.1*
Slab 3	6.29		7.29		6.85	6.81
	77.8		*90.2*		*84.7*	*84.2*
Slab 4	5.48		5.85		8.17	6.50
	55.9		*59.7*		*83.4*	*66.3*

(Note: Italicized entries show percentage of standard-test pull-out strength.
All four power levels represented. Number of replicates differ.)

TABLE 3.4 : Pull-Out Strength Summary							
Test Type : Cracked Slab, Power-Level 2							
	Series						Average
	A	B	C	D	F	G	
Slab 1	2.08	5.92	3.98	6.21	4.33	6.34	5.16
	24.4	*69.5*	*46.7*	*73.0*	*50.9*	*74.6*	*60.6*
Slab 2	1.04	3.08	1.87	3.11	2.13	2.66	2.53
	23.5	*69.7*	*42.3*	*70.4*	*48.1*	*60.3*	*57.2*
Slab 3		3.50		3.49	2.92	4.47	3.51
		43.3		*43.2*	*36.1*	*55.3*	*43.4*
Slab 4	3.17	8.76	6.86	6.42	3.24	5.04	6.07
	32.3	*89.4*	*70.0*	*65.5*	*33.1*	*51.4*	*61.9*

(Note: Italicized entries show percentage of standard-test pull-out strength)

TABLE 3.5 : Pull-Out Strength Summary				
Test Type : Cracked Slab; Series D				
	Distance to Crack			Average
	1	2	3	
Slab1	5.53	5.83	7.26	6.21
	65.0	*68.6*	*85.3*	*73.0*
Slab 2	2.68	2.97	3.67	3.11
	60.8	*67.3*	*83.1*	*70.4*
Slab 3	2.55	3.04	4.89	3.49
	31.5	*37.6*	*60.5*	*43.2*
Slab 4	5.20	6.90	7.14	6.42
	53.1	*70.4*	*72.9*	*65.5*

(Note: Italicized entries show percentage of standard-test pull-out strength)

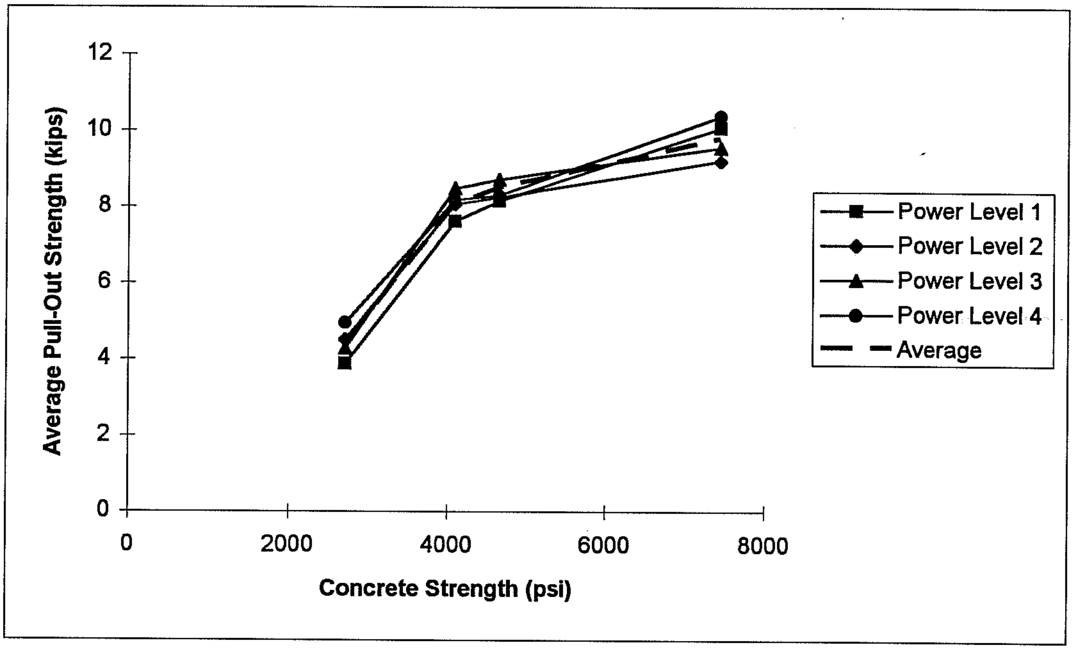


Figure 3.3 Pull-Out Strength vs Concrete Strength

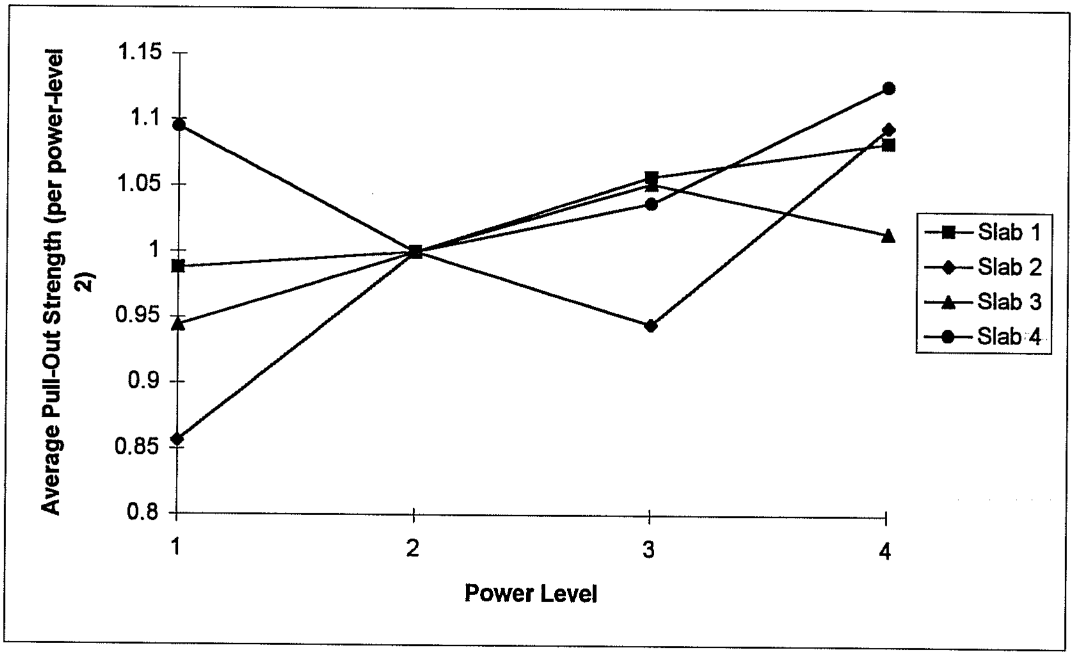


Figure 3.4 Pull-Out Strength vs Power Level

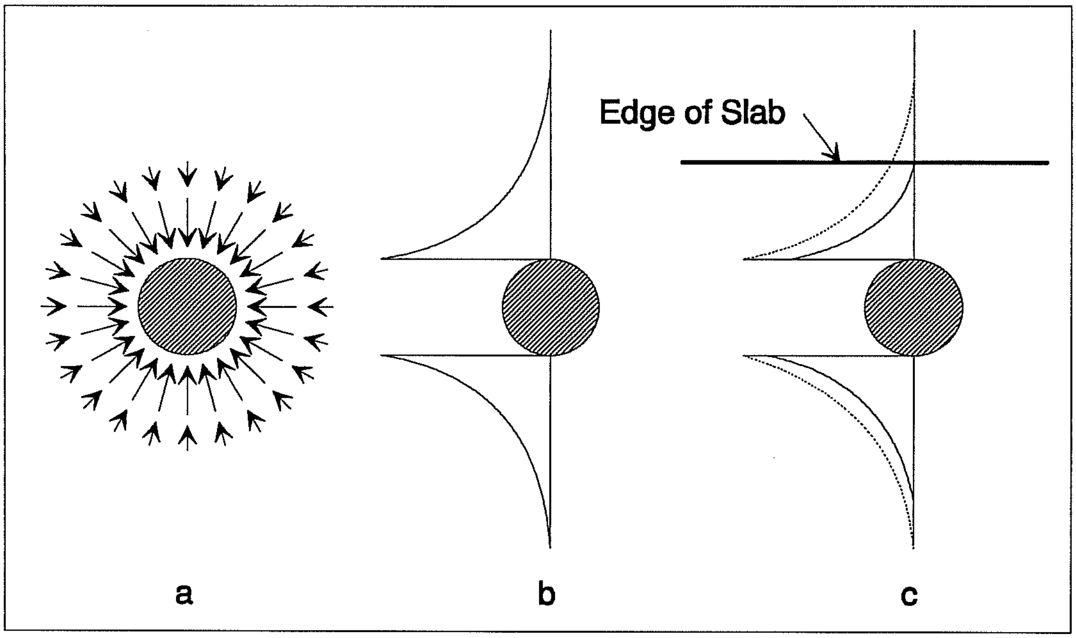


Figure 3.5 a: Radial Compressive Stress Around Nail, b: Stress Distribution for Standard Condition, c: Reduction in Stress due to Edge

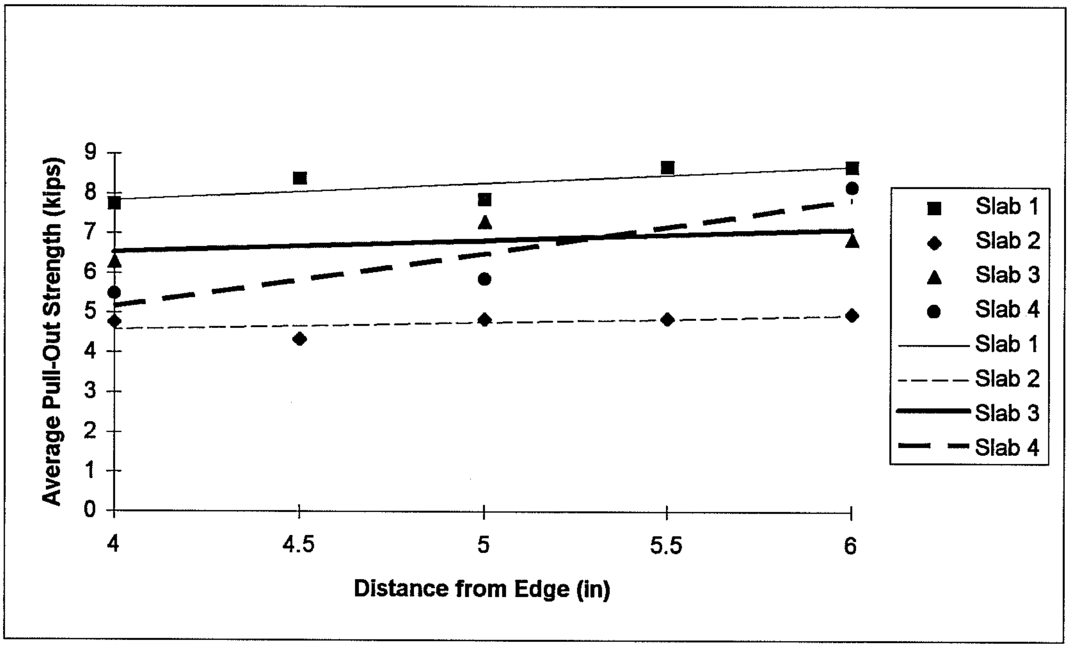


Figure 3.6a Pull-Out Strength vs Edge Distance

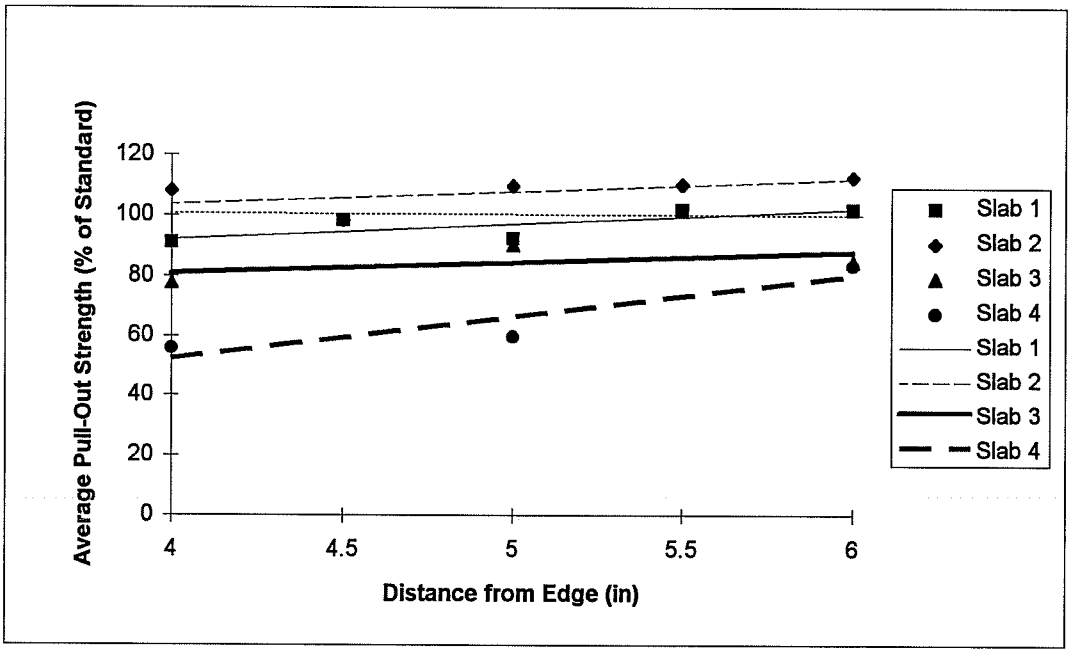


Figure 3.6b Pull-Out Strength vs Edge Distance

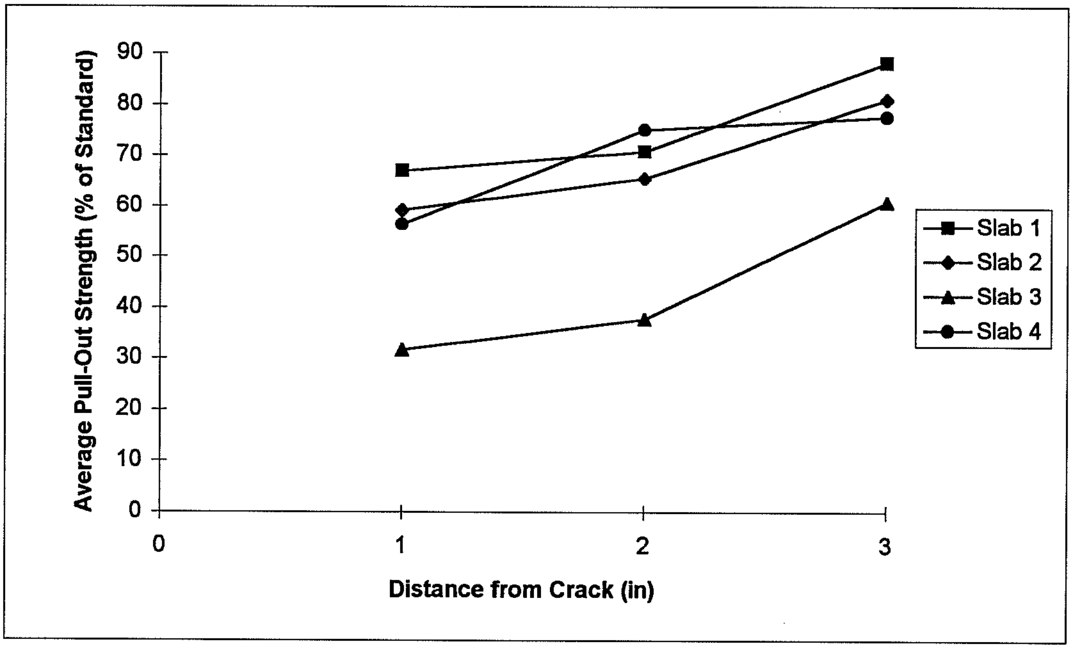


Figure 3.7 Pull-Out Strength vs Distance from Crack

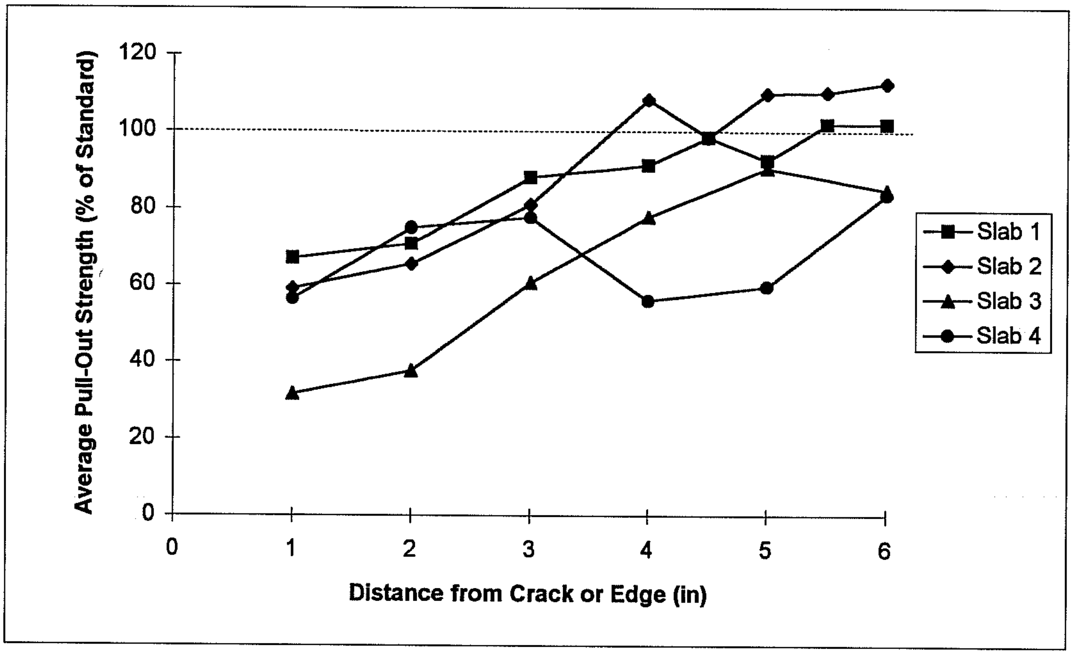


Figure 3.8 Superposition of Crack-Distance and Edge-Distance Results

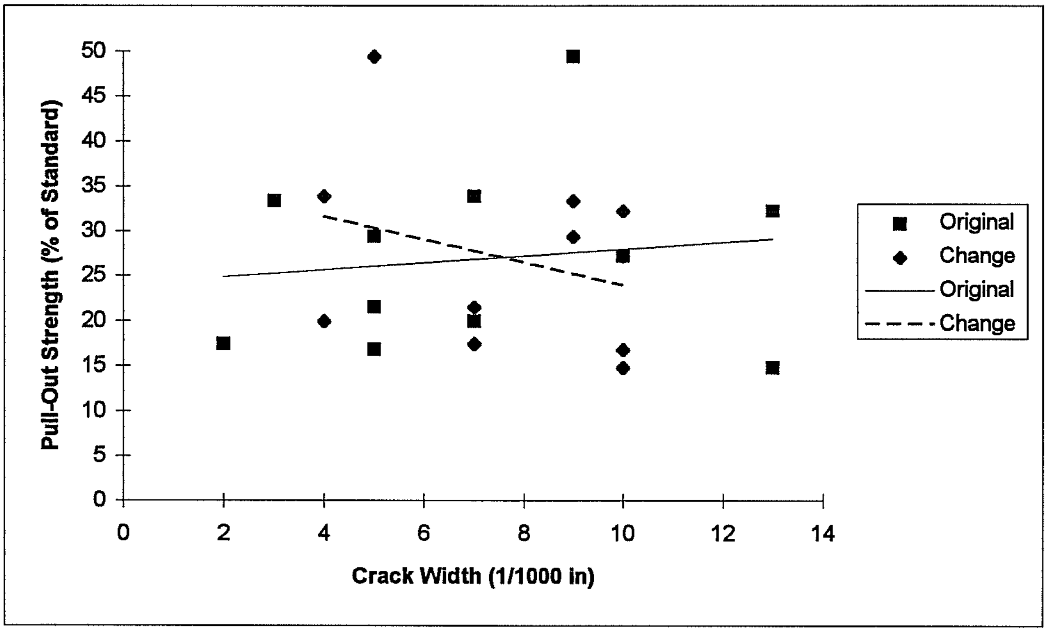


Figure 3.9 Pull-Out Strength vs Crack Width: Series A
Nail in Crack, High Tension Across Crack

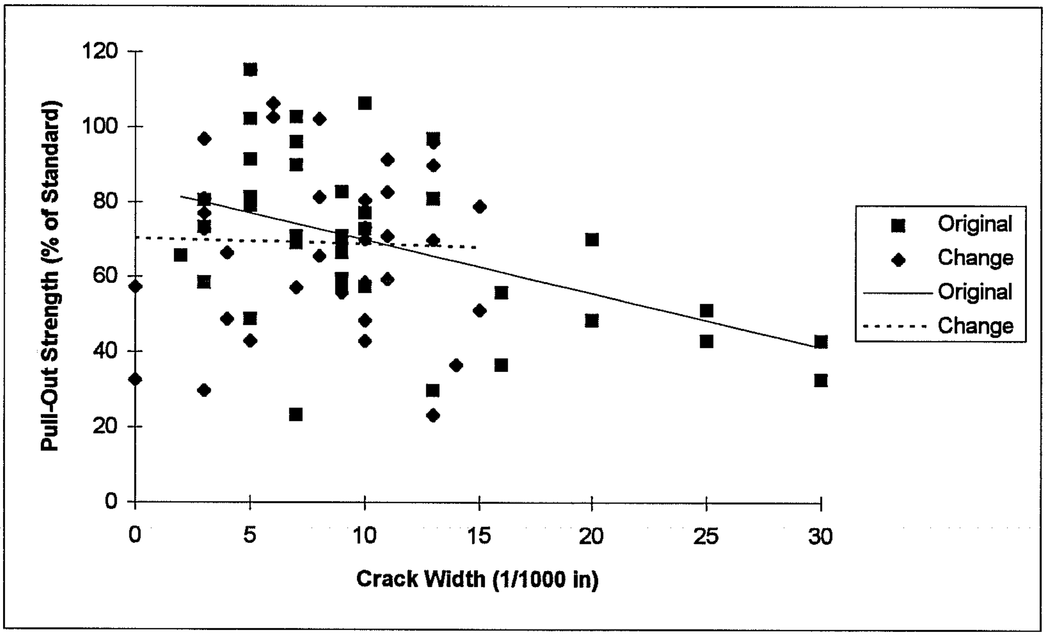


Figure 3.10 Pull-Out Strength vs Crack Width: Series B
Nail in Crack

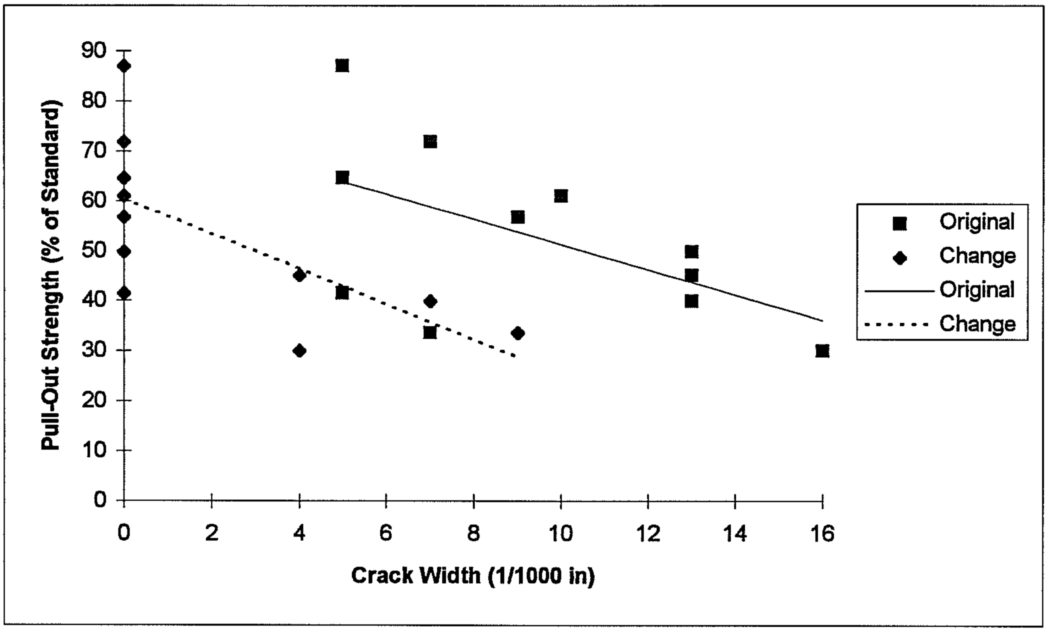


Figure 3.11 Pull-Out Strength vs Crack Width: Series C
Nail in Crack, Low Tension Across Crack

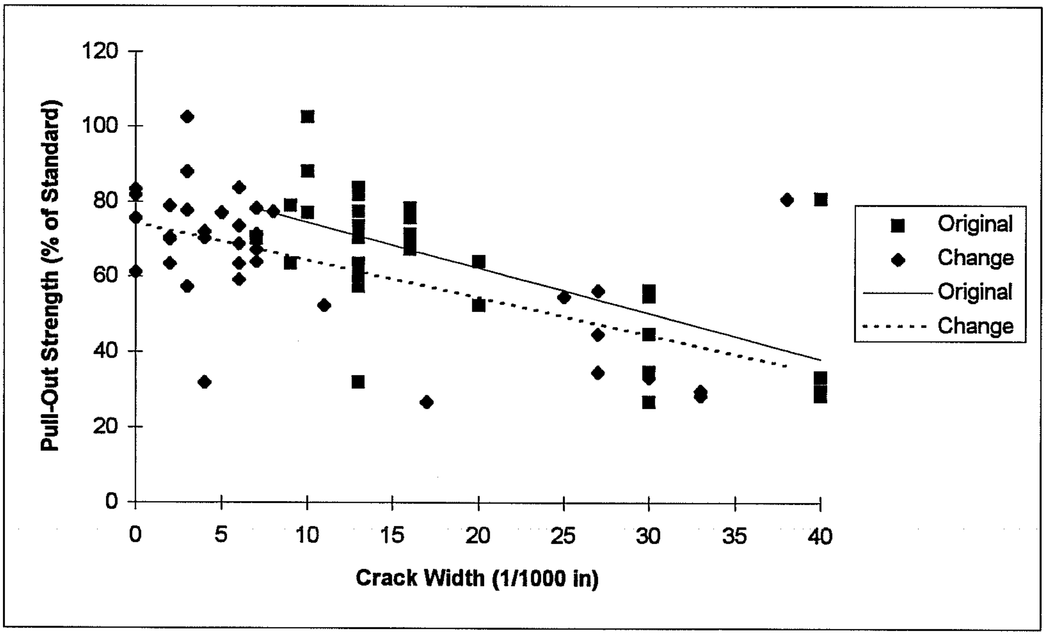


Figure 3.12 Pull-Out Strength vs Crack Width: Series D
Nail Near Crack

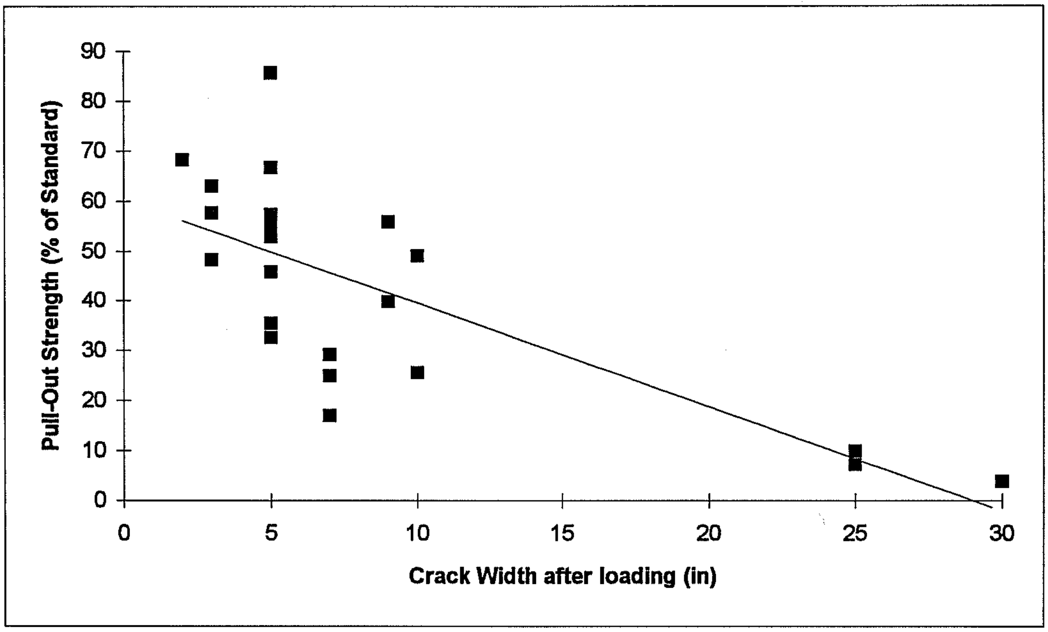


Figure 3.13 Pull-Out Strength vs Crack Width: Series F
Nails Driven to Produce Crack, High Tension Across Crack

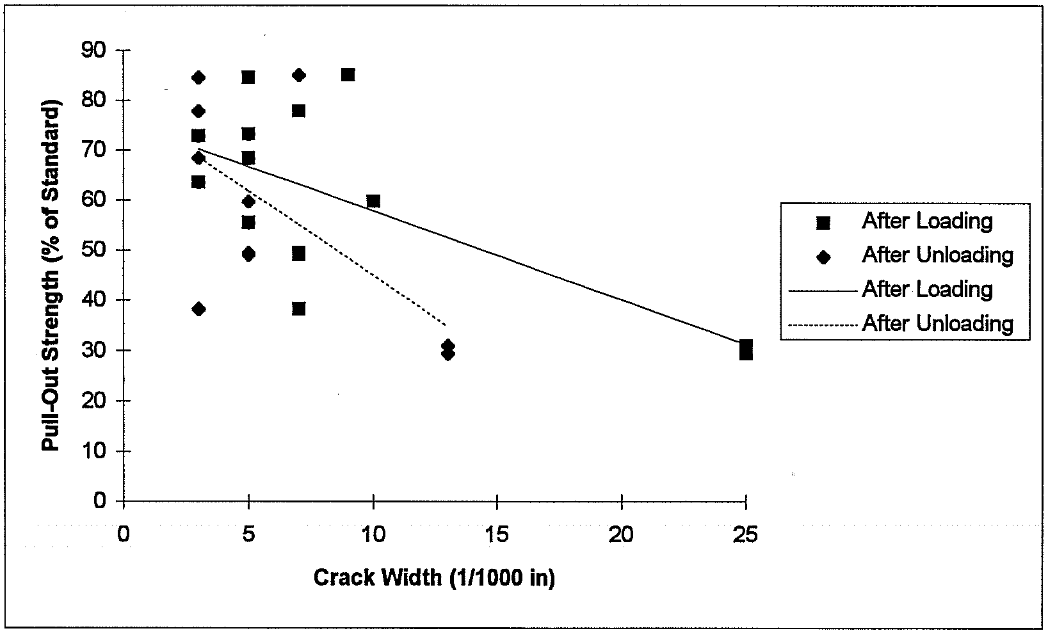


Figure 3.14 Pull-Out Strength vs Crack Width: Series G
Nails Driven to Produce Crack, No Tension Across Crack

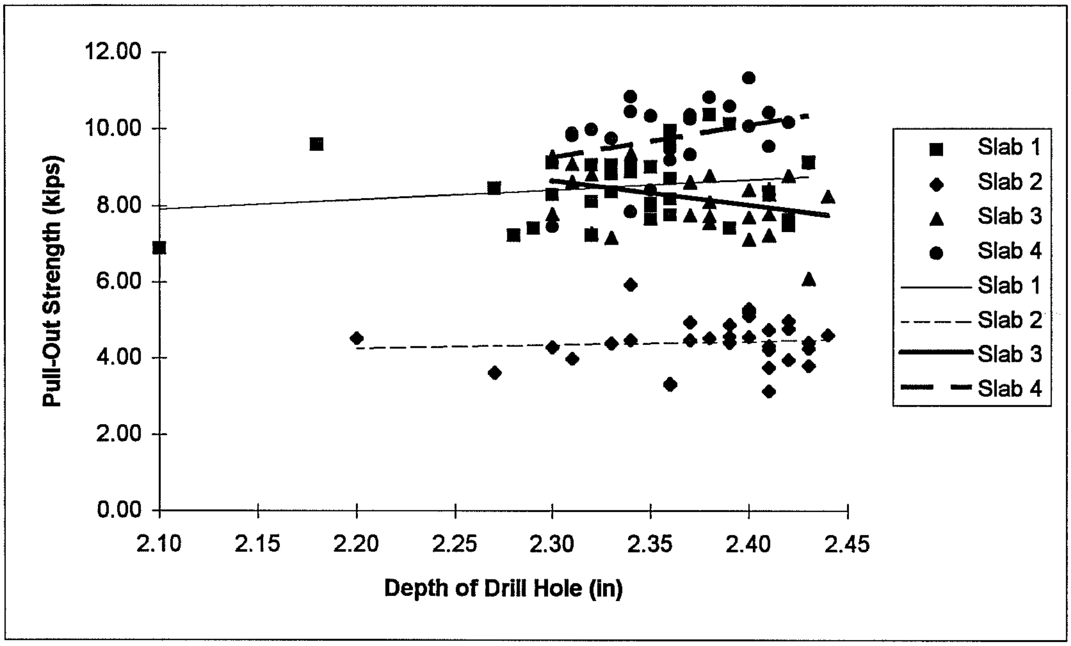


Figure 3.15 Pull-Out Strength vs Depth of Drill Hole

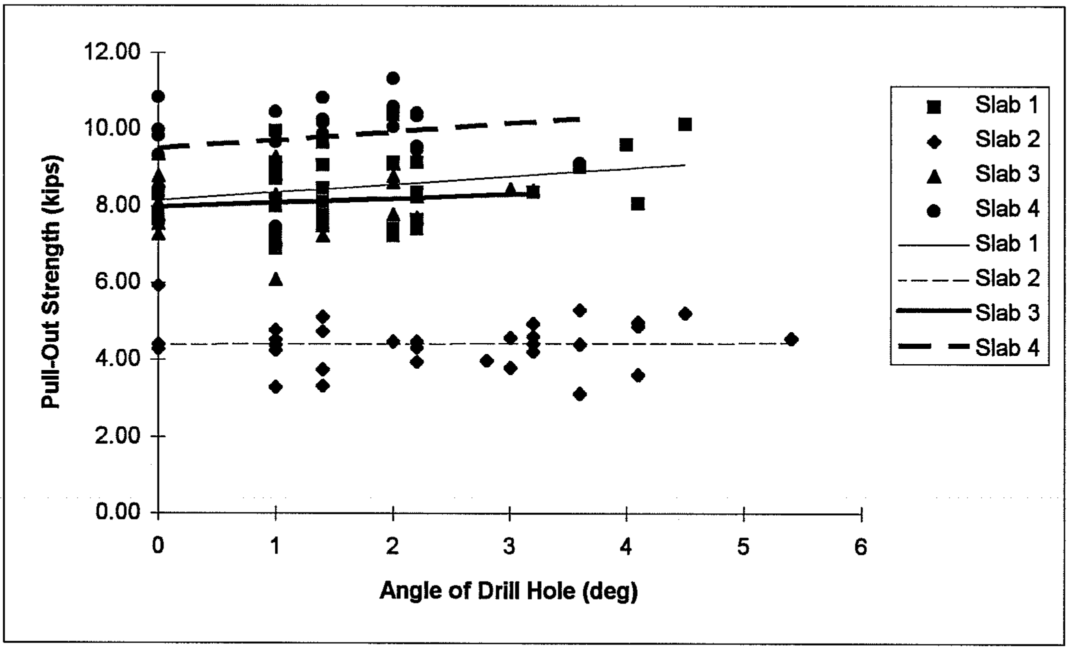


Figure 3.16 Pull-Out Strength vs Angle of Drill Hole

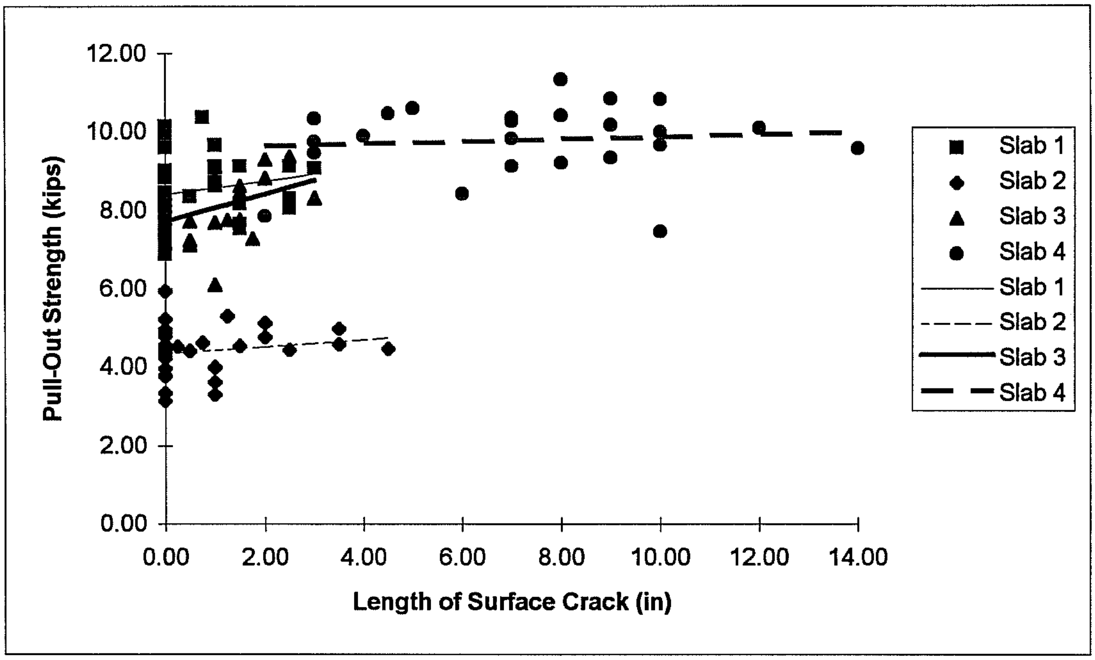


Figure 3.17 Pull-Out Strength vs Surface Crack Length

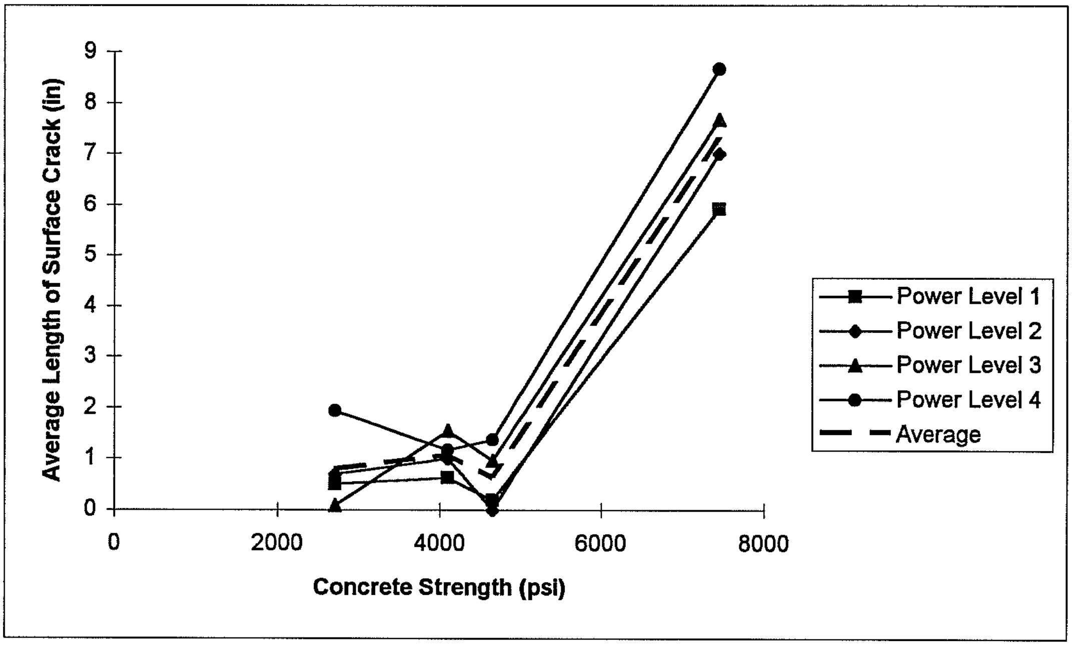


Figure 3.18 Surface Crack Length vs Concrete Strength

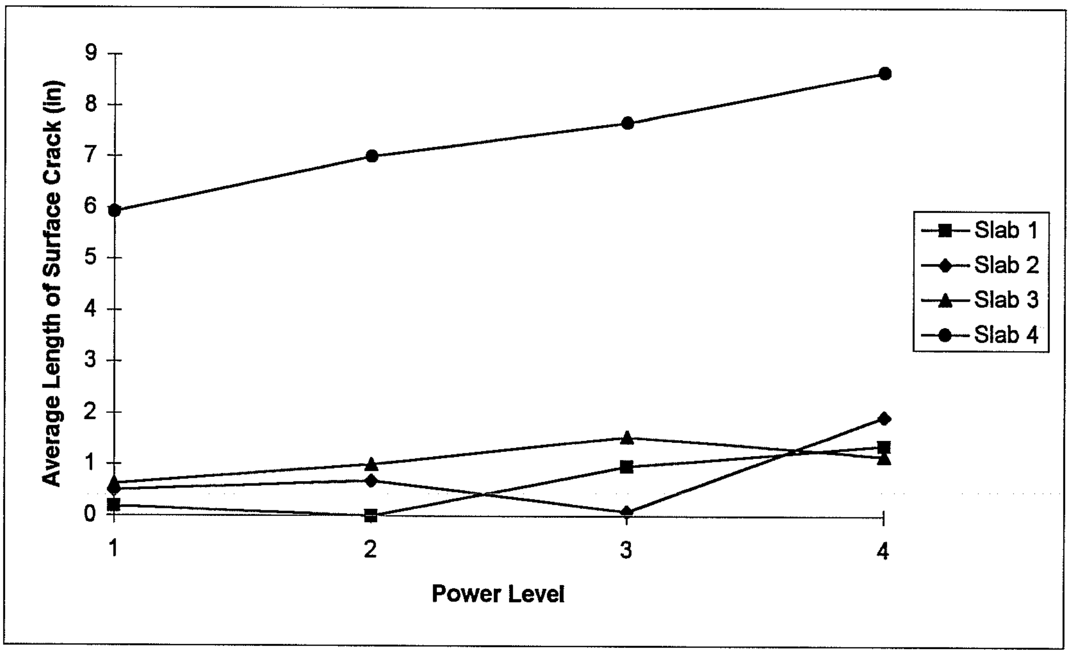


Figure 3.19 Surface Crack Length vs Power Level

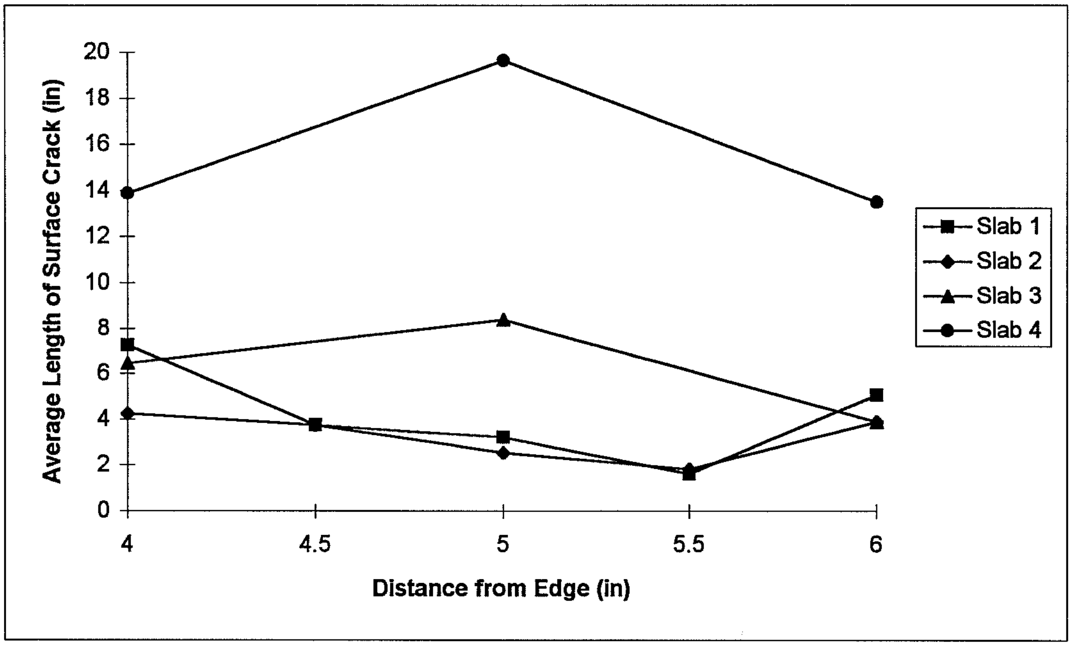


Figure 3.20a Surface Crack Length vs Edge Distance

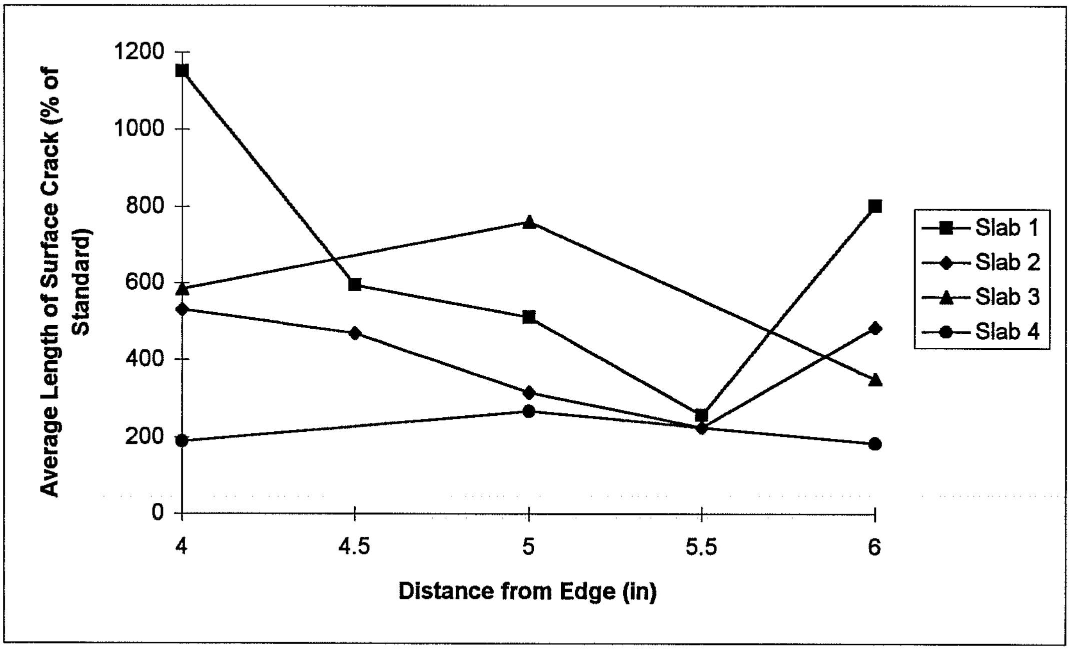


Figure 3.20b Surface Crack Length vs Edge Distance

Chapter 4: Design Criteria

4.1 Introduction

A design equation which can predict the pull-out strength of the reinforcement under a variety of service conditions would be necessary for the engineer wishing to use it in an overlay project. In this study, a large data base of pull-out tests for the powder driven fastener developed by Hilti was created which allows for the formulation of a design approach for the strength of the fastener in direct tension.

The tests indicated three important factors which most influenced the strength of the nails: the strength of the concrete into which the nails were driven, the proximity of the nail to the edge of the slab, and the proximity of the nail to a crack in the slab. Each of these factors will be discussed separately and then incorporated into a recommended design equation.

4.2 Basic Pull-Out Strength

Of all the nails tested in the standard condition, the only factor which had a strong influence on its pull-out strength was the strength of the concrete into which the nail was driven. Figure 3.4 showed that pull-out strength increased with increasing concrete strength. For design purposes, it is desirable to represent this trend with a single equation relating concrete strength to pull-out strength. Considering the scatter in the data, a linear relation would suffice.

Figure 4.1 shows the pull-out strength versus concrete strength for nails tested in the standard condition (near neither an edge nor a crack). The line plotted in Figure 4.1 represents the basic design pull-out strength of a nail in the standard condition. The line is plotted such that 95% of the data points recorded lie above it. The equation of this line is shown in Figure 4.1. Therefore,

$$P_s = f_c / 820 \qquad (4.1a)$$

where:

P_s = pull-out strength, in kips, and
f_c = concrete strength, in psi.

It is recommended that equation 4.1a not be used for concrete strengths much lower than 2700 psi or much greater than 7500 psi since the recorded data did not include such concrete strengths. Such extrapolation could prove to be inaccurate.

The SI equivalent to the above equation is:

$$P_s = 0.78\, f_c \qquad (4.1b)$$

where:

P_s = pull-out strength, in kN, and
f_c = concrete strength, in MPa.

4.3 Edge Effect

As can be seen from Figure 3.7b, the proximity of the nail to an edge tends to reduce its pull-out strength. As the distance to an edge increases, so does the pull-out strength. Figure 4.2a shows the average pull-out strength (as a percentage of the standard strength) versus the distance from an edge for each slab. The rate at which the pull-out strength increases with edge distance is approximately the same for each slab. Therefore, the average rate of increase (also shown in Figure 4.2a) will be used in determining the edge effect.

The concrete strength also influences the reduction in pull-out capacity when the nail is driven near an edge. As was mentioned earlier, low strength concrete is not affected by edge distance as much as the higher strength concretes. Figure 4.2b shows how the pull-out strength for nails driven four inches from an edge of the slab is related to concrete strength. The dashed line shows the linear regression for the data and is used for obtaining the rate of reduction in pull-out strength with concrete strength. The solid line has the same slope as the dashed line but is plotted such that 95% of the recorded data lies above it. The solid line shows the relationship which will be used in conjunction with Figure 4.2a to determine the edge effect. The edge effect is a percentage of the standard pull-out strength and is always less than unity. Therefore,

$$E_e = [105 - .01f_c + 8.0\,(d_e - 4)]/100 \leq 1.0 \qquad (4.2a)$$

where:

E_e = edge effect, less than unity,

f_c = concrete strength, in psi, and

d_e = distance from edge of slab, in inches, not less than 4 inches.

Equation 4.2a is useful for determining the minimum edge distance necessary such that the edge effect has no influence on the nail behavior. By setting E_e equal to 1.0 and solving for d_e in terms of f_c, this minimum edge distance can be determined by:

$$d_e = f_c/\,800 + 3.5 \qquad (4.3a)$$

Edge distances less than 4 inches are not recommended since there is a possibility that the edge will spall.

The SI equivalents to the above equations are:

$$E_e = [105 - 1.45f_c + 3.15\,(d_e - 10)]/100 \leq 1.0 \qquad (4.2b)$$

and

$$d_e = 0.46\,f_c + 9 \qquad (4.3b)$$

where:

E_e = edge effect, less than unity,

f_c = concrete strength, in MPa, and

d_e = distance from edge of slab, in cm, not less than 10 cm.

4.4 Crack Effect

Nails driven near an existing crack have a reduced pull-out strength. As with the edge effect, pull-out strength increases as the distance from a crack increases. Figure 4.3a shows the average pull-out strength (as a percentage of the standard strength) versus the distance from a crack for all slabs. The rate of increase in pull-out strength for each slab is approximately the same, however, the magnitude of pull-out strength varies among the slabs. This behavior was also noticed when determining the edge effect and was attributed to the concrete strength. For the crack effect, however, this is not the case. Nails in Slab 2 and slab 4 which are greatly different in strength (2710 psi and 7440 psi, respectively) behaved nearly the same near a crack. Nails in Slab 3, with a concrete strength of 4090 psi, had much lower pull-out strengths. This can be attributed to the width of the existing crack.

Figure 4.3b shows the pull-out strength (as a percentage of standard strength) versus the crack width, prior to driving the nail, for those tests performed at a one-inch crack distance. Slab 3, which had much larger crack widths than the other three slabs, experienced a much greater reduction in pull-out strength. The equation of the regression line relating pull-out strength and crack width is shown in Figure 4.3b as the dashed line. The solid line has a slope equal to that of the regression line, but is plotted such that 95% of the recorded data lies above it. The equation of the solid line can be used in conjunction with Figure 4.3a in order to determine the crack effect. The crack effect is a percentage of the standard pull-out strength and is always less than unity. Therefore,

$$E_c = [64 - 1.25w_c + 11.65\,(d_c - 1)]/100 \leq 1.0 \qquad (4.4a)$$

where:

E_c = crack effect, less than unity,

w_c = crack width, in 1/1000 inch, and

d_c = distance from crack, in inches.

Tests have shown that when the nail is driven directly into the crack, the reduction in pull-out strength is not as great as when the nail is driven near the crack. To take advantage of this improved performance, however, care would have to be taken to drill the hole precisely in the center of the crack. For design purposes, therefore, driving the nail into a crack should be considered as a crack distance of zero inches.

Equation 4.4a is useful for determining the minimum crack distance necessary such that the crack effect has no influence on the nail behavior. By setting E_c equal to 1.0 and solving for d_c in terms of w_c, the minimum crack distance can be determined by:

$$d_c = 4 + 0.11\,w_c \qquad (4.5a)$$

The SI equivalents to the above equations are:

$$E_c = [64 - 49\,w_c + 4.6\,(d_c - 2.5)]/100 \leq 1.0 \qquad (4.4b)$$

and

$$d_c = 10.2 + 10.7\, w_c \qquad (4.5b)$$

where:

E_c = crack effect, less than unity,

w_c = crack width, in mm, and

d_c = distance from crack, in cm.

Equations 4.4a and 4.5a, above, are dependent on the crack width. Unfortunately, the crack width is seldom known by the design engineer. These equations can be used, however, if an approximate crack width is supplied. AASHTO does not specify a maximum allowable crack width in their serviceability criteria, so the actual cracks encountered on a roadway can be quite large. If a large value for w_c (eg.: 50) is applied to equation 4.5a, the minimum crack distance would be 9.5 in. This crack distance is quite close to the minimum edge distance requirements given in equation 4.3a for medium strength concrete. It is reasonable to assume that for large crack widths (approximately 0.05 in.), a condition similar to an edge is produced, in which case, the minimum edge distances provided by equation 4.3a can be applied to crack distances also.

Figure 3.8 shows the continuity between crack distance and edge distance pull-out strengths. Figure 4.4 also shows this continuity by plotting the average pull-out strengths (as a percentage of standard strength) for all the slabs versus crack distance and edge distance. The rate of increase in strength with distance is shown in Figure 4.4 and is very similar to that in Figure 4.2a. Since most cracks in a roadway can be assumed to be wide, equations 4.2a and 4.3a can also be applied to nails driven near cracks. Therefore:

$$d_c = f_c / 800 + 3.5 \qquad (4.6)$$

Equations 4.2a and 4.4a, which quantify the effects of driving a nail near an edge or a crack, will not be necessary if the minimum edge distance and minimum crack distance provided by equations 4.3a and 4.6 are used. However, should a nail be driven closer to an edge or crack than specified by equations 4.3a and 4.6, equations 4.2a and 4.4a will provide an estimate for the anticipated reduction in strength due to the edge or crack effects. If the width of the crack near which the nail was driven is not known, a reasonable strength reduction can be obtained by using equation 4.2a in place of 4.4a, replacing, of course, $\mathbf{d_e}$ with $\mathbf{d_c}$.

4.5 Formulation of Design Equation

Equations 4.1 through 4.6, which summarize and quantify the trends noticed in the behavior of the nails during the test program, can be used in the formulation of design equations.

In order to achieve the maximum pull-out capacity of the nail, the effects of driving the nail near an edge or a crack must be minimized. This can be accomplished by specifying the minimum distance from an edge or crack that a nail can be driven. This minimum distance is given by equation 4.3a or 4.3b.

With these distances satisfied, the maximum pull-out strength of the nail can be expected. This strength is equal to the basic pull-out strength of a nail driven in a standard condition and is given by equation 4.1a or 4.1b.

If it is necessary to drive a nail close to an edge (closer than the minimum edge distance specified by equation 4.3a or 4.3b), or if it is necessary to evaluate the strength of a nail driven near an edge, the pull-out strength must be reduced by a factor which accounts for the edge effects. The pull-out strength, therefore, will be the basic pull-out strength, given by equation 4.1a or 4.1b, multiplied by the edge effect factor given by equation 4.2a or 4.2b.

If it is necessary to drive a nail close to a crack (closer than the minimum crack distance specified by equation 4.3a or 4.3b), or if it is necessary to evaluate the strength of a nail driven near a crack, the pull-out strength must be reduced by a factor which accounts for the crack effects. The pull-out strength, therefore, will be the basic pull-out strength, given by equation 4.1a or 4.1b, multiplied by the crack effect factor. If the width of the crack near which the nail is driven is unknown, the crack effect factor is given by equation 4.2a or 4.2b where $\mathbf{d_e}$ is replaced with $\mathbf{d_c}$. If the width of the crack near which the nail is driven is known, the crack effect factor can be given by equation 4.4a or 4.4b.

Driving the nail into a crack should be considered as a crack distance of zero inches.

The design equation for the pull-out strength of the nail takes the following form:

$$P_n = (P_s)(E_e)(E_c) \tag{4.7}$$

where:

P_n = the nominal pull-out strength,

P_s = the basic pull-out strength, defined by equation 4.1a or 4.1b,

E_e = the edge effect, defined by equation 4.2a or 4.2b, and

E_c = the crack effect, defined by equation 4.2a, 4.2b, 4.4a, or 4.4b.

In keeping with Load and Resistance Factor Design philosophy, an appropriate strength reduction factor should be applied to equation 4.7 above. Considering that a 95% confidence level was taken in formulating the design equations, and considering that the nails exhibit favorable post failure behavior (ie.: maintaining a significant portion of the peak load over large deformations), it is reasonable for the strength reduction factor to be large. The actual value, however, should be determined after shear tests are performed.

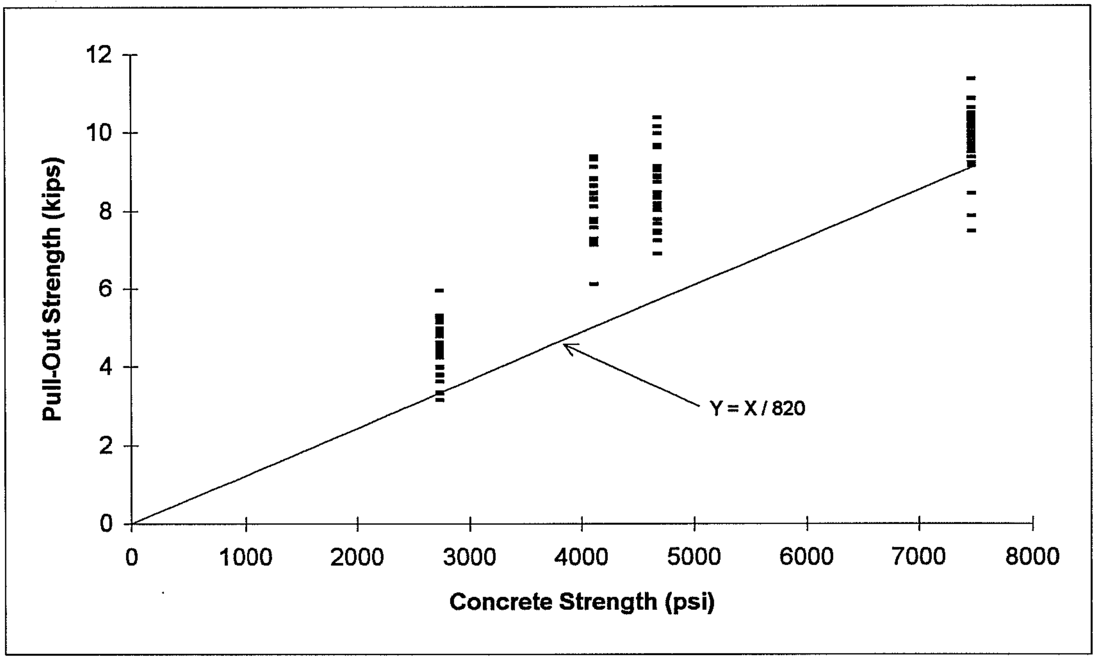


Figure 4.1 Pull-Out Strength vs Concrete Strength, Standard Condition

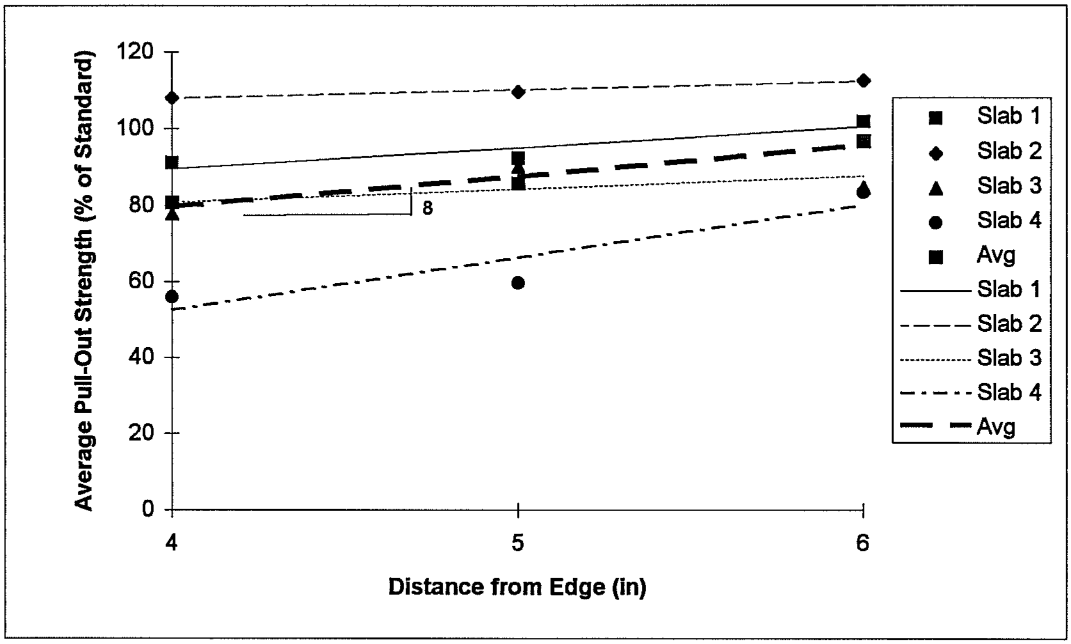


Figure 4.2a Pull-Out Strength vs Edge Distance

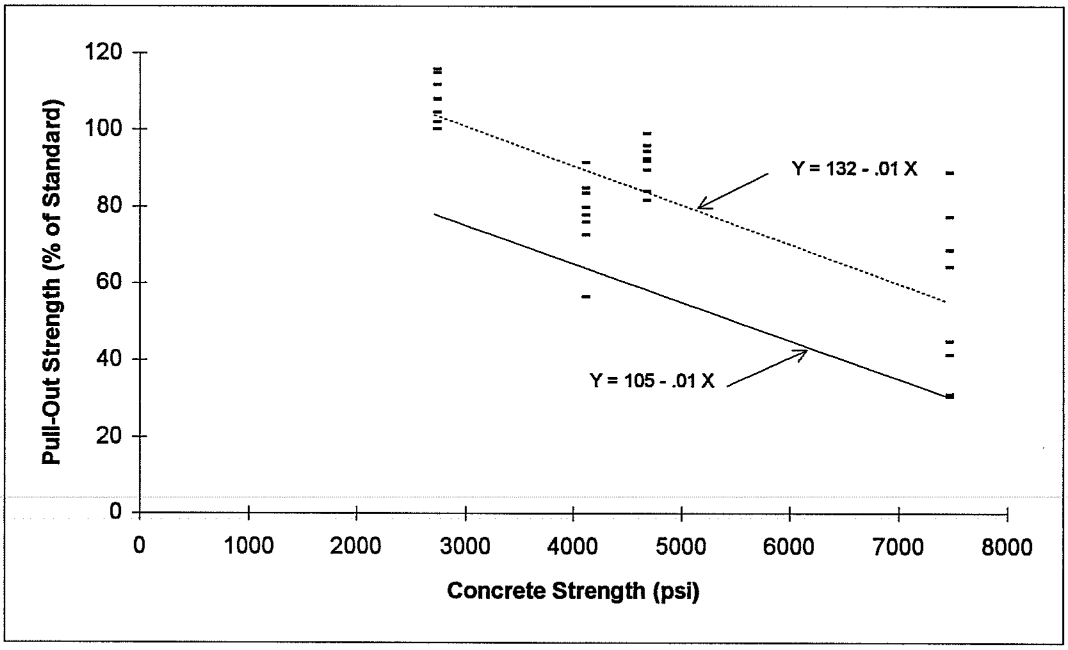


Figure 4.2b Pull-Out Strength vs Concrete Strength, 4 -inch Edge Distance

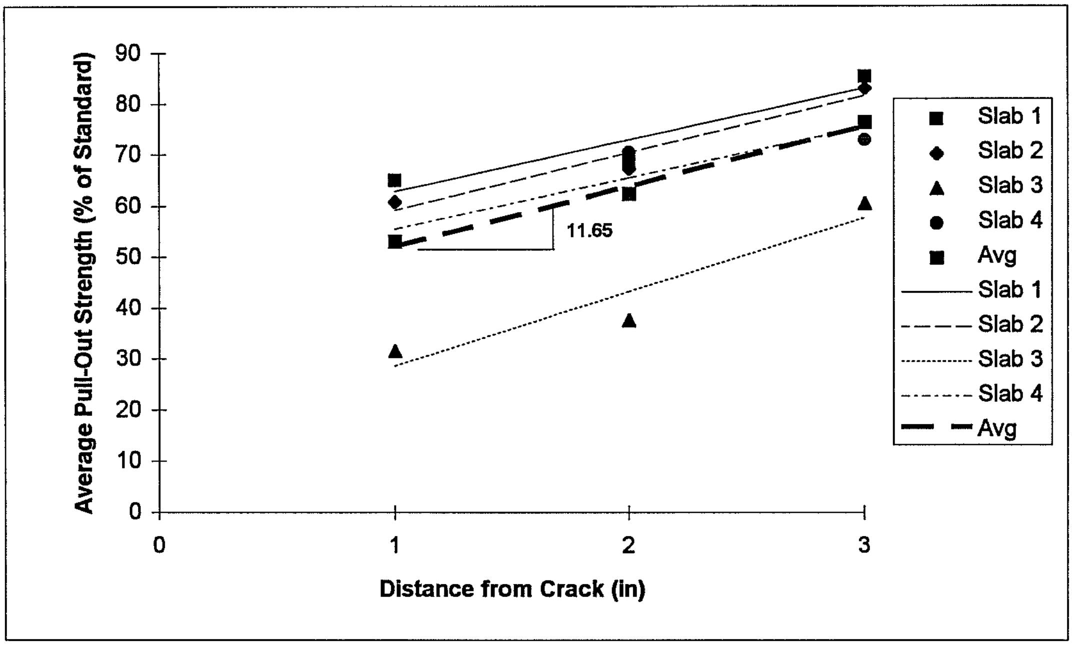


Figure 4.3a Pull-Out Strength vs Crack Distance

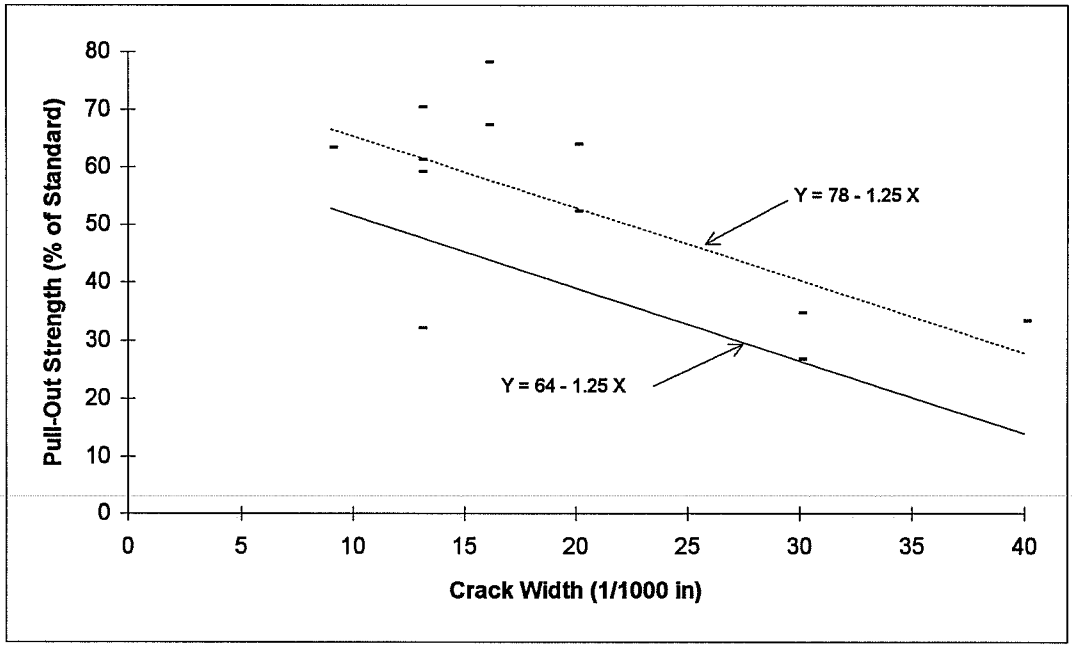


Figure 4.3b Pull-Out Strength vs Crack Width, 1-inch Crack Distance

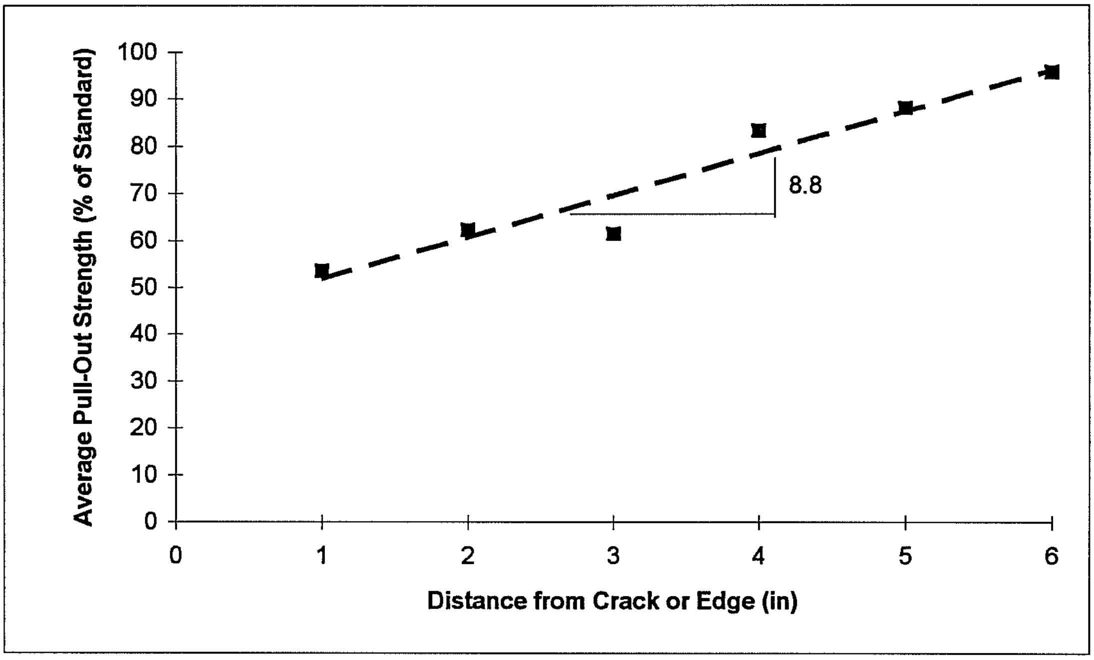


Figure 4.4 Pull-Out Strength vs Distance from Crack or Edge
Average of All Slabs

Chapter 5: Summary and Conclusions

5.1 Summary

Although scarification and bonding agents have a history of successful applications, the fact that adequate bond cannot be guaranteed over a large range of situations makes them less than ideal remedies for the problem of delamination between new concrete cast against an existing concrete surface. Another solution would be to set epoxy-grouted dowels normal to the surface of the interface to provide a mechanical transfer of forces. The use of such dowels, however, is very costly and is usually limited to those applications where they are required by specification, such as in bridge deck overlays. The reason for the high cost is that installing dowels is a very slow, tedious, labor intensive process. After the holes are drilled, they must be carefully cleaned of all dust; otherwise the epoxy will not bond well to the walls of the drill hole. Adequate cleaning requires that the hole be scrubbed with a stiff brush and vacuumed. After the hole is filled with epoxy and the dowel is set, it must stand undisturbed until the epoxy cures. This delay will increase construction costs.

The Hilti Corporation developed a product designed to provide a mechanical transfer of forces across an interface without the labor intensive installation procedure of epoxy-grouted dowels. These powder-driven fasteners, called "jumbo" nails, are installed through the use of an explosive charge. Aside from dispensing with epoxy or cementitious grout, the holes into which the nails are driven do not have to be cleaned nearly as well as for the epoxy grouted dowels, and the nails are ready for service immediately after the installation is complete. This savings in time will reduce construction costs and allow for the use of mechanical fasteners in overlay projects where fasteners were previously considered uneconomical.

In this test program, the tensile behavior, in concrete, of the powder-driven nail, developed by the Hilti Corporation, was studied through the use of simple pull-out tests. Tensile pull-out tests are fundamental to understanding the behavior of the nails and to give an indication of their performance for design purposes.

5.2 Conclusions

The drilling procedure recommended by Hilti was used when installing the nail. That is, the drill hole should was to be 2.36 in. (60 mm) deep, and as normal to the concrete surface as possible. Tests showed that slight variations from this recommended procedure had a negligible effect on the performance of the nail. The modified drill bit, which produced the stepped hole, was used. This not only reduced the amount of surface cracking, but also ensured that the correct diameter drill hole was provided. Tests on nails driven in into holes drilled with a bit other than that provided by Hilti were not conducted, and therefore, the effect of such a procedure is not known.

Many of the variables considered to affect the nail's performance were studied. The most important ones were concrete strength, proximity of the nail to an edge of the slab, and proximity of the nail to a crack in the slab. The results show that nails driven into weaker concretes have a lower pull-out strength. They also show that proximity to an edge or a crack reduces the pull-out capacity of the nail. Design equations which include the effects of these three factors were developed.

Although various coarse aggregates were used in the concrete, they seemed not to have any effect on the pull-out strength of the nail. There was reason to believe that the coarse aggregate influenced the occurrence of cone-type failures, but not enough data exist to substantiate this effect.

The few cone-type failures that did occur resulted in pull-out strengths that were little different from those nails which pulled cleanly from the concrete. The post-failure capacity of the nails that failed with cones, however, was greatly reduced. The only aspect of nail behavior that correlates well with the occurrence of cone-type failures is the degree of sintering. High levels of sintering accompanied cone-type failures, while low levels of sintering resulted in clean pull-outs. The cause of the various levels of sintering was not determined.

Tests performed by the Hilti Corporation concluded that of the two mechanisms which control the behavior of the nail, clamping is responsible for approximately 70% of the pull-out strength while sintering is responsible for the other 30%. Although the degree of sintering cannot be manipulated, the magnitude of the clamping can. This is largely accomplished by the condition of the concrete in which the nail is driven. In general, any characteristic of the concrete which will reduce the confining stresses around the nail will result in a decrease in its pull-out strength. The confining stresses are directly related to concrete strength (and, therefore, its modulus) around the nail and control its pull-out capacity. Driving the nail near an edge or a crack has the effect of relaxing some of the confining stresses around the nail, and, therefore, reduces the pull-out capacity.

5.3 Design Recommendations

In order to achieve the maximum pull-out capacity of the nail, the effects of driving the nail near an edge or a crack must be minimized. This can be accomplished by specifying the minimum distance from an edge or crack that a nail can be driven. This minimum distance should be taken as:

$$d_{e,min} = d_{c,min} = f_c / 800 + 3.5$$

where:

$d_{e,min}$ = minimum distance from an edge, in inches, not less than 4 in.,
$d_{c,min}$ = minimum distance from a crack, in inches, and
f_c = concrete strength, in psi.

With the above distances satisfied, the maximum pull-out strength of the nail can be expected. This strength is equal to the basic pull-out strength of a nail driven in a standard condition and is given by:

$$P_s = f_c / 820$$

where:

P_s = pull-out strength, in kips, and
f_c = concrete strength, in psi.

Appendix: Test Data

The Appendix contains the data recorded for the test program. The variables pertinent to each test and observations on the nails' performance are presented. In order to facilitate the recording of data, a convenient notation scheme was used.

Nail Designation: The first letter identifies the slab in which the nail was tested and, therefore, provides information on the concrete strength and aggregate type. Slab 1, which was cast with river gravel, was denoted with the letter 'R'. Similarly, 'S' (soft limestone) and 'H' (hard limestone) denoted slabs 2 and 3, respectively. The forth slab, also cast with soft limestone, but with a much higher strength, was arbitrarily assigned 'T'.

The first number identifies the power level of the charge used in driving the nail. The power level ranged from 1 to 4 and was adjusted by a dial on the driving tool.

The second letter identified, roughly, the location of the nail on the slab with an 'S' representing a standard test where the nail was driven in the central part of the slab away from an edge or a crack. An 'E' represents those tests where the nail's proximity to the edge of the slab was considered as a variable. A 'C' represented those tests where the presence of a crack in the slab was considered as a variable.

The second number identified the replicate of the particular test type. Some test groups had eight or nine replicates, while others had only three.

Since there were several variations of tests which involved cracked slabs, an additional letter was appended after the replicate number. In series 'A', the slab was cracked (by loading it in flexure) and then unloaded. Nails were driven into the cracks. After loading the slab in flexure, again, the nails were pulled out. In series 'B', the slab was cracked and unloaded. The nails were driven into the cracks and pulled-out without loading the slab. Series 'C' was similar to 'A' except the slab was loaded approximately half as much. In series 'D', after the slab was cracked, nails were driven next to the cracks at distances of one, two, and three inches. This distance was included in the nail designation and followed 'D'. In series 'F', a line of nails was driven across the slab such that a hairline crack developed between the nails. The slab was then loaded in flexure and the nails were pulled out. Series 'G' was similar to 'F' except that the slab was unloaded prior to pull-out of the nails.

Depth: The depth of the drill hole was measured, after it was properly cleaned, with the depth gage of a micrometer.

Angle: The angle the drill hole made with the surface of the concrete was measured in two orthogonal directions. Shown in the tables is the resultant angle the drill hole made with the surface of the concrete.

Edge Distance: The proximity of the nails to the edge of the slab was measured for those tests where this distance was a variable.

Crack Width: The width of the crack in which or near which nails were driven was measured throughout the testing sequence. In general, the width was measured prior to driving the nail, after driving the nail, and after loading and unloading the slab. In series 'B' and 'D', the slab was not loaded, therefore, "na" was included as part of the measurement. Similarly, in series 'F' and 'G', there was no crack prior to driving the nails, but a hairline crack with a width of 0.002" developed between the nails prior to loading. In series 'G', the slab was unloaded prior to pull-out of the nails, so the crack width was measured again.

Surface Cracks: Hairline cracks (0.002" width) developed in the surface of the concrete due to the driving of the nail. The length of all the cracks radiating from the nail were totalled.

Failure Cone: The size of the failure cone, if any, was recorded. A medium cone (med) was approximately six inches in diameter, or smaller, and was usually shallow. A full cone (fl) had a diameter greater than approximately six inches and was usually deep.

Sintering: The level of sintering indicates the amount of concrete remaining attached to the nail after pull-out. This was a fairly subjective judgement since no quantitative values could describe the level of sintering.

Figures 2.16a, 2.16b, and 2.16c show typical examples of low, medium, and high levels of sintering.

Pull-Out: The maximum load applied to the nail was recorded.

Load-displacement plots of each test follow the tables with all replicates of a test type shown on a single plot.

Slab Number:	1A	Aggregate Type:	River Gravel
Date of Cast:	Nov. 6, 1992	Date of Test:	Feb. 1993

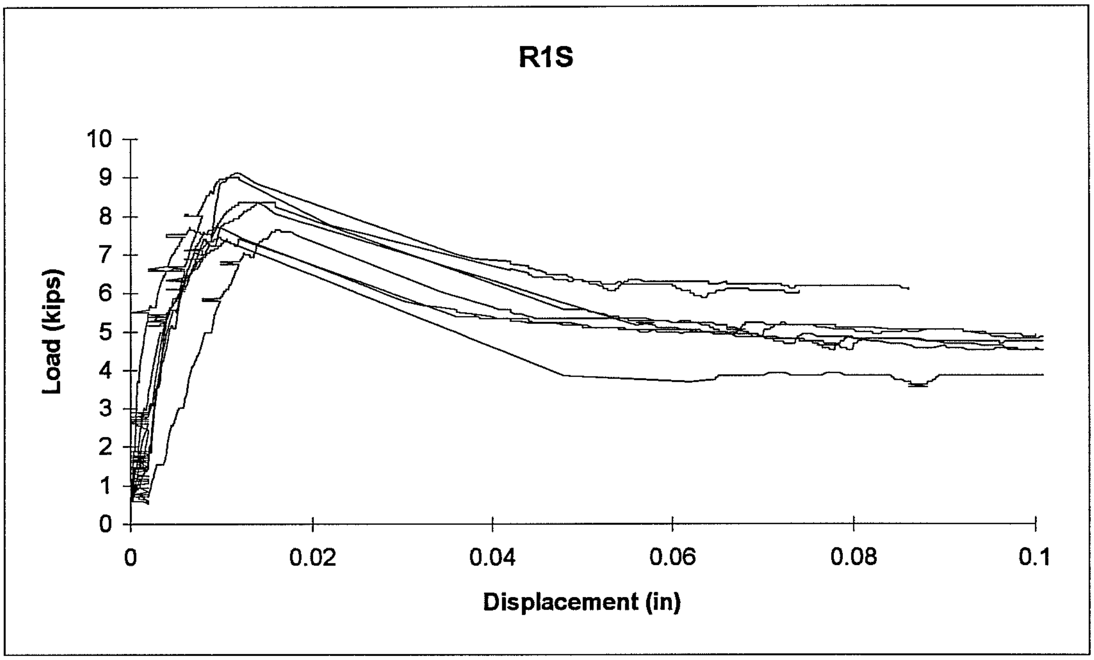
Concrete Strength					
7 Day	3920	3530	3490	Average:	3650
28 Day	4350	4150	4620	Average:	4370
Test Day	4730	4530	4690	Average:	4650

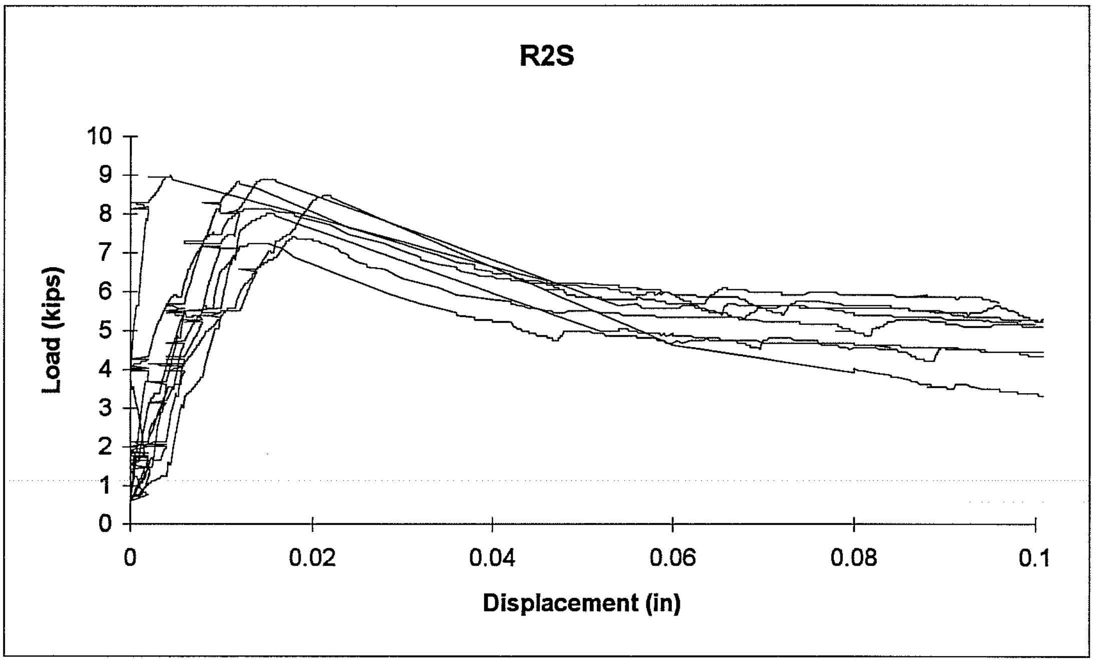
Pull-Out Tests									
Nail #	Depth	Angle	Edge Dist.	Crack Wth.	Surf. Crk.	Fail. Cone	Sintering	Pull-Out	Comments
	inches	degree	inches	1/1000th in.	inches	no/med/fl	lo/med/hi	kips	
R1S1	2.39	2.0	na	na	0.00	no	lo	7.41	
R1S2	2.36	1.4	na	na	0.00	no	lo	7.76	slight spalling after nailing
R1S3	2.33	3.2	na	na	0.50	md	hi	8.36	
R1S4	2.34	3.6	na	na	0.00	no	lo	9.01	
R1S5	2.41	2.2	na	na	0.00	no	lo	8.36	
R1S6	2.42	2.2	na	na	0.00	no	lo	7.65	
R1S7	2.42	1.4	na	na	0.00	no	lo	7.47	
R1S8	2.30	2.0	na	na	1.00	no	lo	9.13	
R2S1	2.35	1.0	na	na	0.00	no	lo	8.00	
R2S2	2.27	1.4	na	na	0.00	md	md	8.46	
R2S3	2.34	1.0	na	na	0.00	md	md	8.89	cone developed after failure
R2S4	2.32	1.4	na	na	0.00	no	lo	8.12	
R2S5	2.35	1.0	na	na	0.00	no	lo	9.01	
R2S6	2.28	2.0	na	na	0.00	no	lo	7.23	
R2S7	2.29	2.2	na	na	0.00	no	lo	7.41	tip of nail flattened
R2S8	2.33	1.0	na	na	0.00	no	lo	8.83	
R3S1	2.39	4.5	na	na	0.00	no	lo	10.14	
R3S2	2.38	2.0	na	na	0.75	no	lo	10.37	
R3S3	2.32	1.0	na	na	0.00	no	lo	7.23	suspect void during drilling
R3S4	2.36	1.4	na	na	1.00	md	hi	9.66	
R3S5	2.10	1.0	na	na	0.00	no	lo	6.88	nail bent

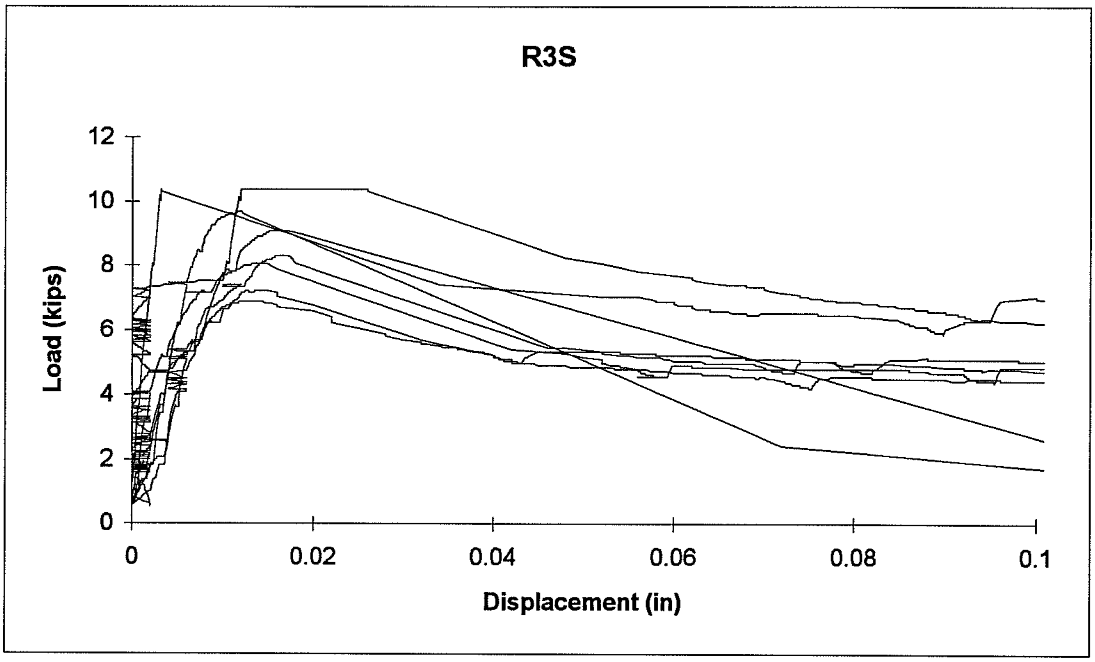
Pull-Out Tests									
Nail #	Depth	Angle	Edge Dist.	Crack Wth.	Surf. Crk.	Fail. Cone	Sintering	Pull-Out	Comments
	inches	degree	inches	1/1000th in.	inches	no/med/fl	lo/med/hi	kips	
R3S6	2.33	1.4	na	na	1.00	fl	hi	9.07	
R3S7	2.35	4.1	na	na	2.50	no	lo	8.06	nail bent
R3S8	2.30	0.0	na	na	2.50	md	md	8.30	
R4S1	2.36	1.0	na	na	0.00	no	lo	9.96	
R4S2	2.18	4.0	na	na	0.00	md	md	9.60	
R4S3	2.32	1.0	na	na	3.00	no	lo	9.07	
R4S4	2.36	1.0	na	na	1.00	no	lo	8.71	
R4S5	2.43	1.0	na	na	1.50	no	lo	9.13	
R4S6	2.36	1.0	na	na	1.50	md	lo	8.18	
R4S7	2.30	2.2	na	na	2.50	no	lo	9.13	
R4S8	2.35	0.0	na	na	1.50	no	lo	7.65	
R1E1	2.34	1.0	6.0	na	6.00	no	lo	7.40	near existing test holes
R1E2	2.41	1.0	4.0	na	1.75	med	lo	8.43	near existing test holes
R1E3	2.29	1.4	4.5	na	2.50	med	hi	6.89	near existing test holes
R1E4	2.43	1.4	5.0	na	1.50	no	lo	8.56	near existing test holes
R1E5	2.33	1.0	5.5	na	0.00	no	lo	8.03	near existing test holes
R1E6	2.33	1.0	4.0	na	5.00	no	lo	8.16	
R1E7	2.39	2.0	4.5	na	1.00	no	lo	9.32	
R1E8	2.34	2.8	5.0	na	0.00	no	lo	7.92	
R1E9	2.32	0.0	5.5	na	0.00	no	lo	8.56	
R2E1	2.54	1.0	6.0	na	0.00	no	med	10.08	near existing test holes
R2E2	2.38	0.0	4.0	na	7.00	no	lo	8.03	near existing test holes
R2E3	2.38	2.2	4.5	na	4.50	med	hi	7.33	near existing test holes
R2E4	2.47	1.0	5.0	na	0.00	no	lo	9.20	near existing test holes
R2E5	2.44	2.0	5.5	na	2.00	no	lo	8.88	near existing test holes
R2E6	2.41	0.0	4.0	na	5.50	no	lo	7.81	
R2E7	2.44	1.0	4.5	na	3.50	no	lo	8.98	
R2E8	2.40	1.0	5.0	na	2.00	no	lo	7.31	
R2E9	2.38	1.4	5.5	na	0.50	no	lo	9.45	

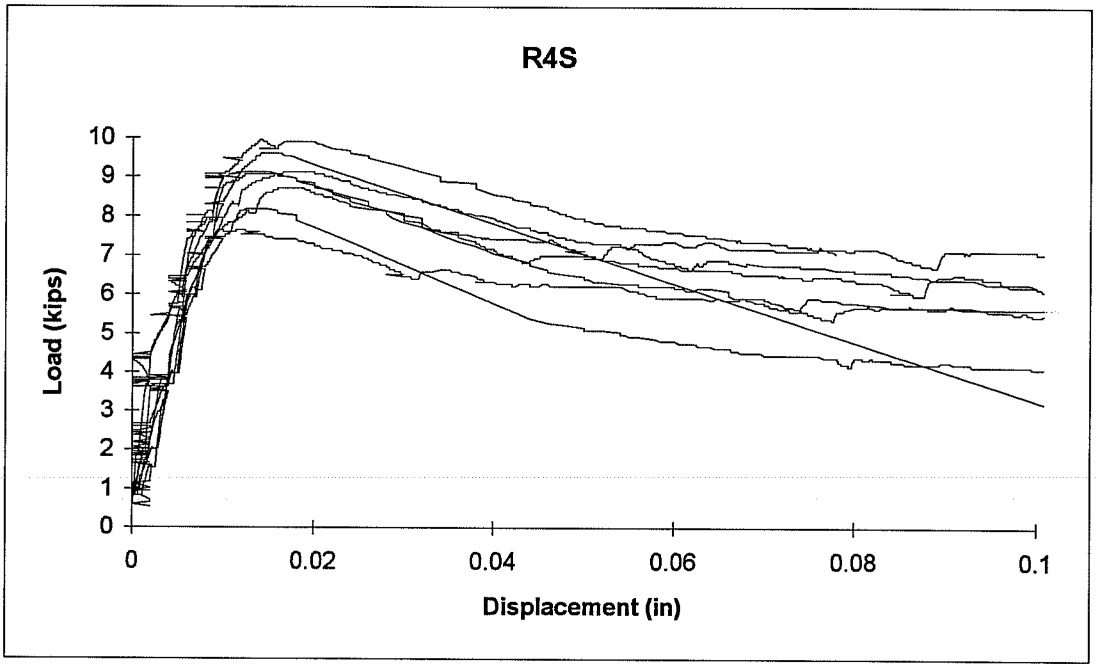
Pull-Out Tests									
Nail #	Depth	Angle	Edge Dist.	Crack Wth.	Surf. Crk.	Fail. Cone	Sintering	Pull-Out	Comments
	inches	degree	inches	1/1000th in.	inches	no/med/fl	lo/med/hi	kips	
R3E1	2.28	3.2	6.0	na	6.00	no	lo	8.13	
R3E2	2.22	3.0	4.0	na	8.00	no	lo	7.14	crack on side of conc. 1.5"
R3E3	2.32	4.1	4.5	na	0.75	no	lo	7.27	
R3E4	2.21	7.0	5.0	na	4.50	no	lo	6.84	crack on side of conc. 1"
R3E5	2.32	2.0	5.5	na	4.00	med	med	8.08	
R3E6	2.20	3.2	4.0	na	5.75	no	lo	7.62	nail bent
R3E7	2.45	1.0	4.5	na	2.75	fl	hi	9.75	wedge-shaped cone along side
R3E8	2.35	4.5	5.0	na	1.00	no	lo	6.95	nail bent
R3E9	2.38	3.2	5.5	na	1.00	no	lo	9.19	
R4E1	2.31	3.2	6.0	na	8.25	no	lo	9.03	
R4E2	2.35	1.0	4.0	na	13.50	no	lo	7.87	crack on side of concrete
R4E3	2.35	2.2	4.5	na	8.00	no	lo	9.47	crack on side of concrete
R4E4	2.30	1.0	5.0	na	11.75	no	lo	7.65	
R4E5	2.45	4.0	5.5	na	1.50	no	lo	9.29	nail bent
R4E6	2.34	3.2	4.0	na	11.50	no	lo	6.95	crack on side of concrete
R4E7	2.24	2.0	4.5	na	7.00	no	lo	7.98	crack on side of concrete
R4E8	2.38	2.2	5.0	na	5.00	no	lo	8.41	crack on side of concrete
R4E9	2.36	4.0	5.5	na	4.00	no	lo	7.78	nail bent
R2C1A	2.38	1.0	na	5/13/20	0.00	no	lo	1.77	350 k-in moment applied to
R2C2A	2.34	0.0	na	5/16/25	0.00	no	lo	2.42	slab to increase crack width
R2C3A	2.36	1.0	na	3/16/25	0.00	no	lo	2.75	
R2C4A	2.45	2.0	na	5/20/30	0.00	no	lo	1.38	
R2C1B	2.41	0.0	na	7/20/na	0.00	no	lo	5.76	
R2C2B	2.35	0.0	na	9/20/na	0.00	no	lo	5.84	
R2C3B	2.46	2.0	na	7/20/na	0.00	no	lo	7.91	
R2C4B	2.40	3.0	na	9/20/na	0.00	no	lo	4.89	
R2C5B	2.40	0.0	na	2/10/na	0.00	no	lo	5.40	
R2C6B	2.46	1.4	na	3/13/na	0.00	no	lo	4.81	
R2C7B	2.45	2.2	na	3/13/na	0.00	no	lo	6.04	

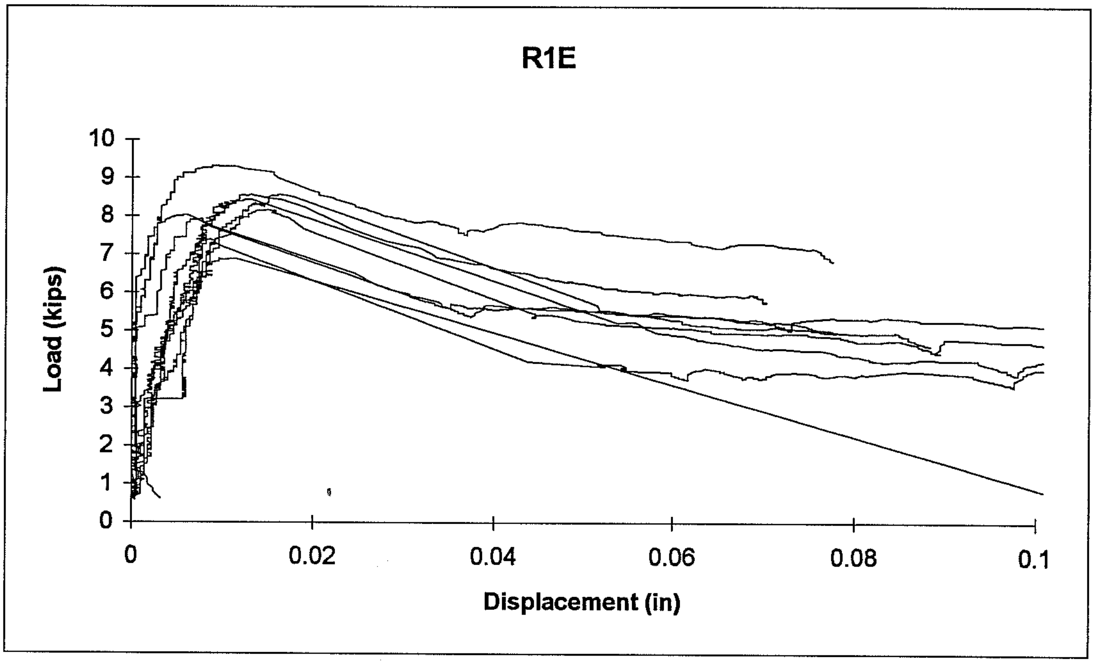
Pull-Out Tests									
Nail #	Depth	Angle	Edge Dist.	Crack Wth.	Surf. Crk.	Fail. Cone	Sintering	Pull-Out	Comments
	inches	degree	inches	1/1000th in.	inches	no/med/fl	lo/med/hi	kips	
R2C8B	2.48	1.4	na	3/13/na	0.00	no	lo	6.63	
R2C9B	2.45	1.0	na	5/20/na	0.00	no	lo	6.51	
R2C10B	2.33	1.4	na	7/16/na	0.00	no	lo	5.69	
R2C11B	2.44	0.0	na	9/16/na	0.00	no	lo	4.71	
R2C12B	2.44	2.0	na	9/20/na	0.00	no	lo	6.81	
R2C1C	2.42	1.0	na	7/16/25	0.00	no	lo	2.77	slab re-loaded to 175 k-in
R2C2C	2.42	2.0	na	5/20/20	0.00	no	lo	3.42	
R2C3C	2.44	3.0	na	10/20/20	0.00	no	med	5.03	
R2C4C	2.37	3.2	na	9/20/20	0.00	no	lo	4.68	
R2C1D1	2.37	3.0	na	16/9/na	1.00	no	lo	5.55	
R2C2D1	2.34	1.0	na	13/9/na	4.00	no	lo	5.80	
R2C3D1	2.40	3.0	na	9/7/na	3.00	no	lo	5.23	
R2C1D2	2.35	4.0	na	16/10/na	5.50	no	lo	5.67	
R2C2D2	2.34	2.0	na	13/9/na	3.50	med	med	5.94	
R2C3D2	2.35	1.0	na	16/9/na	3.50	no	lo	5.89	
R2C1D3	2.32	0.0	na	10/7/na	0.00	med	hi	7.25	
R2C2D3	2.32	3.2	na	13/7/na	0.00	med	med	6.07	
R2C3D3	2.34	3.2	na	10/7/na	0.00	no	lo	8.46	
R2C1F	2.25	1.0	na	na/2/5	0.00	fl	hi	5.49	slab loaded to 295 k-in after
R2C2F	2.34	3.2	na	na/2/5	0.00	no	lo	4.36	crack developed between nails
R2C3F	2.29	2.0	na	na/2/5	0.00	no	lo	4.72	
R2C1G	2.36	1.0	na	na/2/5/3	0.00	no	lo	5.64	slab unloaded for G series
R2C2G	2.37	2.8	na	na/2/5/3	0.00	med	hi	6.98	
R2C4F	2.38	2.8	na	na/2/3	0.00	no	lo	5.19	slab loaded to 495 k-in after
R2C5F	2.39	4.0	na	na/2/9	0.00	no	lo	3.28	crack developed between nails
R2C6F	2.46	2.0	na	na/2/5	0.00	no	lo	2.92	
R2C3G	2.32	1.0	na	na/2/7/3	0.00	no	lo	6.41	slab unloaded


R1S
Load (kips)
10
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

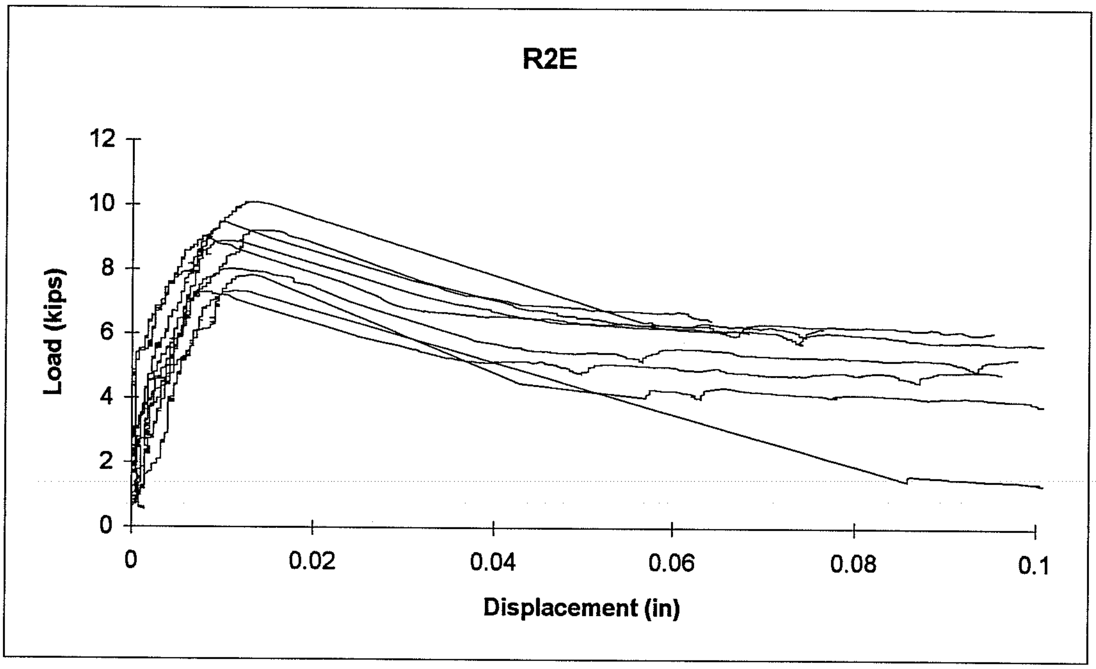

R2S
Load (kips)
10
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


R3S
Load (kips)
12
10
8
6
4
2
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

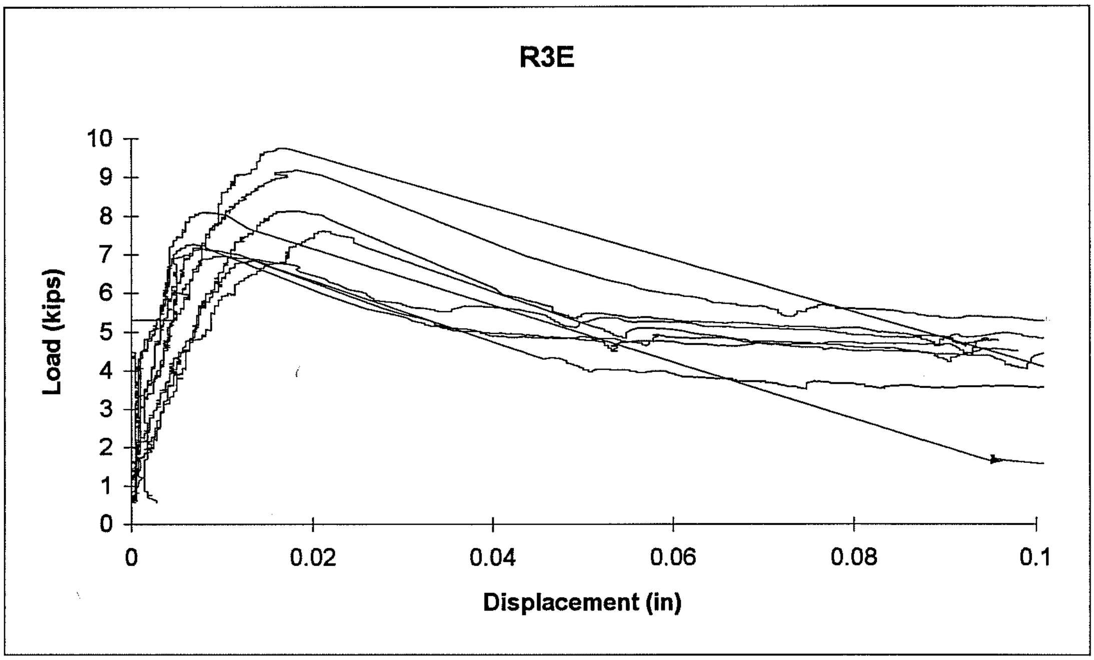

R4S
Load (kips)
10
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

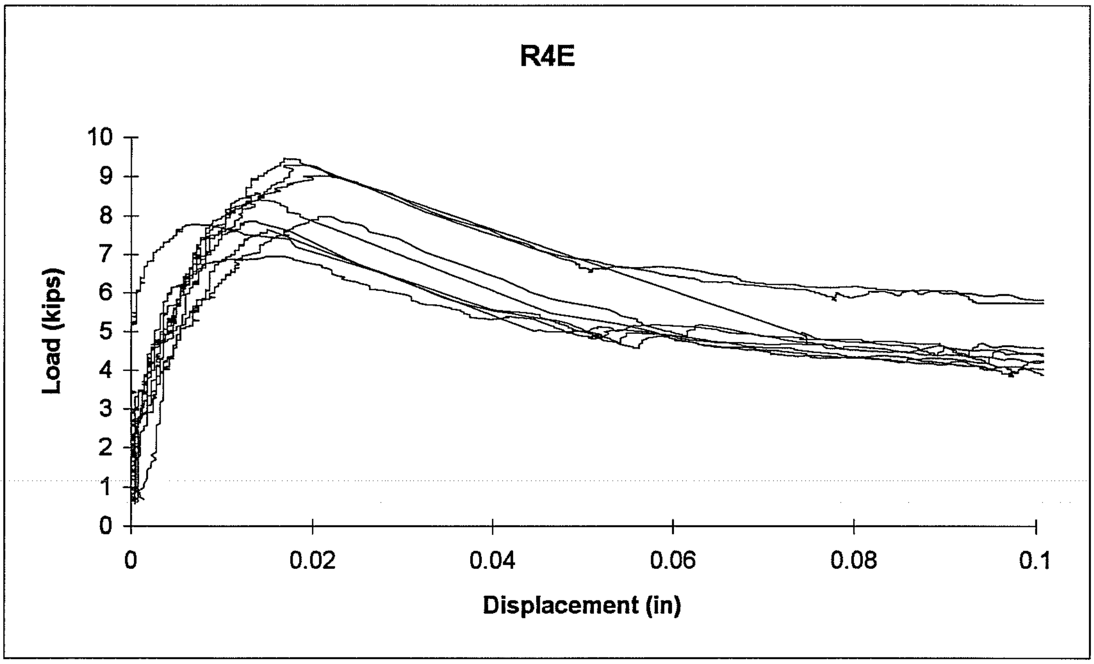


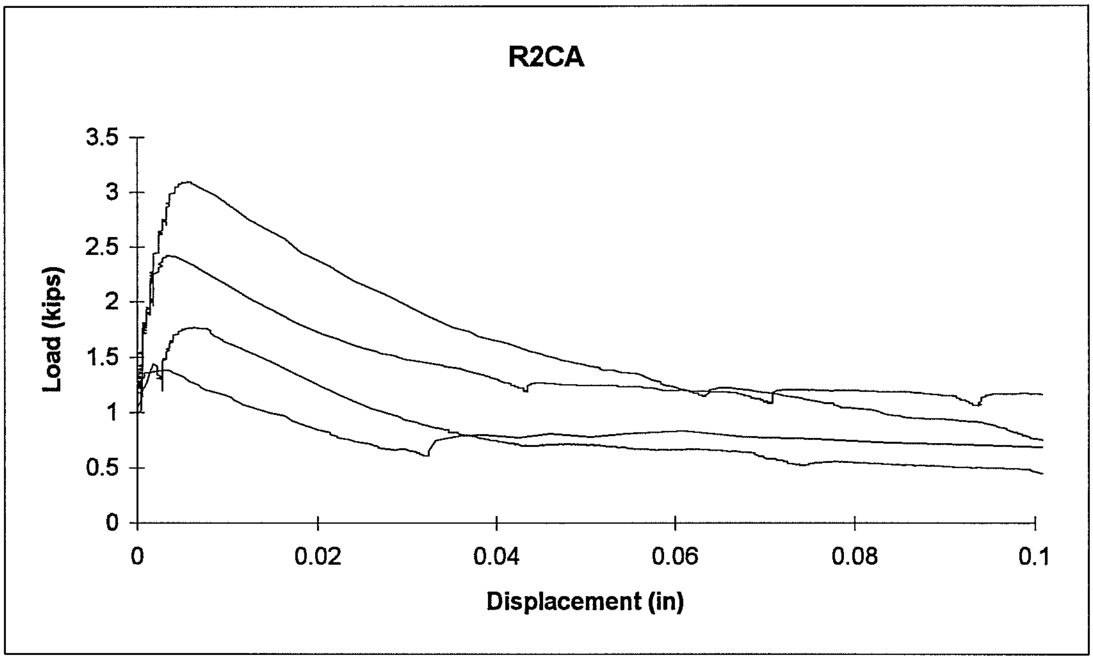
R1E
Load (kips)
10
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

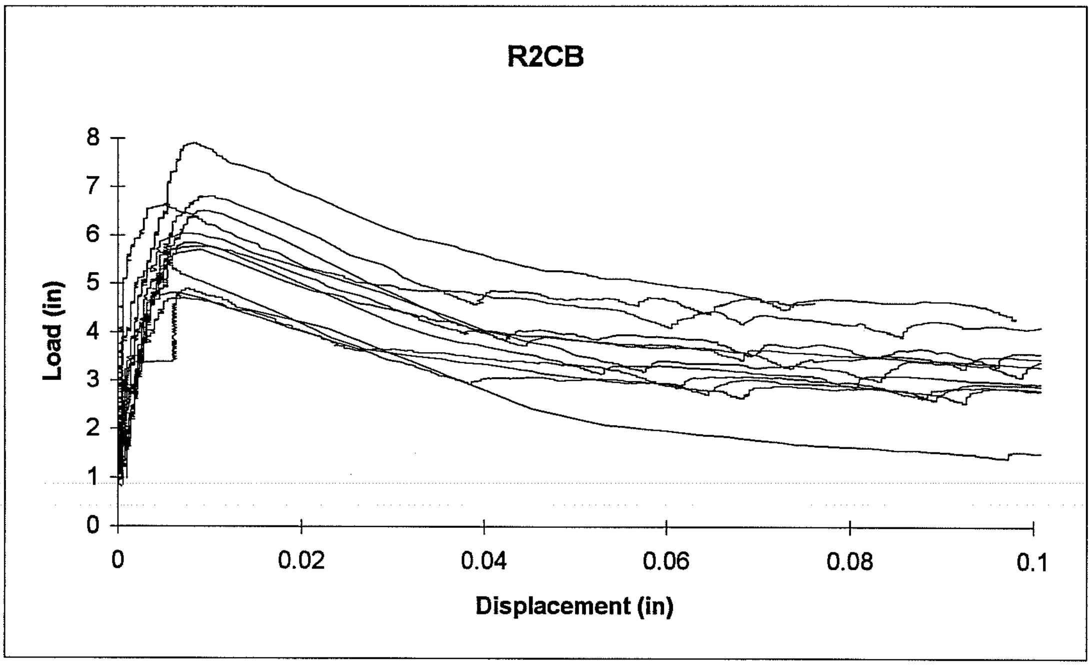


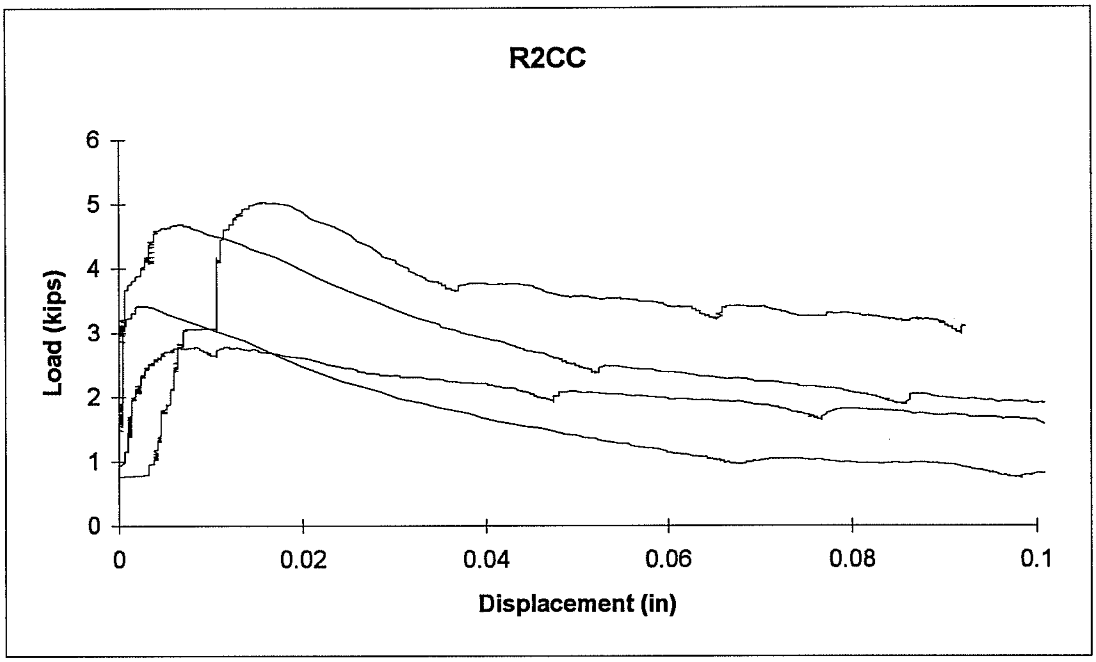
R2E
Load (kips)
12
10
8
6
4
2
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

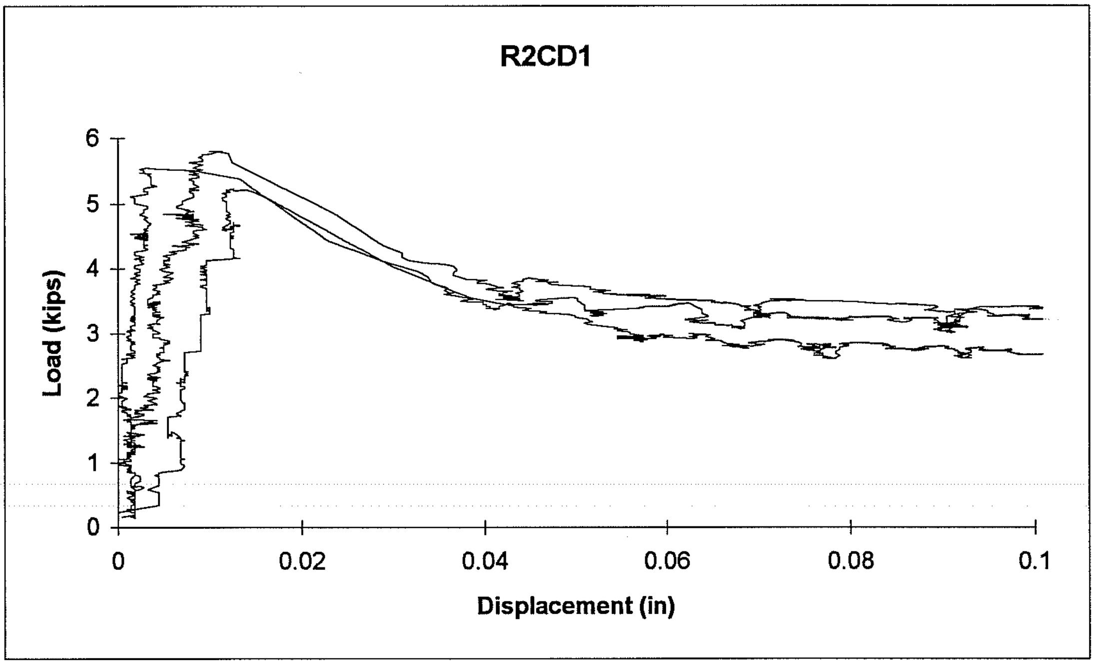

R3E
10
9
8
7
6
5
4
3
2
1
0
Load (kips)
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

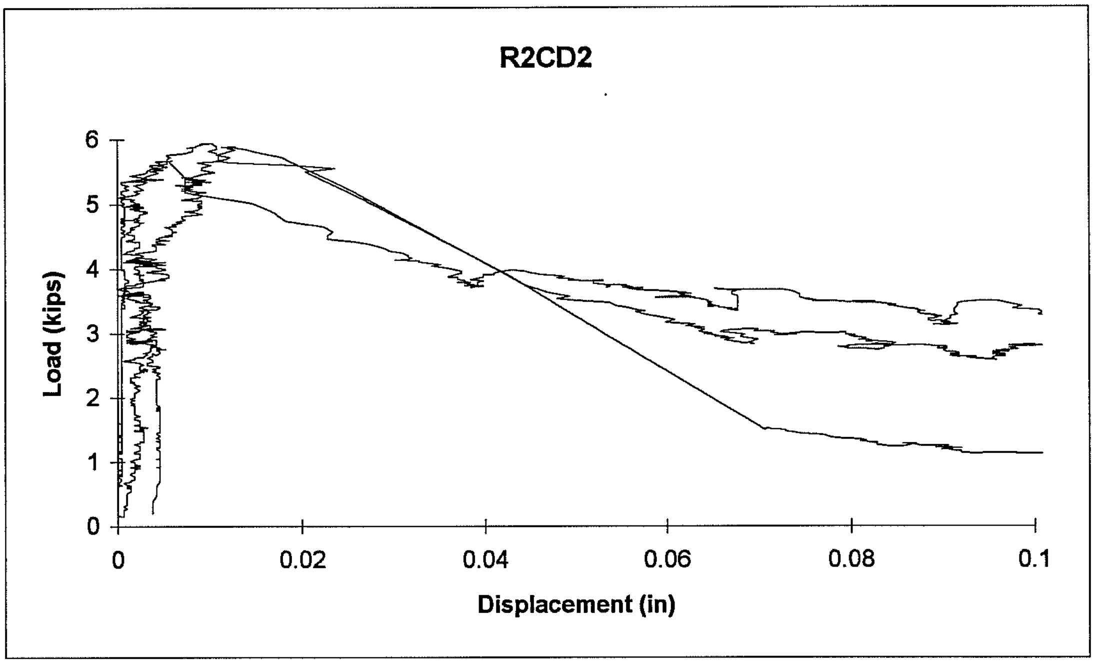

R4E
10
9
8
7
6
5
4
3
2
1
0
Load (kips)
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

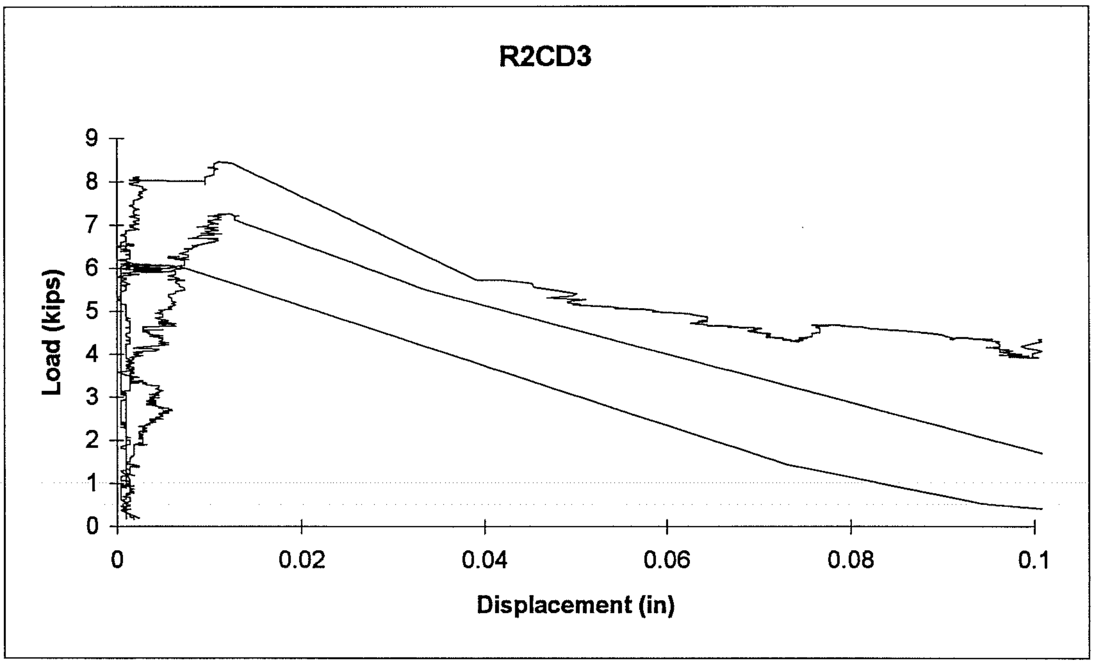

R2CA
Load (kips)
3.5
3
2.5
2
1.5
1
0.5
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

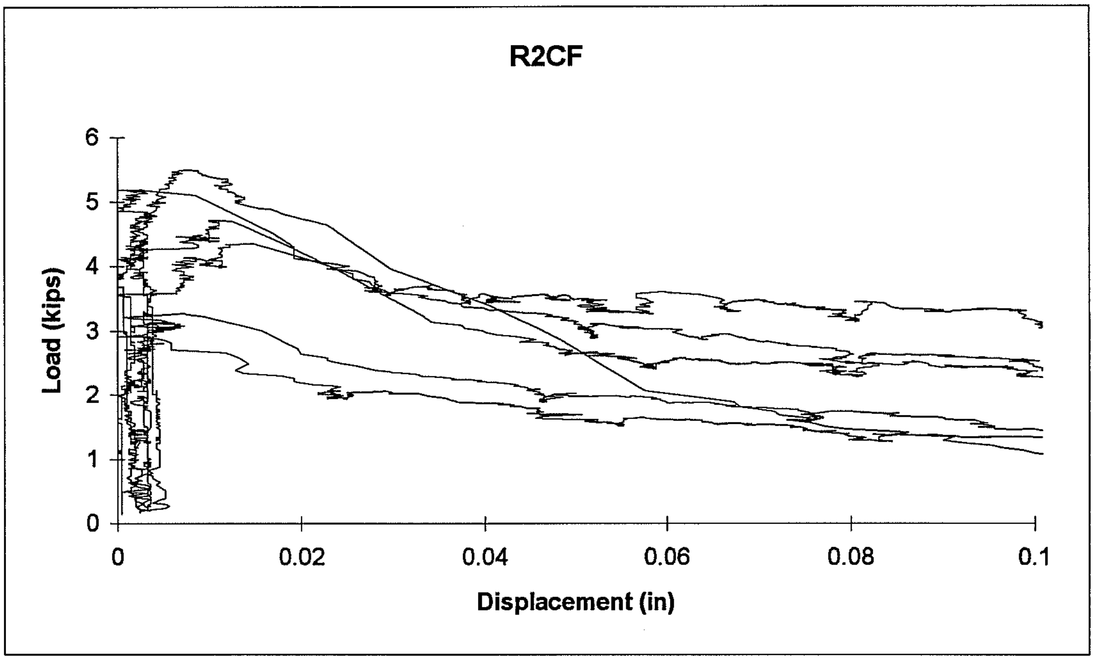

R2CB
Load (in)
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

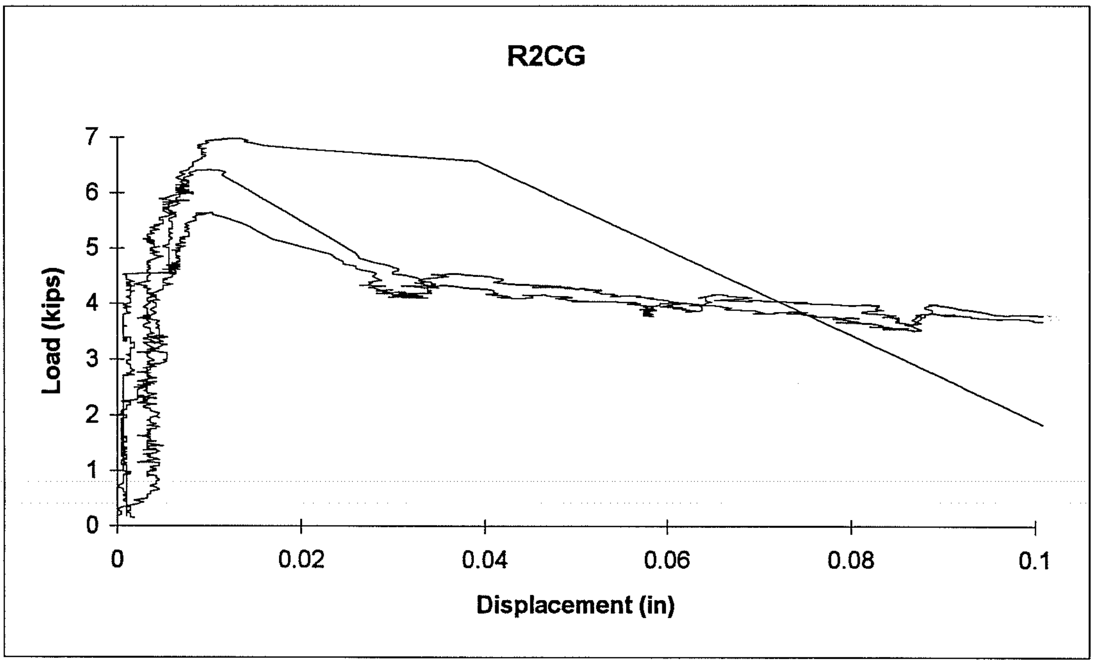

R2CC
Load (kips)
0
1
2
3
4
5
6
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


R2CD1
Load (kips)
0
1
2
3
4
5
6
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


R2CD2
Load (kips)
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


R2CD3
Load (kips)
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


R2CF
Load (kips)
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


R2CG
Load (kips)
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

Slab Number:	2A	Aggregate Type:	Soft Limestone
Date of Cast:	Dec. 3, 1992	Date of Test:	Feb. 1993

Concrete Strength					
7 Day	1970	1970	1990	Average:	1980
28 Day	2710	2680	2680	Average:	2690
Test Day	2870	2500	2750	Average:	2710

Pull-Out Tests

Nail #	Depth	Angle	Edge Dist.	Crack Wth.	Surf. Crk.	Fail. Cone	Sintering	Pull-Out	Comments
	inches	degree	inches	1/1000th in.	inches	no/med/fl	lo/med/hi	kips	
S1S1	2.33	1.0	na	na	0.00	no	lo	4.39	
S1S2	2.36	1.0	na	na	1.00	no	lo	3.31	
S1S3	2.31	2.8	na	na	1.00	no	lo	3.99	nail bent
S1S4	2.36	1.4	na	na	0.00	no	lo	3.33	popping sounds after failure
S1S5	2.20	1.0	na	na	1.50	no	lo	4.53	
S1S6	2.42	2.2	na	na	0.00	no	lo	3.95	
S1S7	2.41	3.6	na	na	0.00	no	lo	3.14	
S1S8	2.43	3.6	na	na	0.50	no	lo	4.41	nail bent
S2S1	2.40	5.4	na	na	0.00	no	lo	4.56	nail bent
S2S2	2.39	4.1	na	na	0.00	no	lo	4.88	
S2S3	2.40	4.5	na	na	0.00	no	lo	5.22	
S2S4	2.41	2.2	na	na	0.00	no	lo	4.33	
S2S5	2.41	3.2	na	na	0.00	no	lo	4.22	
S2S6	2.37	3.2	na	na	0.00	no	med	4.95	
S2S7	2.27	4.1	na	na	1.00	no	lo	3.62	
S2S8	2.37	2.2	na	na	4.50	no	lo	4.47	
S3S1	2.43	1.0	na	na	0.00	no	lo	4.26	
S3S2	2.43	3.0	na	na	0.00	no	lo	3.80	
S3S3	2.41	1.4	na	na	0.00	no	lo	3.76	
S3S4	2.38	1.0	na	na	0.25	no	lo	4.52	
S3S5	2.39	0.0	na	na	0.50	no	lo	4.40	

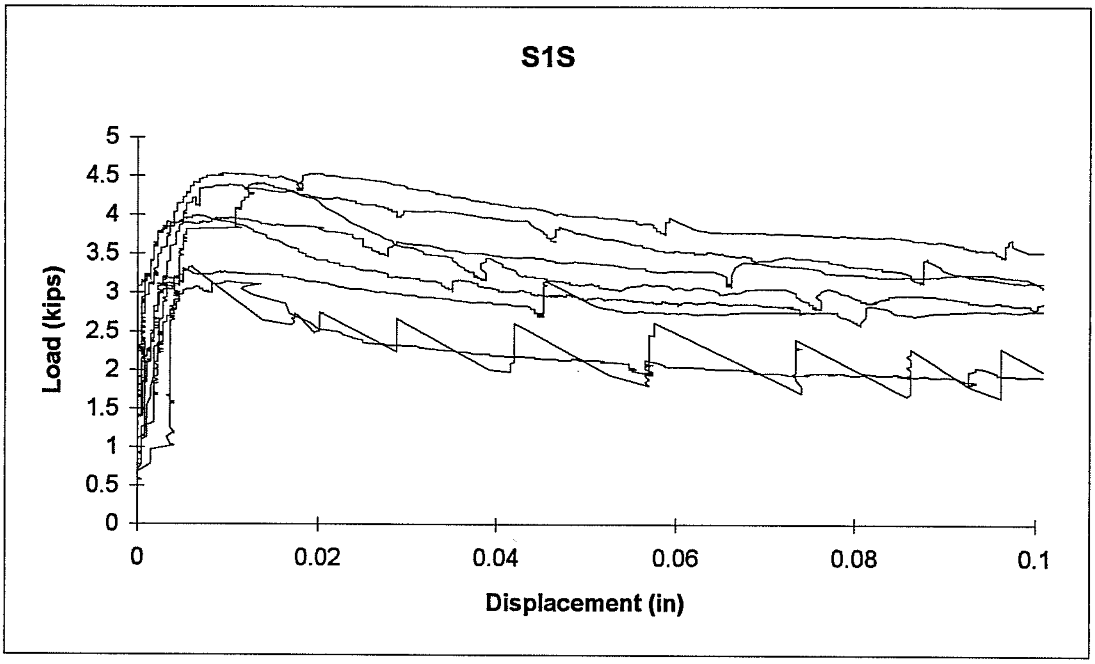
Pull-Out Tests									
Nail #	Depth	Angle	Edge Dist.	Crack Wth.	Surf. Crk.	Fail. Cone	Sintering	Pull-Out	Comments
	inches	degree	inches	1/1000th in.	inches	no/med/fl	lo/med/hi	kips	
S3S6	2.34	2.0	na	na	0.00	no	lo	4.47	
S3S7	2.42	1.0	na	na	0.00	no	med	4.77	
S3S8	2.30	0.0	na	na	0.00	no	lo	4.29	
S4S1	2.40	1.4	na	na	2.00	no	lo	5.11	
S4S2	2.42	4.1	na	na	3.50	no	lo	4.97	nail bent
S4S3	2.44	3.2	na	na	0.75	no	lo	4.61	
S4S4	2.34	0.0	na	na	0.00	no	lo	5.93	
S4S5	2.40	3.6	na	na	1.25	no	lo	5.30	
S4S6	2.41	1.4	na	na	2.00	no	lo	4.75	
S4S7	2.39	3.0	na	na	3.50	no	lo	4.58	
S4S8	2.39	3.2	na	na	2.50	no	lo	4.43	
S1E1	2.30	2.2	6.0	na	2.00	no	lo	5.41	
S1E2	2.32	0.0	4.0	na	5.00	no	lo	4.93	
S1E3	2.33	1.4	4.5	na	2.00	no	lo	3.94	
S1E4	2.36	2.0	5.0	na	1.00	no	med	4.23	
S1E5	2.33	1.0	5.5	na	1.50	no	lo	4.84	
S1E6	2.33	0.0	4.0	na	0.00	no	lo	4.77	
S1E7	2.33	2.2	4.5	na	4.50	no	lo	3.82	
S1E8	2.32	2.8	5.0	na	1.50	no	lo	5.25	
S1E9	2.35	2.8	5.5	na	1.00	no	lo	4.94	
S2E1	2.36	1.0	6.0	na	2.50	no	lo	5.55	
S2E2	2.43	3.0	4.0	na	2.50	no	lo	5.06	nail bent
S2E3	2.40	3.6	4.5	na	0.50	no	lo	4.45	
S2E4	2.32	4.5	5.0	na	0.75	no	lo	4.34	nail bent
S2E5	2.42	2.2	5.5	na	0.50	no	lo	5.22	
S2E6	2.38	2.2	4.0	na	4.00	no	lo	5.11	
S2E7	2.39	2.2	4.5	na	2.50	no	lo	5.09	
S2E8	2.44	4.1	5.0	na	5.75	no	lo	4.56	
S2E9	2.45	5.4	5.5	na	2.00	no	med	4.45	nail bent

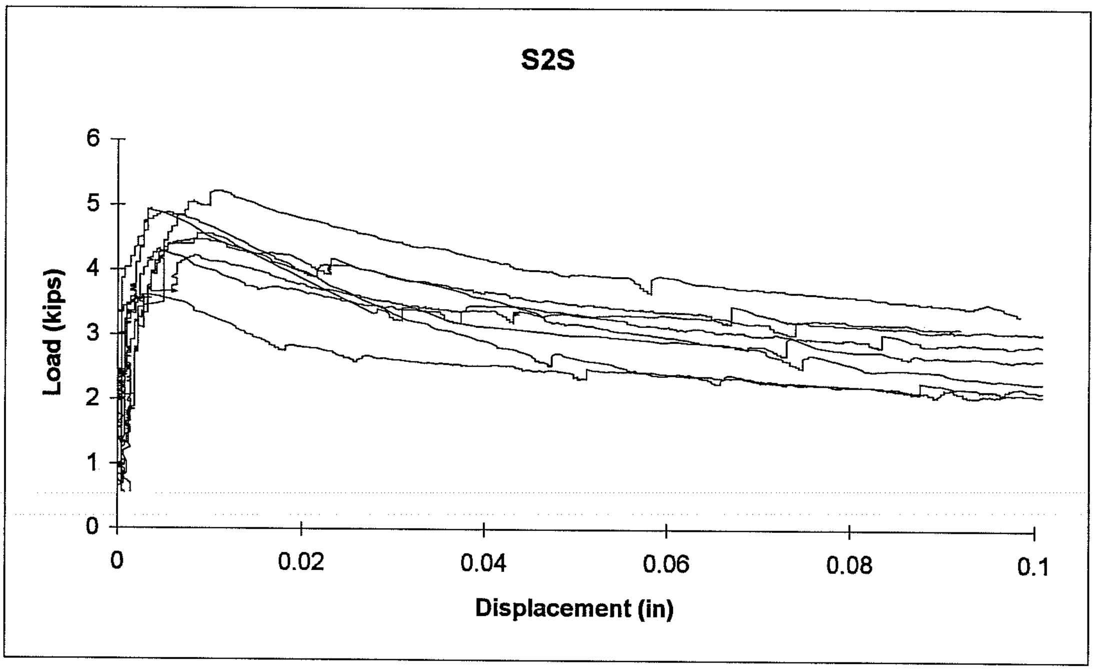
Pull-Out Tests

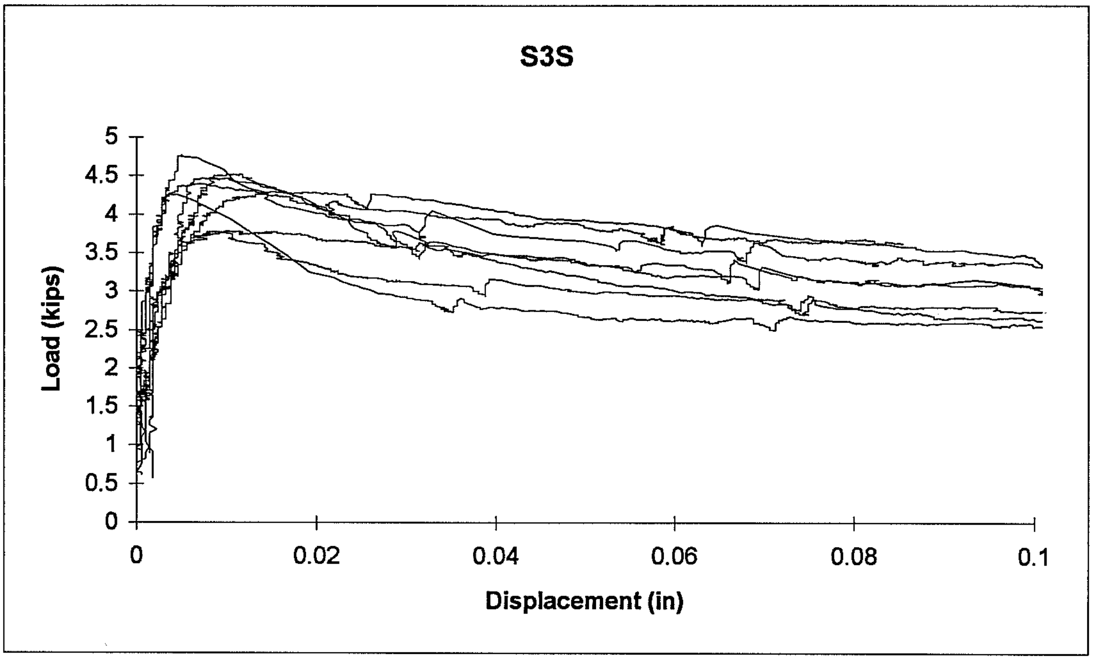
Nail #	Depth	Angle	Edge Dist.	Crack Wth.	Surf. Crk.	Fail. Cone	Sintering	Pull-Out	Comments
	inches	degree	inches	1/1000th in.	inches	no/med/fl	lo/med/hi	kips	
S3E1	2.32	2.2	6.0	na	11.00	no	lo	4.72	
S3E2	2.31	2.2	4.0	na	4.00	no	lo	4.76	cracks to side of concrete
S3E3	2.34	1.0	4.5	na	7.50	no	lo	4.50	cracks to side of concrete
S3E4	2.35	2.2	5.0	na	1.50	no	lo	5.72	
S3E5	2.30	1.0	5.5	na	2.00	no	lo	6.21	
S3E6	2.31	2.0	4.0	na	4.50	no	lo	4.42	
S3E7	2.33	1.0	4.5	na	0.00	no	lo	3.36	
S3E8	2.26	1.0	5.0	na	0.75	no	lo	4.72	
S3E9	2.30	1.4	5.5	na	3.50	no	lo	3.78	
S4E1	2.44	2.8	6.0	na	0.00	no	lo	4.17	
S4E2	2.55	1.0	4.0	na	4.00	no	lo	4.50	crack to side of concrete
S4E3	2.55	1.4	4.5	na	4.00	no	lo	5.25	crack to side of concrete
S4E4	2.26	1.4	5.0	na	4.00	no	lo	4.85	
S4E5	2.34	3.6	5.5	na	0.00	no	lo	4.80	
S4E6	2.29	1.0	4.0	na	10.00	no	lo	4.61	
S4E7	2.43	0.0	4.5	na	9.00	no	lo	4.28	
S4E8	2.46	0.0	5.0	na	5.00	no	lo	5.02	crack to side of concrete
S4E9	2.45	1.0	5.5	na	4.00	no	lo	4.60	
S2C1A	2.40	2.0	na	2/13/20	0.00	no	lo	0.79	slab re-loaded to 175 k-in to
S2C2A	2.43	2.0	na	10/20/30	0.00	no	lo	1.23	increase crack width
S2C3A	2.49	1.0	na	13/20/30	0.00	no	lo	0.67	
S2C4A	2.51	0.0	na	13/20/30	0.00	no	lo	1.46	
S2C1B	2.39	1.4	na	3/13/na	0.00	no	lo	2.65	
S2C2B	2.47	2.0	na	9/13/na	0.00	no	lo	3.01	
S2C3B	2.43	3.0	na	7/16/na	0.00	no	lo	3.21	
S2C4B	2.46	1.0	na	5/16/na	0.00	no	lo	4.14	
S2C5B	2.43	1.0	na	10/13/na	0.00	no	lo	3.30	
S2C6B	2.38	0.0	na	5/9/na	0.00	no	lo	2.21	
S2C7B	2.37	0.0	na	10/10/na	0.00	no	lo	2.60	

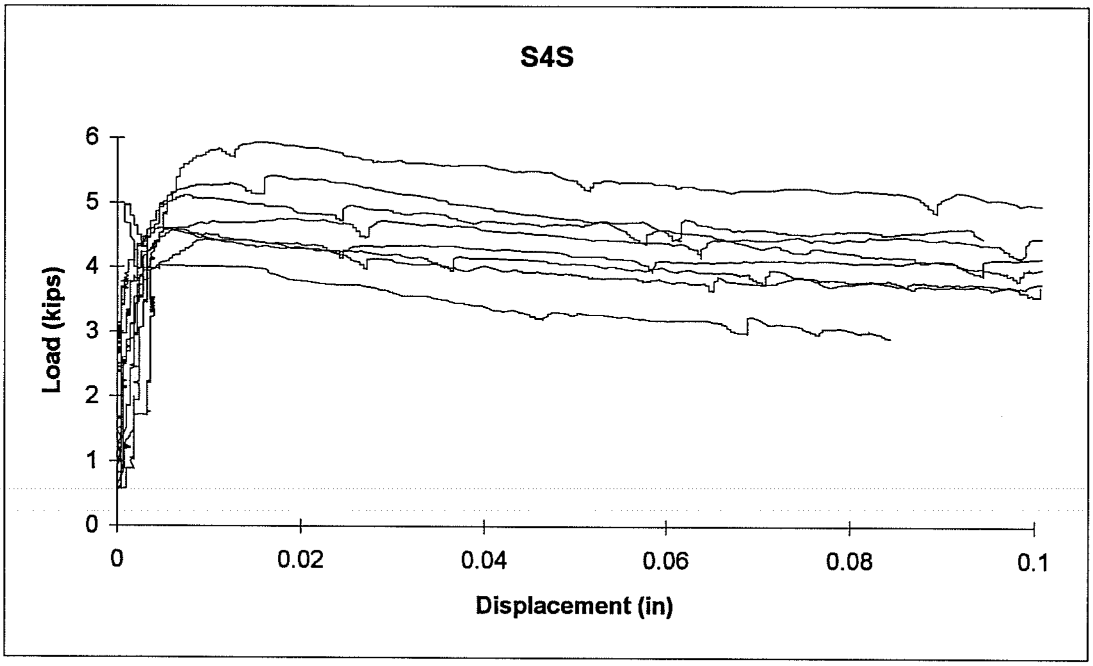
Pull-Out Tests

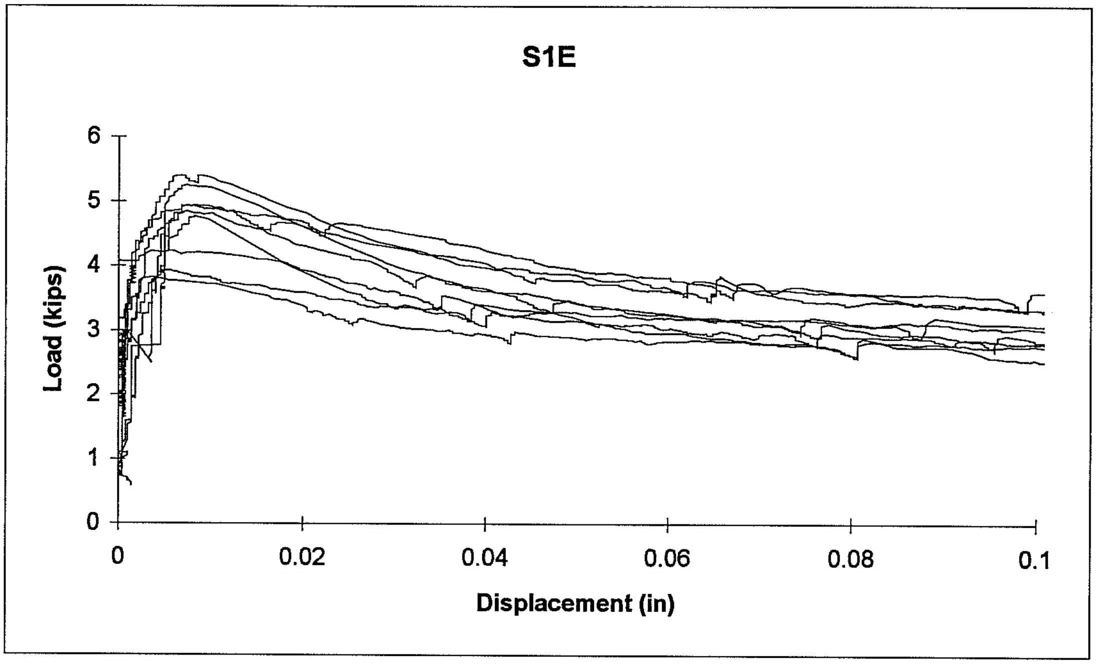
Nail #	Depth	Angle	Edge Dist.	Crack Wth.	Surf. Crk.	Fail. Cone	Sintering	Pull-Out	Comments
	inches	degree	inches	1/1000th in.	inches	no/med/fl	lo/med/hi	kips	
S2C8B	2.47	2.0	na	10/13/na	0.00	no	lo	3.49	
S2C1C	2.37	1.0	na	13/13/20	0.00	no	lo	1.81	slab re-loaded to 115 k-in
S2C2C	2.48	1.4	na	16/16/20	0.00	no	lo	1.36	
S2C3C	2.37	1.0	na	13/20/20	0.00	no	lo	2.26	
S2C4C	2.43	1.0	na	13/16/20	0.00	no	lo	2.04	
S2C1D1	2.39	2.2	na	13/13/na	1.50	no	lo	2.78	
S2C2D1	2.42	1.0	na	20/13/na	4.00	no	lo	2.90	
S2C3D1	2.43	2.0	na	20/9/na	4.50	no	lo	2.37	
S2C1D2	2.39	2.2	na	16/16/na	5.00	no	lo	3.43	
S2C2D2	2.42	2.2	na	13/7/na	4.00	no	lo	2.88	
S2C3D2	2.37	1.4	na	13/10/na	2.50	no	lo	2.60	
S2C1D3	2.42	3.2	na	13/13/na	2.50	no	lo	3.71	
S2C2D3	2.39	2.2	na	13/13/na	6.00	no	lo	3.78	
S2C3D3	2.42	1.0	na	16/13/na	1.00	no	lo	3.52	
S2C1F	2.33	1.0	na	na/2/2	0.00	no	lo	3.09	slab loaded to 195 k-in after
S2C2F	2.38	1.0	na	na/2/3	0.00	no	lo	2.61	crack developed between nails
S2C3F	2.36	3.2	na	na/2/7	0.00	no	lo	1.32	
S2C4F	2.33	1.0	na	na/2/5	0.00	no	lo	1.48	
S2C1G	2.34	2.0	na	na/2/3/3	0.00	no	lo	3.30	slab loaded to 195 k-in after
S2C2G	2.35	2.2	na	na/2/3/3	0.00	no	lo	2.88	crack developed between nails,
S2C3G	2.36	3.0	na	na/2/7/5	0.00	no	lo	2.24	then unloaded
S2C4G	2.33	1.4	na	na/2/7/5	0.00	no	lo	2.22	

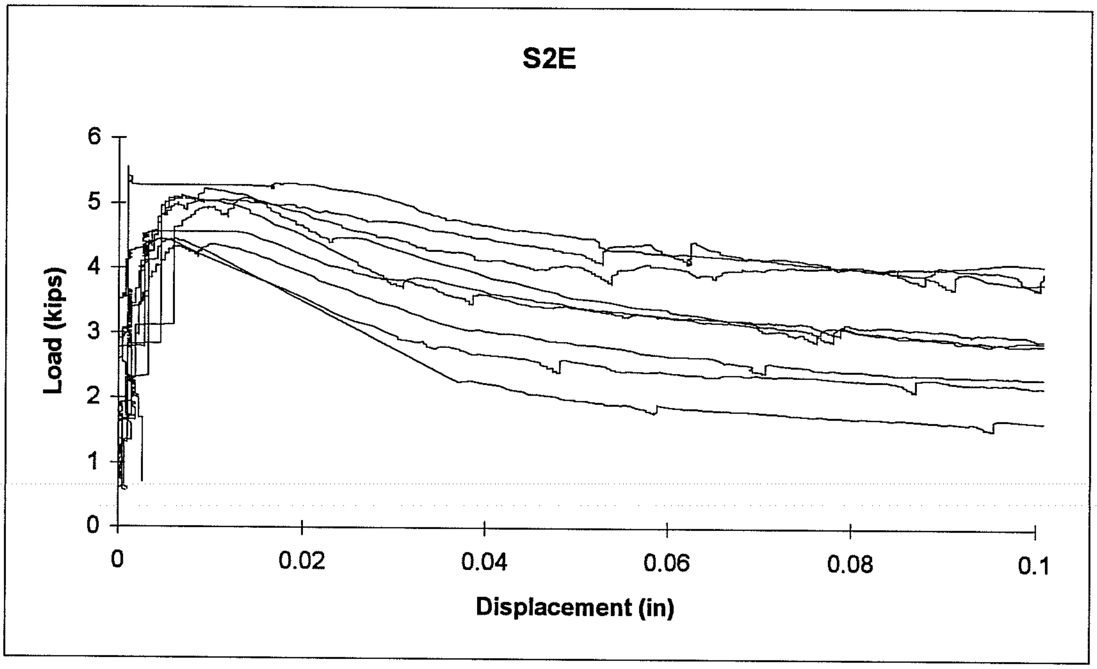

S1S
Load (kips)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

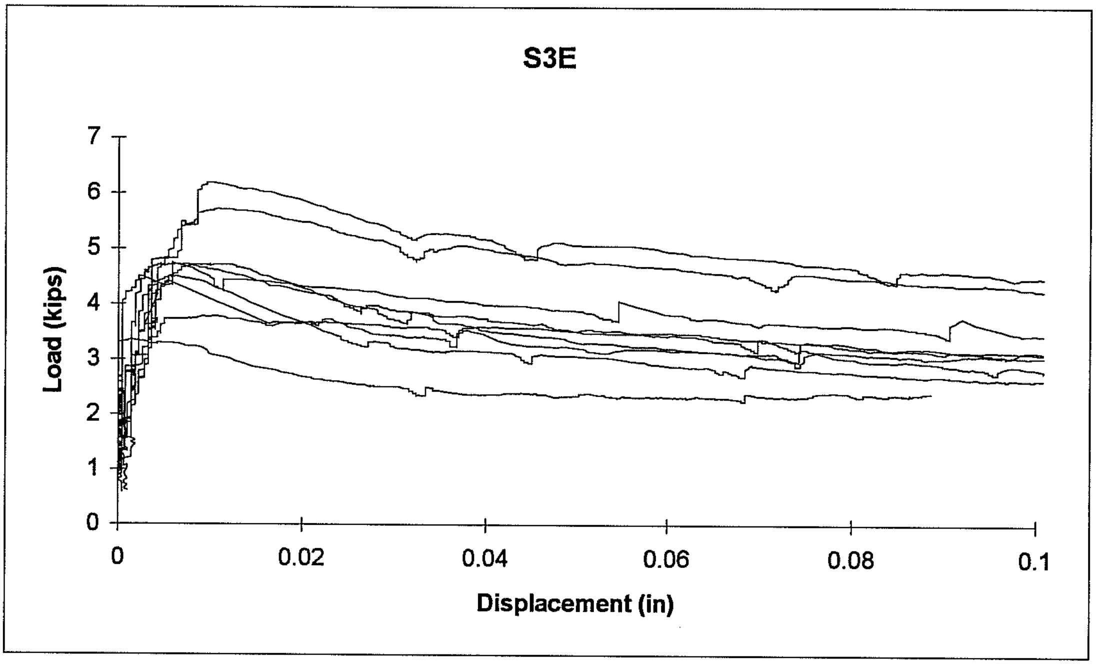

S2S
Load (kips)
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

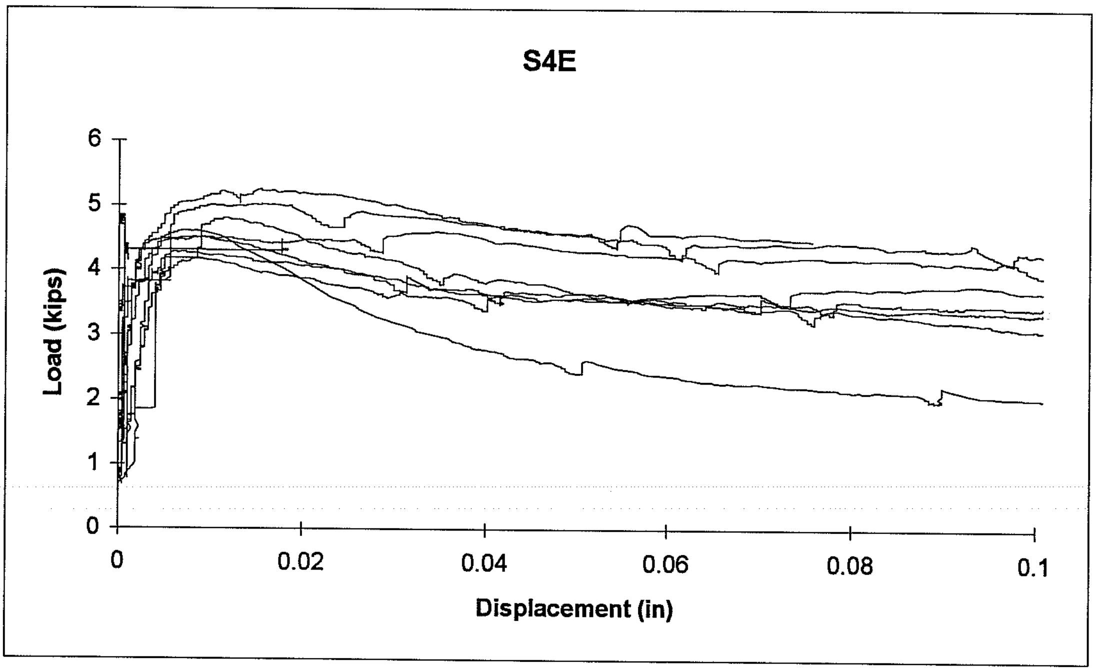

S3S
Load (kips)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

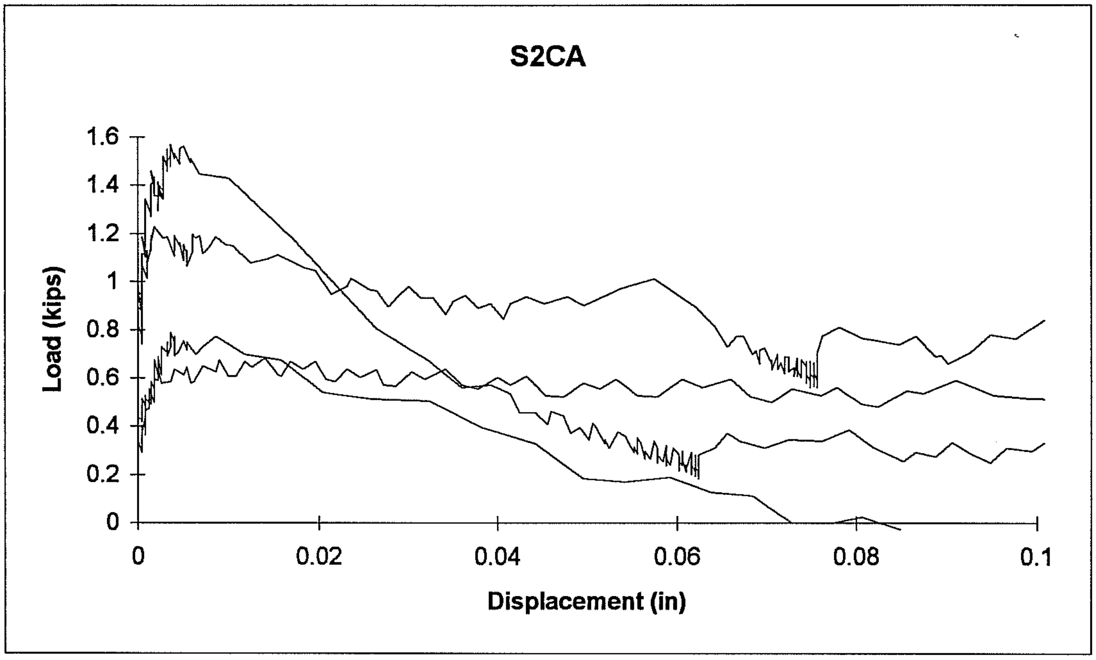

S4S
Load (kips)
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

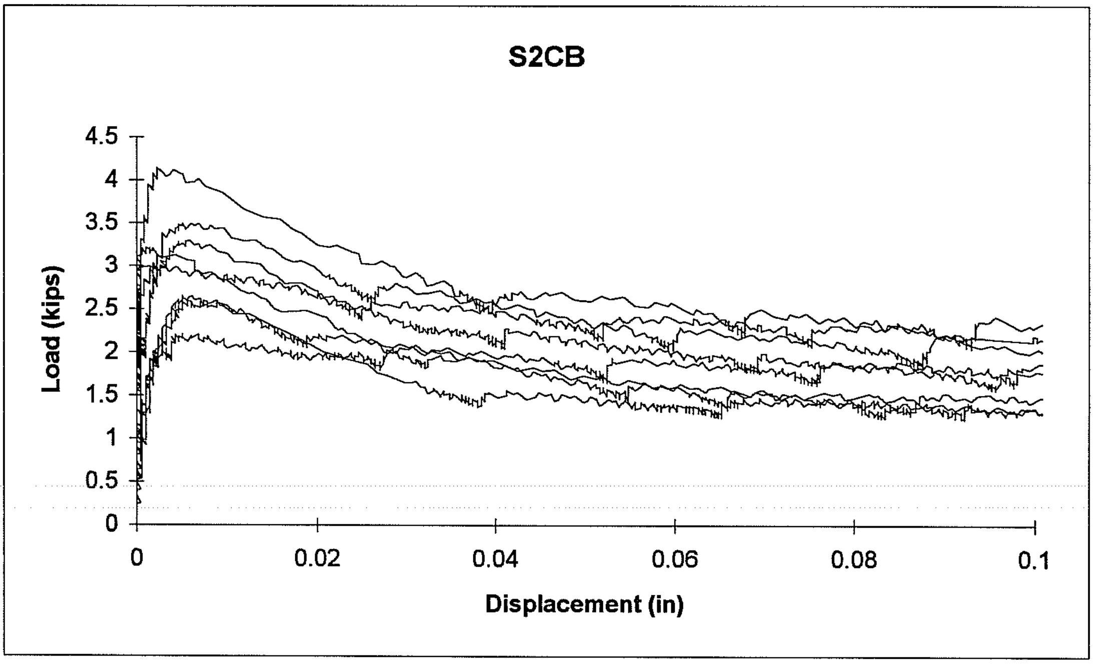

S1E
Load (kips)
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

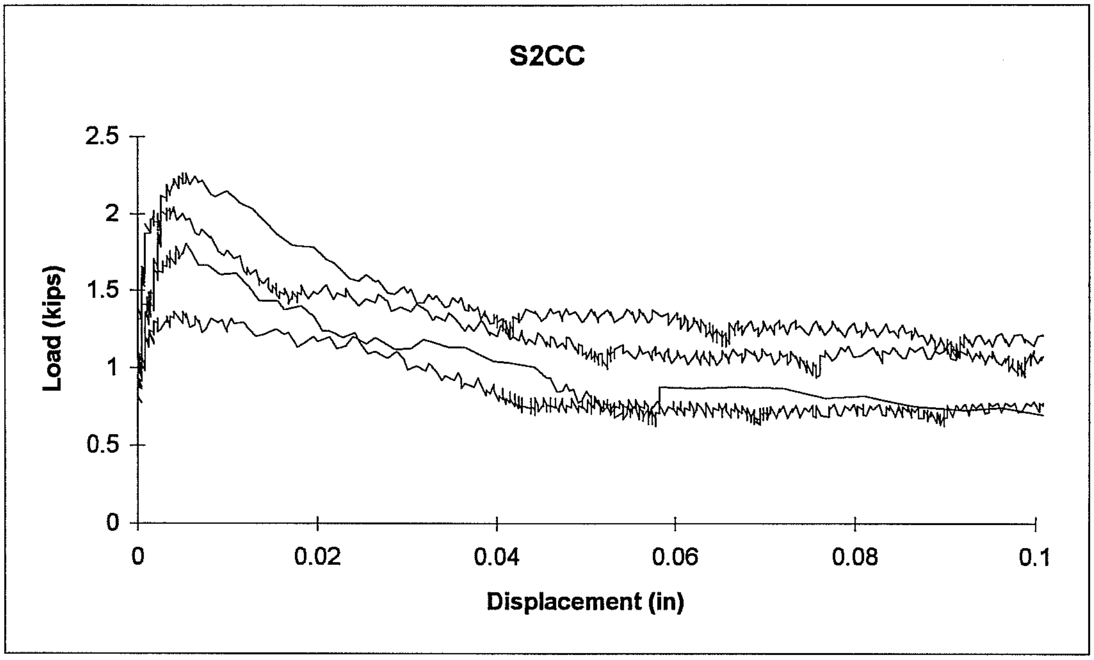

S2E
Load (kips)
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

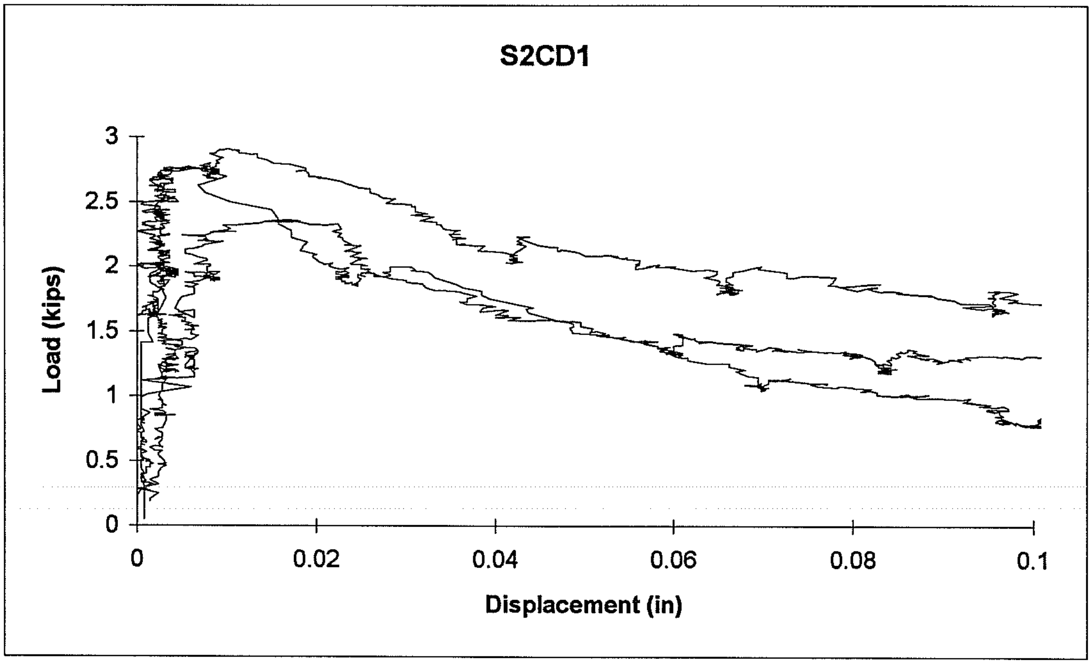

S3E
Load (kips)
Displacement (in)
0
1
2
3
4
5
6
7
0
0.02
0.04
0.06
0.08
0.1

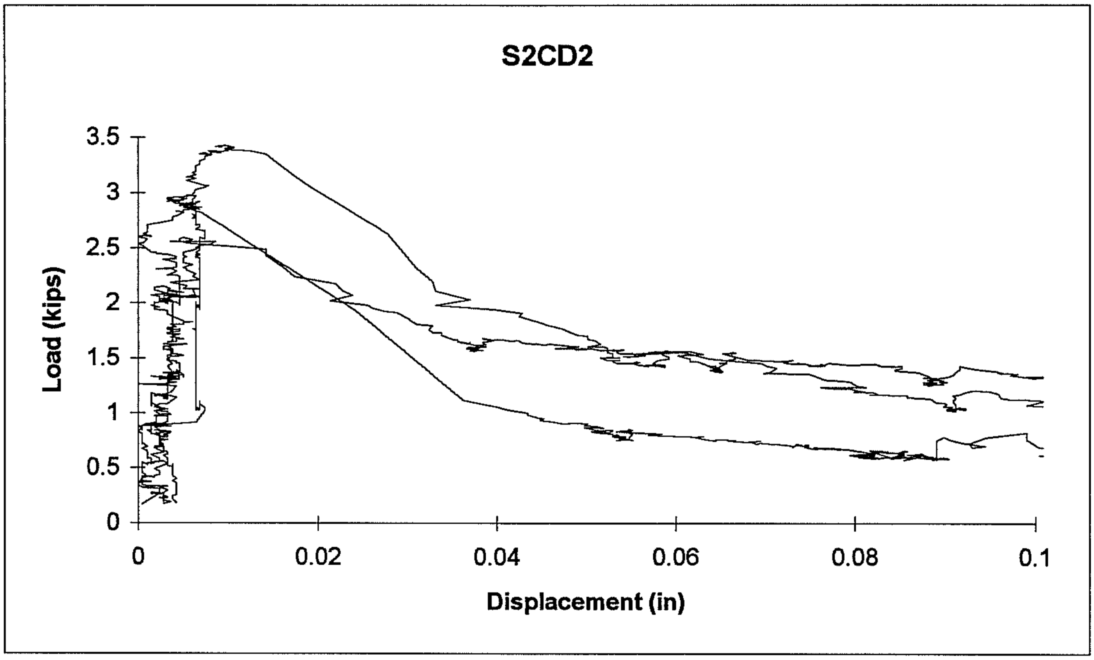

S4E
Load (kips)
Displacement (in)
0
1
2
3
4
5
6
0
0.02
0.04
0.06
0.08
0.1

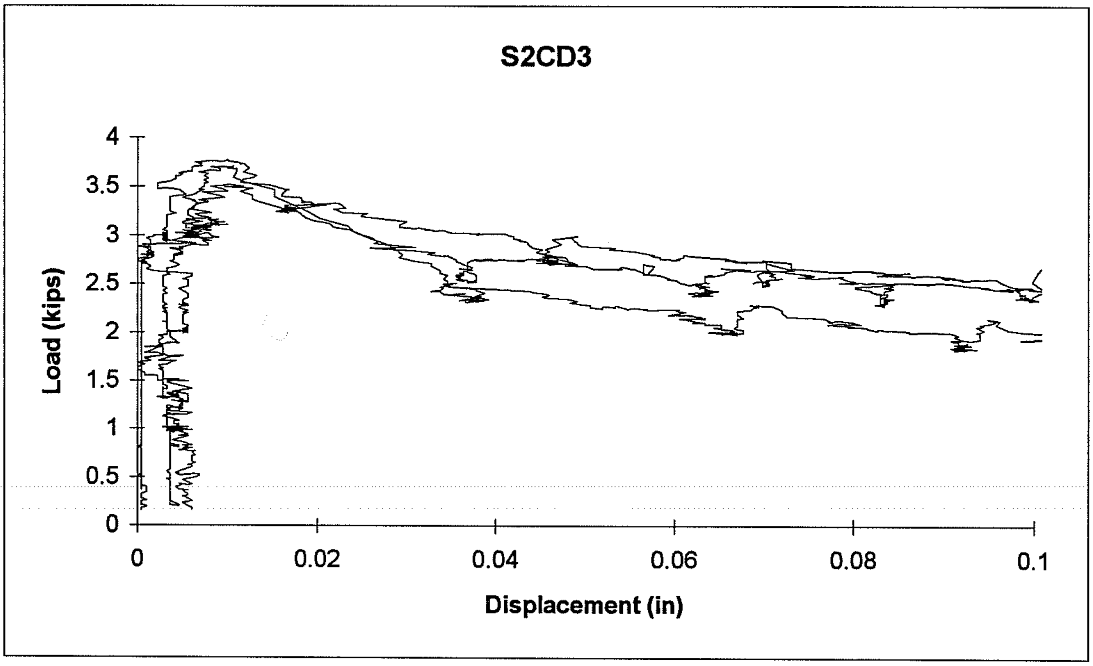

S2CA
Load (kips)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

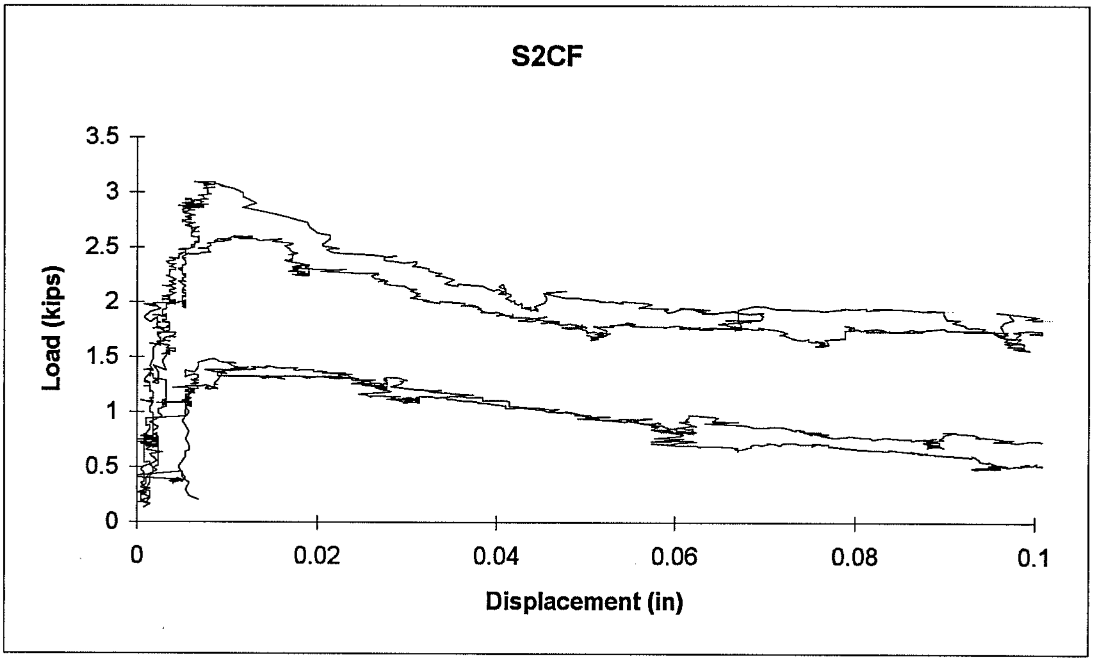

S2CB
Load (kips)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

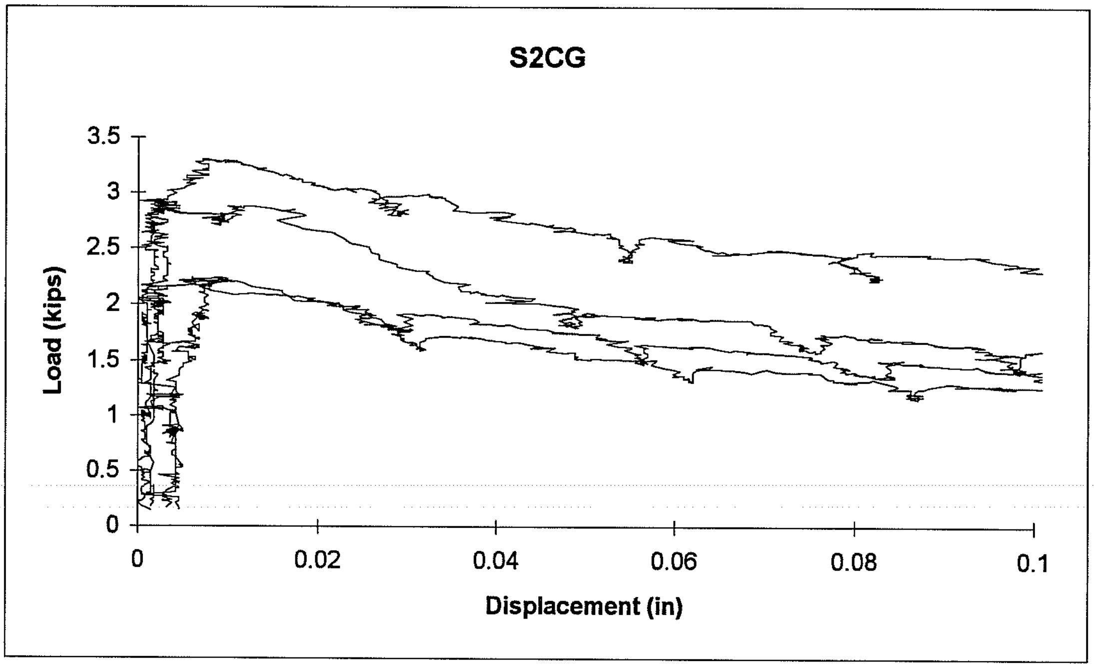

S2CC
2.5
2
1.5
1
0.5
0
Load (kips)
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


S2CD1
3
2.5
2
1.5
1
0.5
0
Load (kips)
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


S2CD2
3.5
3
2.5
2
1.5
1
0.5
0
Load (kips)
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


S2CD3
4
3.5
3
2.5
2
1.5
1
0.5
0
Load (kips)
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


S2CF
Load (kips)
3.5
3
2.5
2
1.5
1
0.5
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


S2CG
Load (kips)
3.5
3
2.5
2
1.5
1
0.5
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

Slab Number:	3A	Aggregate Type:	Hard Limestone
Date of Cast:	Dec. 11, 1992	Date of Test:	March, 1993

Concrete Strength					
7 Day	3140	3100	3030	Average:	3090
28 Day	3810	3950	3840	Average:	3870
Test Day	4160	4030	4080	Average:	4090

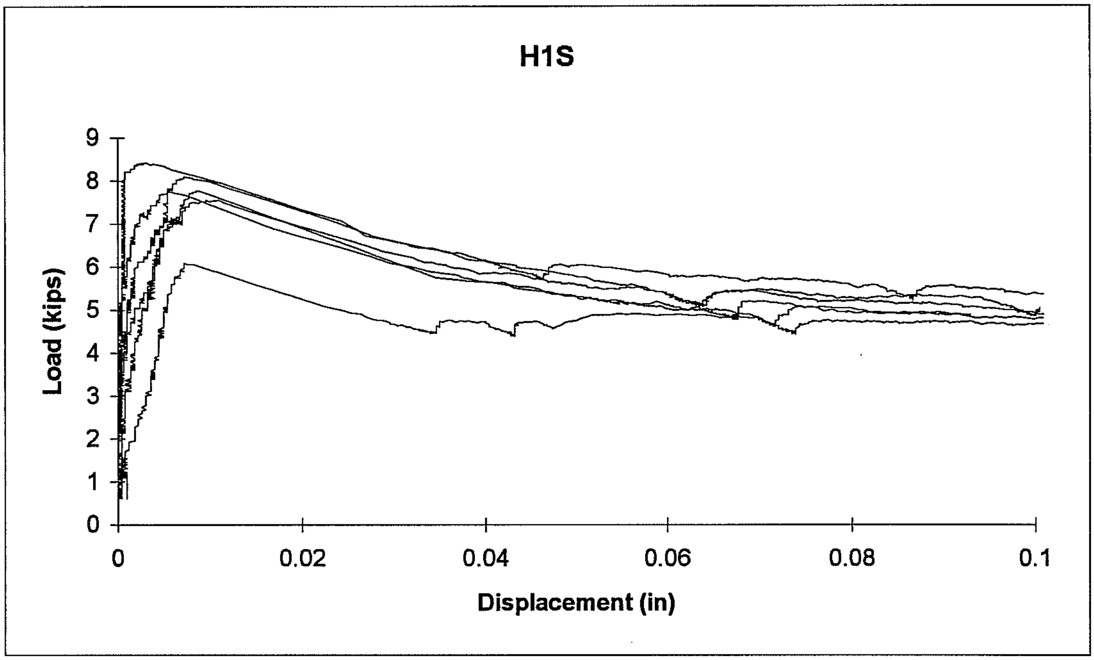
Pull-Out Tests

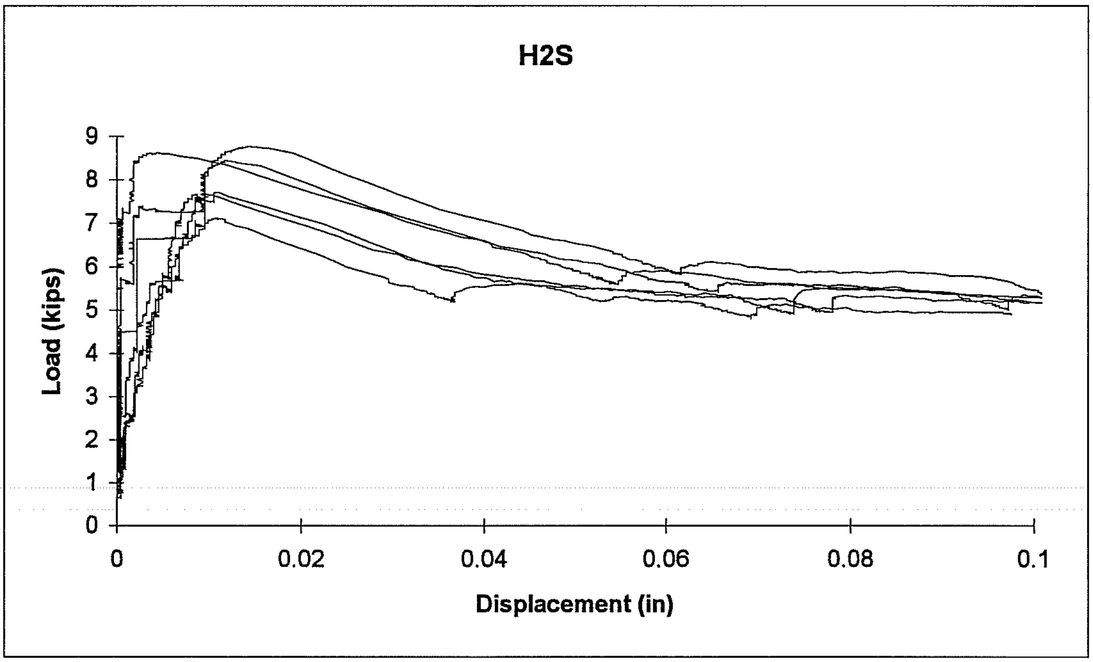
Nail #	Depth	Angle	Edge Dist.	Crack Wth.	Surf. Crk.	Fail. Cone	Sintering	Pull-Out	Comments
	inches	degree	inches	1/1000th in.	inches	no/med/fl	lo/med/hi	kips	
H1S1	2.43	1.0	na	na	1.00	no	med	6.09	several loading & unloading cycles
H1S2	2.40	3.2	na	na	0.00	no	med	8.42	
H1S3	2.41	2.0	na	na	0.00	no	lo	7.78	
H1S4	2.38	0.0	na	na	0.00	no	med	8.09	
H1S5	2.38	0.0	na	na	1.50	no	lo	7.55	
H1S6	2.37	0.0	na	na	1.25	no	lo	7.75	
H2S1	2.41	3.0	na	na	1.50	no	lo	8.45	
H2S2	2.40	2.2	na	na	1.00	no	lo	7.69	
H2S3	2.37	2.0	na	na	1.50	no	lo	8.62	
H2S4	2.38	0.0	na	na	0.50	no	lo	7.72	
H2S5	2.38	0.0	na	na	1.00	no	lo	8.78	
H2S6	2.40	1.0	na	na	0.50	no	lo	7.11	
H3S1	2.30	1.0	na	na	2.00	no	lo	9.29	
H3S2	2.31	2.0	na	na	1.00	no	lo	9.10	
H3S3	2.32	1.0	na	na	2.00	fl	hi	8.81	
H3S4	2.31	0.0	na	na	1.00	no	lo	8.63	
H3S5	2.30	0.0	na	na	1.50	no	lo	7.77	
H3S6	2.32	0.0	na	na	1.75	no	lo	7.27	
H4S1	2.34	0.0	na	na	2.50	no	lo	9.36	
H4S2	2.41	1.0	na	na	3.00	no	lo	8.30	tip of nail flattened slightly

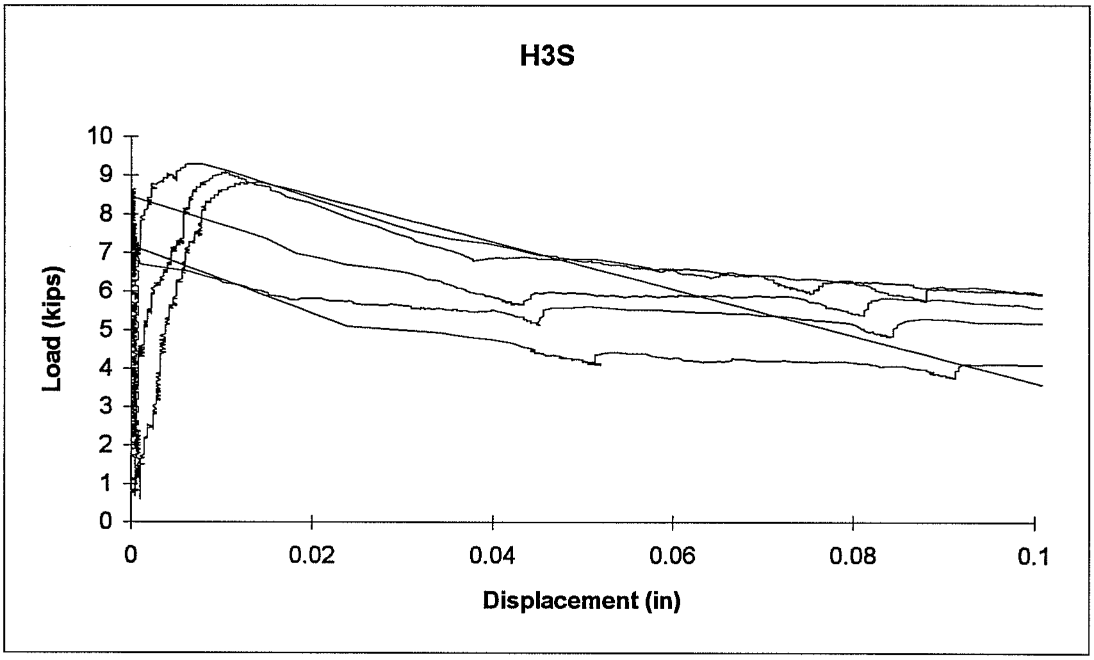
Pull-Out Tests

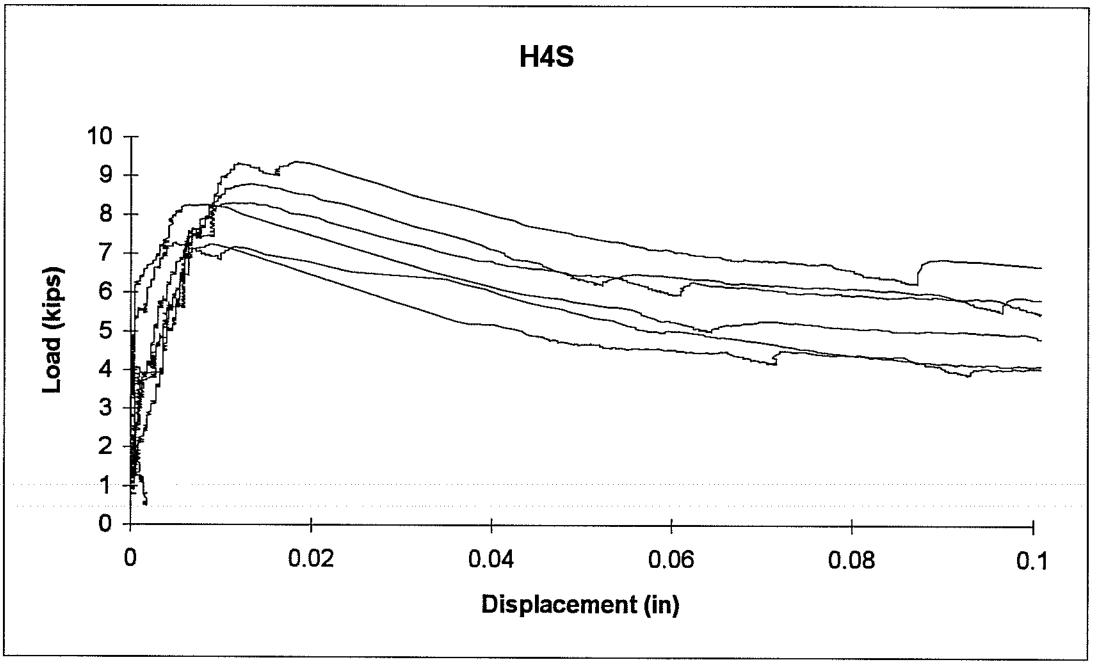
Nail #	Depth	Angle	Edge Dist.	Crack Wth.	Surf. Crk.	Fail. Cone	Sintering	Pull-Out	Comments
	inches	degree	inches	1/1000th in.	inches	no/med/fl	lo/med/hi	kips	
H4S3	2.42	2.0	na	na	1.00	no	lo	8.78	
H4S4	2.33	1.0	na	na	0.00	no	lo	7.16	
H4S5	2.44	2.2	na	na	0.00	no	lo	8.25	
H4S6	2.41	1.4	na	na	0.50	no	lo	7.23	nail bent
H1E1	2.32	0.0	4.0	na	9.00	no	lo	5.87	crack on side of slab
H1E2	2.38	0.0	5.0	na	8.00	no	lo	7.48	
H1E3	2.35	1.4	6.0	na	4.00	no	lo	7.83	
H1E4	2.39	2.2	4.0	na	4.00	no	lo	6.85	nail bent
H1E5	2.37	0.0	5.0	na	13.00	no	lo	7.67	crack on side of slab
H1E6	2.36	1.0	6.0	na	3.00	no	lo	7.83	
H2E1	2.33	0.0	4.0	na	10.00	no	lo	6.44	crack on side of slab
H2E2	2.36	2.8	5.0	na	5.00	no	lo	8.25	
H2E3	2.35	2.8	6.0	na	1.00	no	lo	6.43	
H2E4	2.36	0.0	4.0	na	3.50	no	lo	7.39	
H2E5	2.36	3.2	5.0	na	5.00	no	lo	7.58	
H2E6	2.39	1.0	6.0	na	0.00	no	lo	6.26	tip of nail flattened slightly
H3E1	2.42	2.0	4.0	na	7.00	no	lo	6.14	crack on side of slab
H3E2	2.38	1.0	5.0	na	3.00	no	lo	7.60	
H3E3	2.36	1.4	6.0	na	2.50	no	lo	6.78	
H3E4	2.36	1.0	4.0	na	2.00	no	lo	6.74	
H3E5	2.38	3.2	5.0	na	7.00	no	lo	7.46	crack on side of slab
H3E6	2.39	3.0	6.0	na	1.50	no	lo	7.13	
H4E1	2.40	1.4	4.0	na	5.00	no	lo	4.57	crack on side of slab
H4E2	2.37	2.2	5.0	na	10.00	no	lo	5.89	
H4E3	2.33	0.0	6.0	na	16.00	no	lo	5.71	
H4E4	2.38	1.0	4.0	na	11.00	no	lo	6.29	crack on side of slab
H4E5	2.42	4.0	5.0	na	16.00	no	lo	6.41	crack on side of slab
H4E6	2.40	3.0	6.0	na	3.00	no	lo	6.79	nail bent slightly

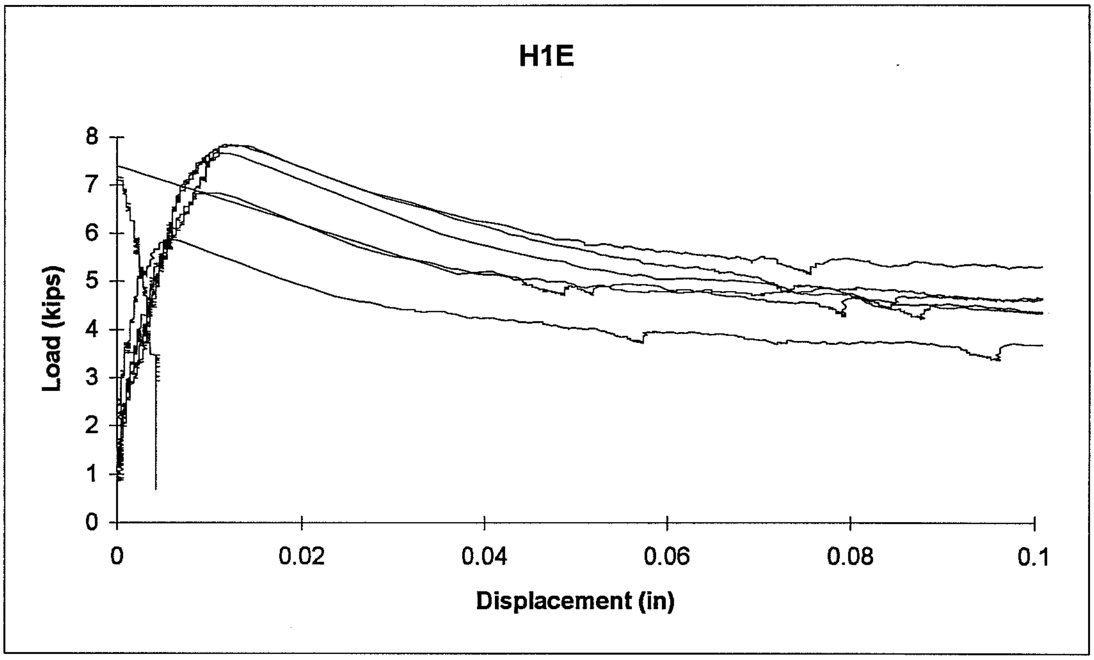
Pull-Out Tests									
Nail #	Depth	Angle	Edge Dist.	Crack Wth.	Surf. Crk.	Fail. Cone	Sintering	Pull-Out	Comments
	inches	degree	inches	1/1000th in.	inches	no/med/fl	lo/med/hi	kips	
H2C1B	2.46	2.2	na	30/30/na	0.00	no	lo	2.63	
H2C2B	2.51	2.0	na	25/30/na	0.00	no	lo	3.47	
H2C3B	2.45	1.4	na	7/20/na	0.00	no	lo	1.88	
H2C4B	2.50	1.4	na	30/40/na	0.00	no	lo	3.47	
H2C5B	2.52	2.2	na	25/40/na	0.00	no	lo	4.13	
H2C6B	2.40	1.0	na	13/16/na	0.00	no	lo	2.40	
H2C7B	2.41	2.2	na	16/30/na	0.00	no	lo	2.96	
H2C8B	2.36	3.0	na	20/30/na	0.00	no	lo	3.91	
H2C9B	2.41	1.0	na	16/25/na	0.00	no	lo	4.50	
H2C10B	2.39	1.0	na	20/30/na	0.00	no	lo	5.65	
H2C1D1	2.40	1.4	na	30/3/na	4.50	no	lo	2.80	
H2C2D1	2.37	3.0	na	30/13/na	3.50	no	lo	2.16	
H2C3D1	2.41	1.0	na	40/10/na	4.50	no	lo	2.69	
H2C1D2	2.40	0.0	na	40/7/na	8.50	no	lo	2.30	
H2C2D2	2.37	1.0	na	30/5/na	7.50	no	lo	4.41	
H2C3D2	2.44	2.2	na	40/7/na	5.50	no	lo	2.40	
H2C1D3	2.44	2.8	na	40/2/na	2.00	no	lo	6.52	
H2C2D3	2.47	1.4	na	30/3/na	5.00	no	lo	3.61	
H2C3D3	2.46	1.4	na	30/3/na	8.00	no	lo	4.54	
H2C1F	2.35	4.0	na	na/2/10	0.00	no	lo	2.06	slab loaded to 315 k-in after
H2C2F	2.46	3.0	na	na/2/7	0.00	no	lo	1.37	crack developed between nails
H2C3F	2.48	3.2	na	na/2/7	0.00	no	lo	2.01	
H2C4F	2.40	2.2	na	na/2/5	0.00	no	lo	4.46	
H2C5F	2.41	1.4	na	na/2/5	0.00	no	lo	3.70	
H2C6F	2.39	1.0	na	na/2/3	0.00	no	lo	3.89	
H2C1G	2.46	5.0	na	na/2/7/3	0.00	no	lo	3.08	slab unloaded
H2C2G	2.47	3.0	na	na/2/10/5	0.00	no	lo	4.81	
H2C3G	2.35	1.4	na	na/2/5/5	0.00	no	lo	4.47	
H2C4G	2.41	0.0	na	na/2/5/5	0.00	no	lo	5.51	

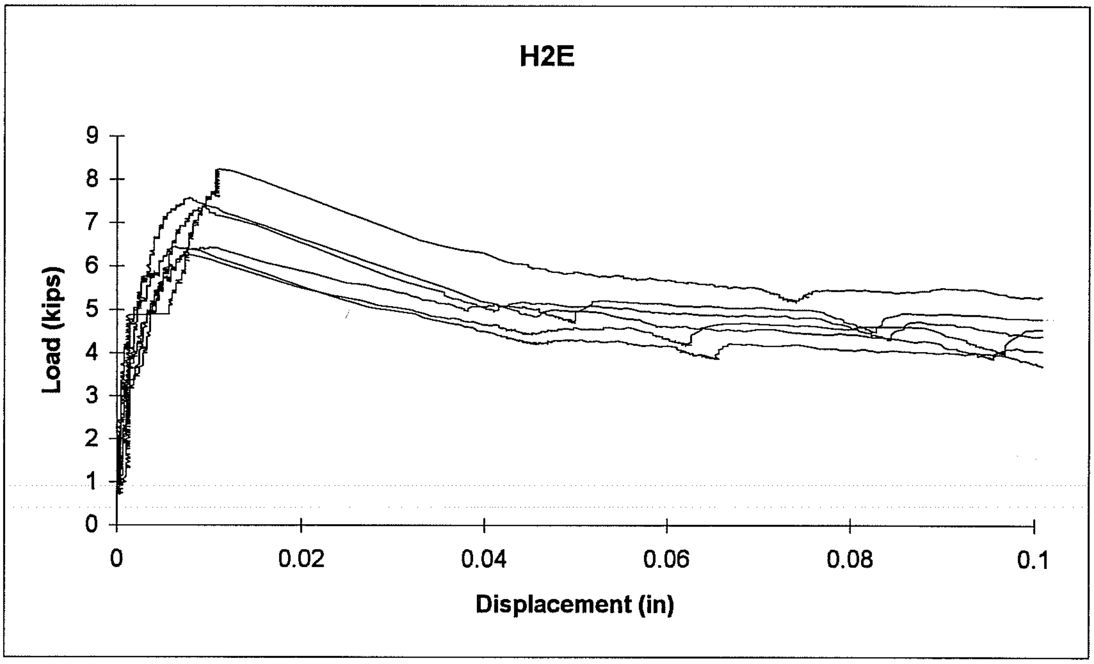

H1S
Load (kips)
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

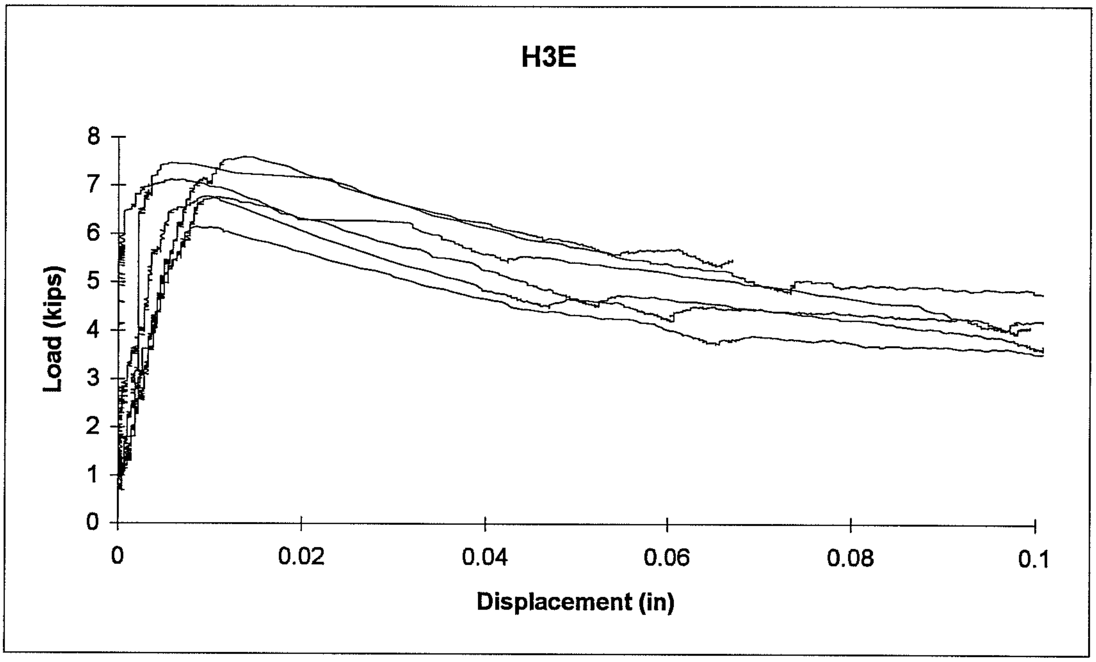

H2S
Load (kips)
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

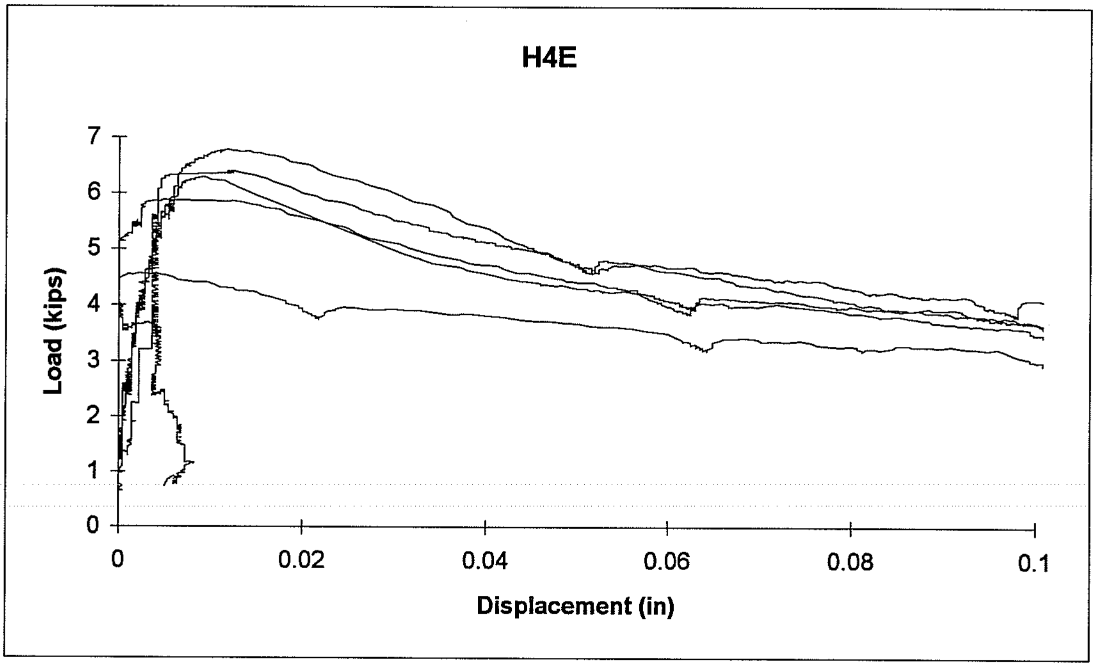

H3S
10
9
8
7
6
5
4
3
2
1
0
Load (kips)
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

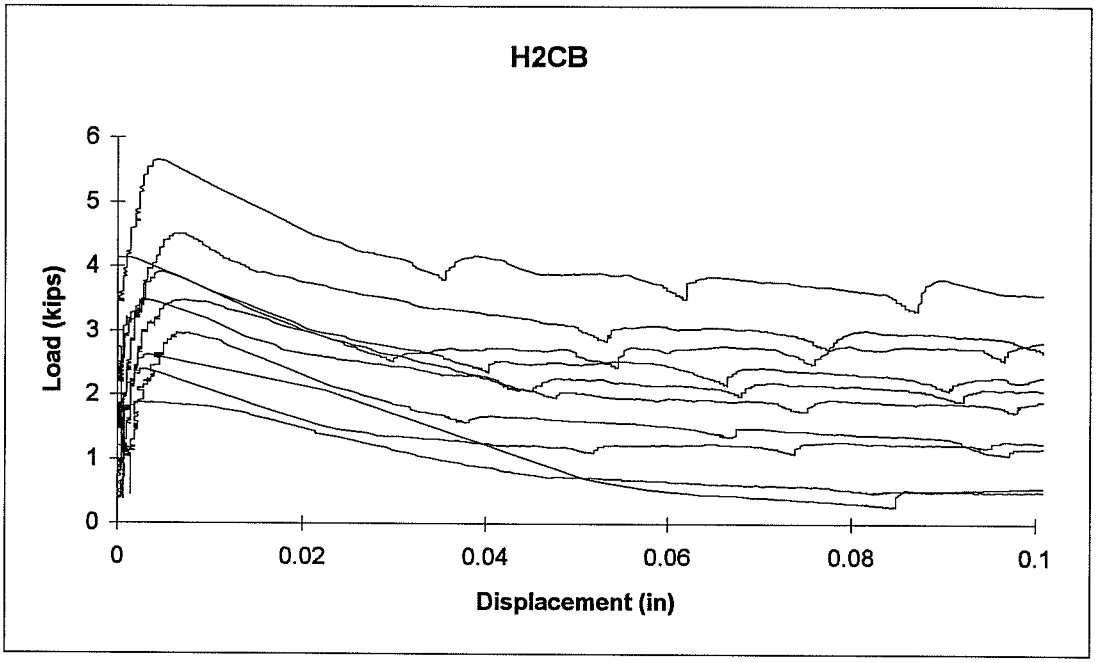

H4S
10
9
8
7
6
5
4
3
2
1
0
Load (kips)
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


H1E
Load (kips)
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

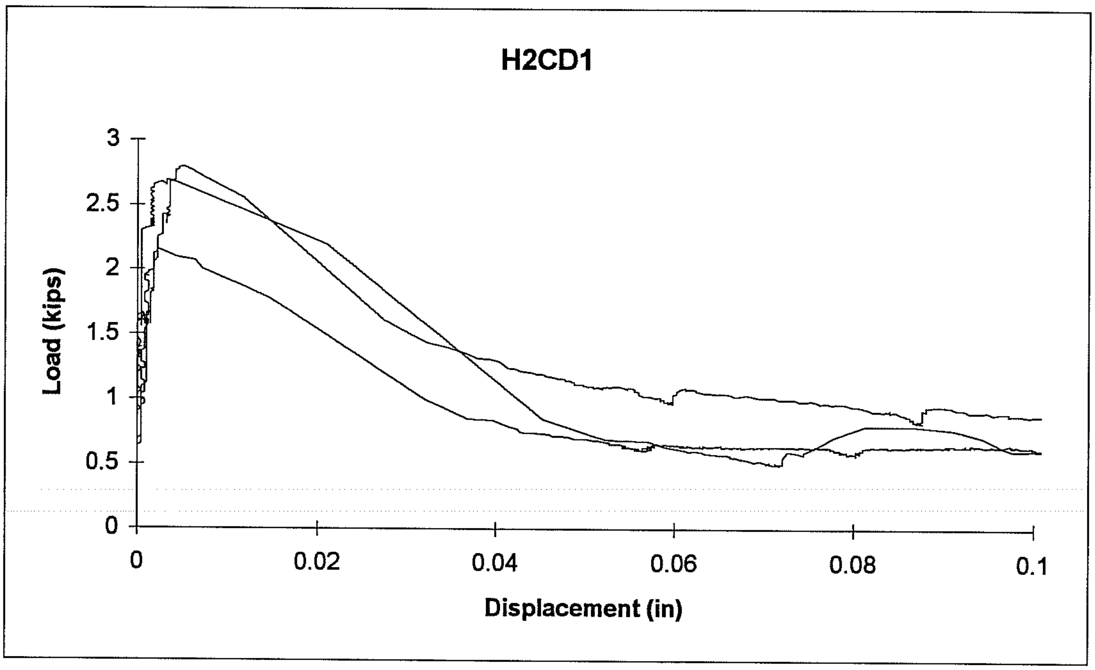

H2E
Load (kips)
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


H3E
Load (kips)
Displacement (in)
0
1
2
3
4
5
6
7
8
0.02
0.04
0.06
0.08
0.1

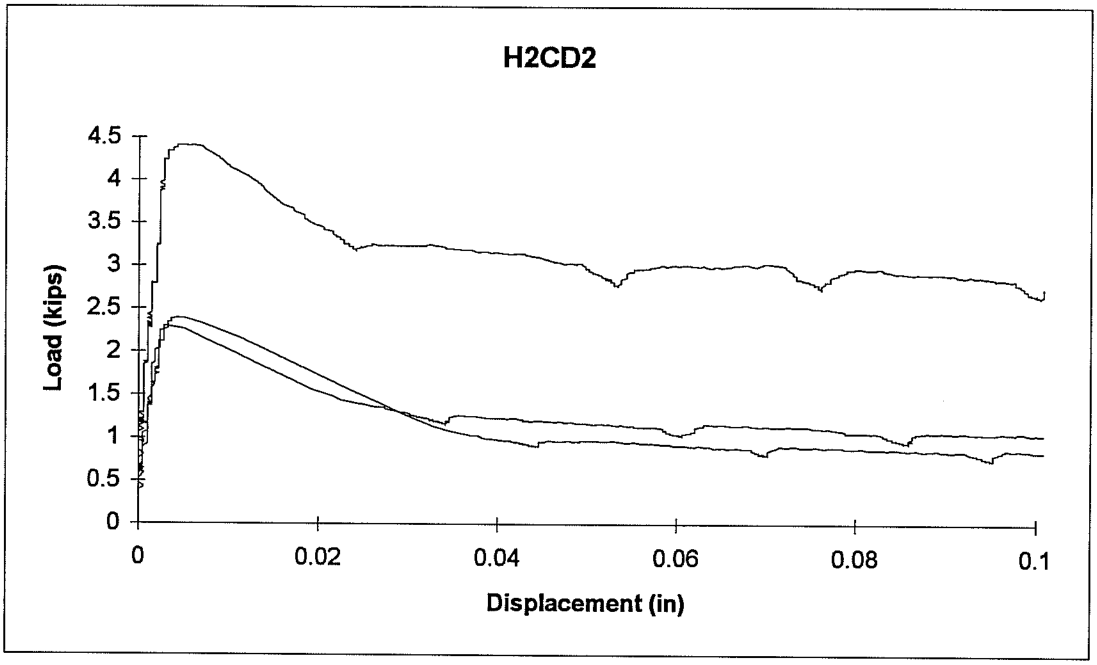

H4E
Load (kips)
Displacement (in)
0
1
2
3
4
5
6
7
0.02
0.04
0.06
0.08
0.1

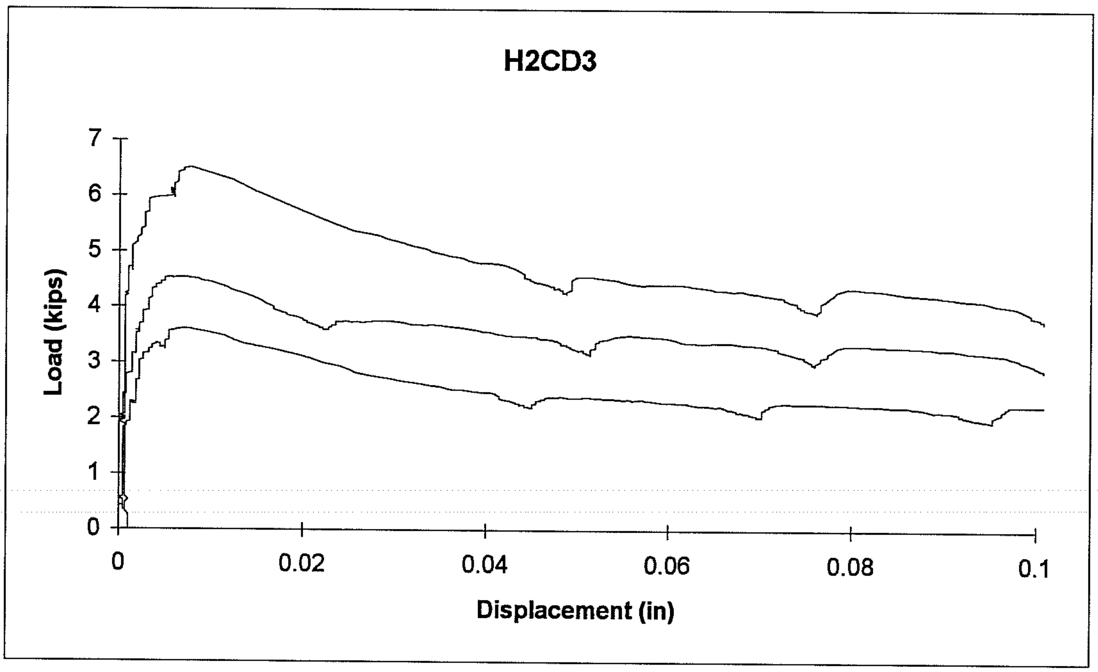


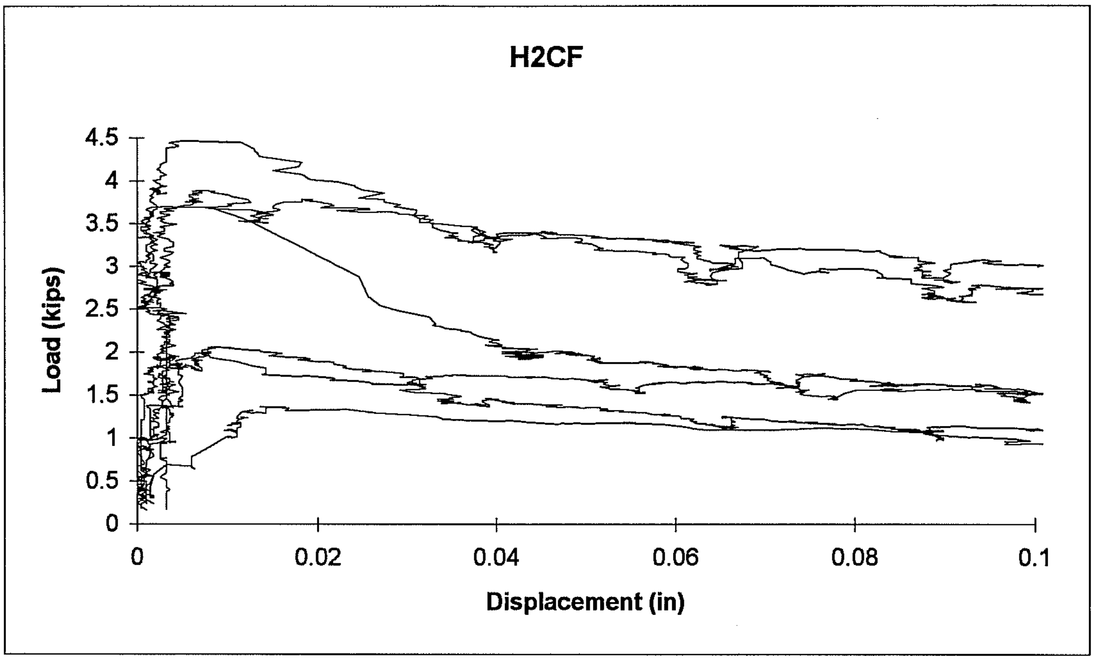
H2CB
Load (kips)
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

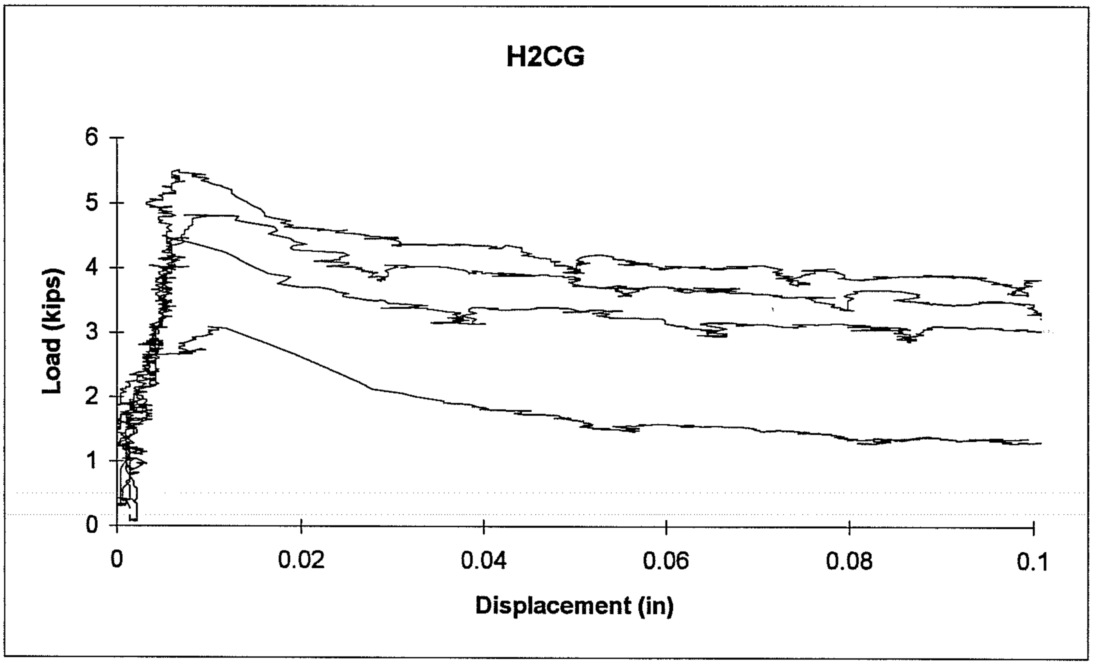


H2CD1
Load (kips)
3
2.5
2
1.5
1
0.5
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


H2CD2
Load (kips)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


H2CD3
Load (kips)
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


H2CF
Load (kips)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


H2CG
Load (kips)
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

Slab Number:	4A	Aggregate Type:	Soft Limestone
Date of Cast:	Jan. 15, 1993	Date of Test:	April, 1993

Concrete Strength					
7 Day	5620	5580	5480	Average:	5560
28 Day	6830	6850	6860	Average:	6850
Test Day	7520	7370	7440	Average:	7440

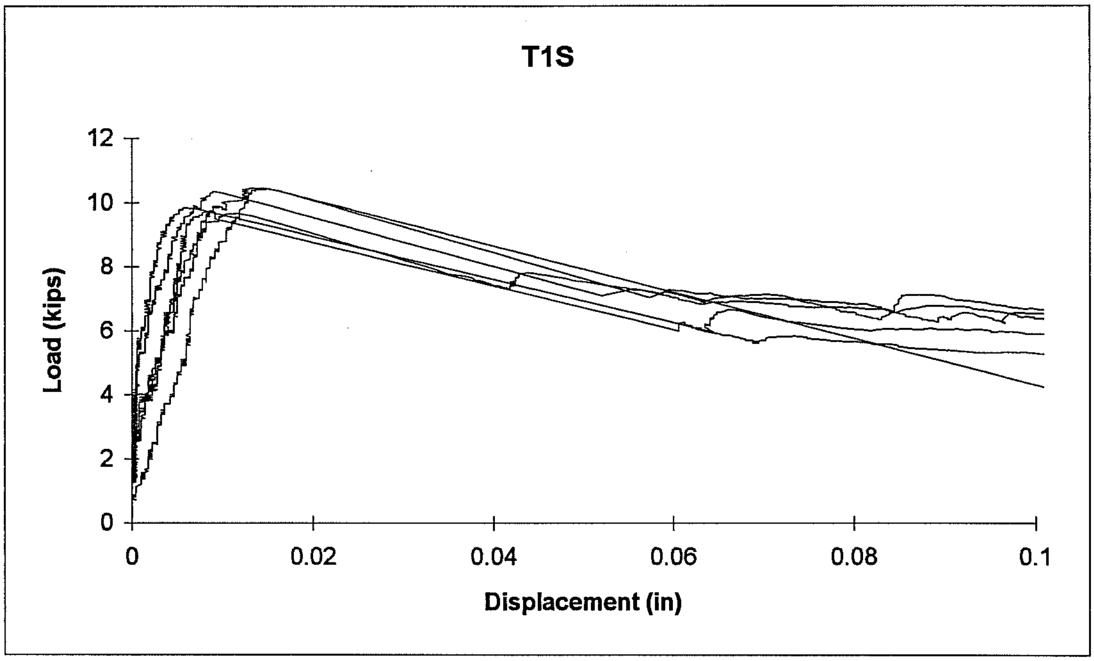
Pull-Out Tests									
Nail #	Depth	Angle	Edge Dist.	Crack Wth.	Surf. Crk.	Fail. Cone	Sintering	Pull-Out	Comments
	inches	degree	inches	1/1000th in.	inches	no/med/fl	lo/med/hi	kips	
T1S1	2.41	2.2	na	na	8.00	no	med	10.42	
T1S2	2.36	1.0	na	na	10.00	no	lo	9.67	
T1S3	2.35	2.0	na	na	3.00	no	lo	10.34	
T1S4	2.34	1.0	na	na	4.50	med	med	10.46	
T1S5	2.31	0.0	na	na	7.00	no	lo	9.83	
T1S6	2.33	1.4	na	na	3.00	no	lo	9.75	
T2S1	2.36	2.2	na	na	3.00	no	med	9.47	nail bent slightly
T2S2	2.41	2.2	na	na	14.00	no	lo	9.56	
T2S3	2.38	1.4	na	na	10.00	no	lo	10.82	
T2S4	2.35	0.0	na	na	6.00	no	med	8.42	
T2S5	2.34	0.0	na	na	2.00	no	med	7.85	
T2S6	2.43	3.6	na	na	7.00	no	lo	9.12	
T3S1	2.31	1.4	na	na	4.00	no	lo	9.89	
T3S2	2.39	2.0	na	na	5.00	no	med	10.60	
T3S3	2.32	0.0	na	na	10.00	no	lo	9.99	
T3S4	2.42	1.4	na	na	9.00	no	lo	10.17	
T3S5	2.30	1.0	na	na	10.00	no	lo	7.45	void detected in hole
T3S6	2.36	2.2	na	na	8.00	no	lo	9.20	
T4S1	2.37	1.4	na	na	7.00	no	lo	10.26	
T4S2	2.37	0.0	na	na	9.00	no	lo	9.34	

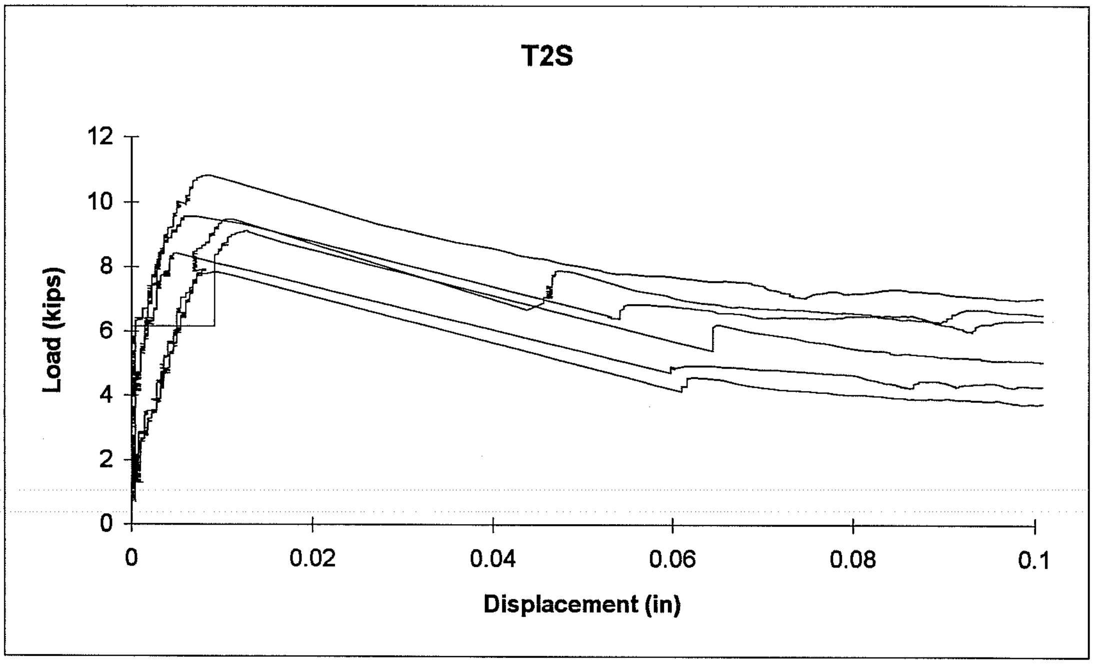
Pull-Out Tests									
Nail #	Depth	Angle	Edge Dist.	Crack Wth.	Surf. Crk.	Fail. Cone	Sintering	Pull-Out	Comments
	inches	degree	inches	1/1000th in.	inches	no/med/fl	lo/med/hi	kips	
T4S3	2.37	2.2	na	na	7.00	no	lo	10.35	nail bent slightly
T4S4	2.40	2.0	na	na	12.00	no	lo	10.08	
T4S5	2.34	0.0	na	na	9.00	no	lo	10.84	
T4S6	2.40	2.0	na	na	8.00	no	lo	11.33	
T1E1	2.32	1.0	4.0	na	4.00	no	lo	4.06	cracks to side of slab
T1E2	2.36	2.2	5.0	na	10.00	no	lo	8.46	
T1E3	2.38	1.0	6.0	na	12.00	no	lo	8.23	
T1E4	2.40	2.0	4.0	na	20.00	no	med	8.70	cracks to side of slab
T1E5	2.37	2.2	5.0	na	23.00	no	lo	6.22	cracks to side of slab
T1E6	2.37	0.0	6.0	na	13.00	no	lo	8.89	
T2E1	2.37	1.0	4.0	na	8.00	no	lo	2.99	cracks to side of slab
T2E2	2.44	1.4	5.0	na	16.00	no	lo	6.58	
T2E3	2.45	2.2	6.0	na	11.00	no	lo	8.16	
T2E4	2.47	5.1	4.0	na	12.00	no	lo	6.72	cracks to side of slab
T2E5	2.38	2.0	5.0	na	16.00	no	lo	4.22	cracks to side of slab
T2E6	2.46	2.2	6.0	na	3.00	no	lo	8.25	nail bent slightly
T3E1	2.32	2.0	4.0	na	15.00	no	lo	6.29	crack to side of slab
T3E2	2.40	1.4	5.0	na	20.00	no	lo	6.53	crack to side of slab
T3E3	2.35	1.0	6.0	na	15.00	no	lo	8.00	
T3E4	2.36	0.0	4.0	na	17.00	no	lo	7.57	crack to side of slab
T3E5	2.37	2.0	5.0	na	22.00	no	lo	5.83	crack to side of slab
T3E6	2.42	1.0	6.0	na	18.00	no	lo	9.15	crack to side of slab
T4E1	2.28	0.0	4.0	na	19.00	no	lo	4.41	
T4E2	2.32	2.0	5.0	na	30.00	med	med	5.52	crack to side of slab
T4E3	2.38	2.0	6.0	na	23.00	no	lo	6.36	
T4E4	2.41	1.0	4.0	na	16.00	no	lo	3.06	
T4E5	2.42	2.2	5.0	na	20.00	no	lo	3.45	crack to side of slab
T4E6	2.38	3.2	6.0	na	13.00	no	lo	8.34	

Pull-Out Tests									
Nail #	Depth	Angle	Edge Dist.	Crack Wth.	Surf. Crk.	Fail. Cone	Sintering	Pull-Out	Comments
	inches	degree	inches	1/1000th in.	inches	no/med/fl	lo/med/hi	kips	
T2C1A	2.36	2.0	na	7/16/20	0.00	no	lo	1.83	slab re-loaded to 295 k-in
T2C2A	2.37	2.0	na	9/20/25	0.00	no	lo	4.55	
T2C3A	2.37	1.0	na	7/16/20	0.00	no	lo	3.12	
T2C1B	2.41	3.2	na	13/16/na	0.00	no	lo	7.46	
T2C2B	2.30	2.2	na	13/16/na	0.00	no	med	8.92	
T2C3B	2.30	1.4	na	13/16/na	0.00	no	lo	7.44	
T2C4B	2.40	1.0	na	5/10/na	0.00	med	med	10.60	
T2C5B	2.36	0.0	na	5/13/na	0.00	no	lo	7.49	
T2C6B	2.37	2.2	na	5/13/na	0.00	no	lo	9.41	
T2C7B	2.47	3.2	na	7/13/na	0.00	no	lo	9.45	
T2C8B	2.32	1.4	na	7/20/na	0.00	no	lo	8.28	
T2C9B	2.36	2.8	na	10/16/na	0.00	no	lo	9.79	
T2C1C	2.32	0.0	na	5/13/13	0.00	no	lo	5.94	slab re-loaded to 155 k-in
T2C2C	2.34	0.0	na	7/16/16	0.00	no	lo	6.62	
T2C3C	2.40	2.0	na	5/13/13	0.00	no	lo	8.02	
T2C1D1	2.33	0.0	na	13/9/na	5.50	no	lo	2.95	
T2C2D1	2.33	2.2	na	16/9/na	4.50	no	lo	7.20	
T2C3D1	2.37	1.4	na	13/7/na	2.50	no	lo	5.45	
T2C1D2	2.35	1.4	na	10/5/na	9.50	no	lo	7.10	
T2C2D2	2.32	4.2	na	7/5/na	7.00	no	lo	6.49	nail bent slightly
T2C3D2	2.32	2.2	na	13/5/na	12.00	no	lo	7.12	
T2C1D3	2.30	2.0	na	13/7/na	9.50	no	lo	7.71	
T2C2D3	2.39	2.8	na	7/5/na	8.50	no	lo	6.45	two crack faces
T2C3D3	2.34	1.0	na	9/7/na	6.50	no	lo	7.27	
T2C1F	2.34	1.0	na	na/2/30	0.00	no	lo	0.36	slab loaded to 295 k-in after
T2C2F	2.38	1.4	na	na/2/25	0.00	no	lo	0.66	crack formed between nails
T2C3F	2.37	3.0	na	na/2/25	0.00	no	med	0.91	

Pull-Out Tests

Nail #	Depth	Angle	Edge Dist.	Crack Wth.	Surf. Crk.	Fail. Cone	Sintering	Pull-Out	Comments
	inches	degree	inches	1/1000th in.	inches	no/med/fl	lo/med/hi	kips	
T2C1G	2.38	2.0	na	na/2/25/13	0.00	no	lo	2.72	slab loaded to 295 k-in, then
T2C2G	2.41	2.0	na	na/2/25/13	0.00	no	lo	2.86	unloaded
T2C4F	2.35	1.4	na	na/2/10	0.00	no	lo	4.51	slab loaded to 255 k-in after
T2C5F	2.41	3.0	na	na/2/9	0.00	no	lo	5.14	cracks formed between nails
T2C6F	2.41	3.2	na	na/2/5	0.00	no	lo	7.88	
T2C3G	2.44	3.2	na	na/2/9/7	0.00	no	lo	7.84	slab loaded to 255 k-in, then
T2C4G	2.46	3.6	na	na/2/5/5	0.00	no	lo	6.74	unloaded


T1S
Load (kips)
12
10
8
6
4
2
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)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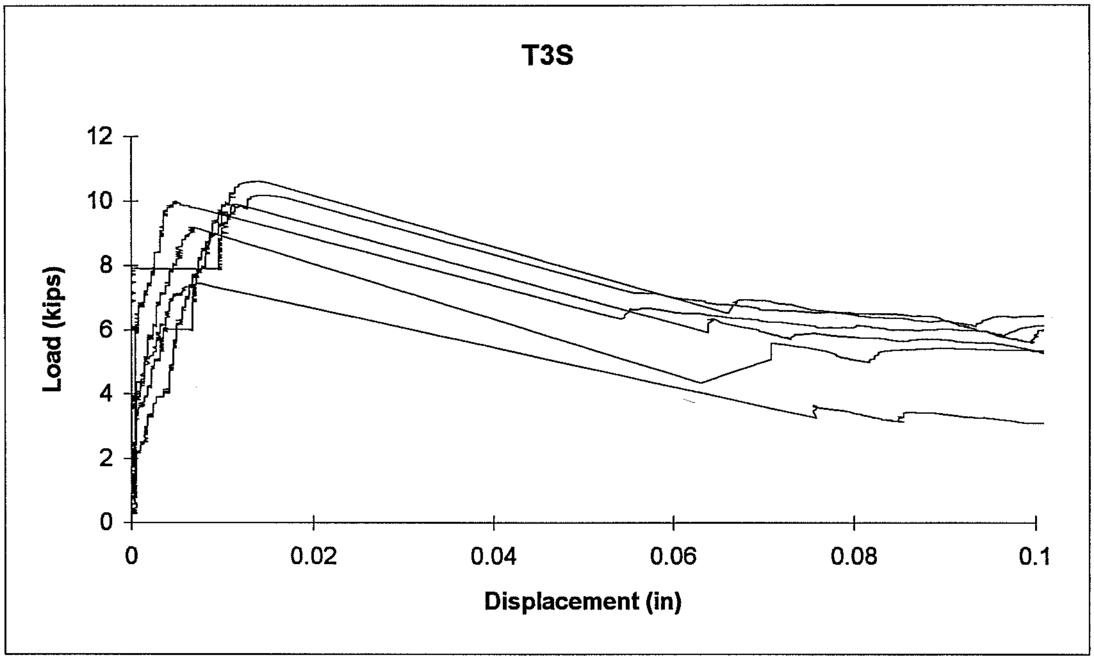
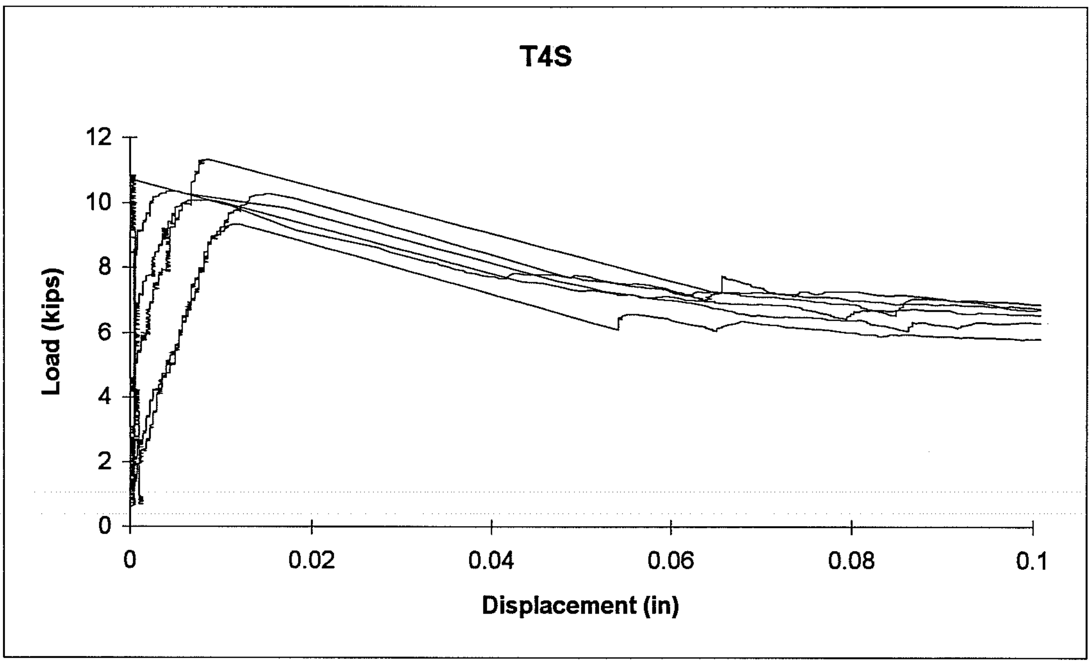
Load (kips)
12
10
8
6
4
2
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


T3S
Load (kips)
Displacement (in)
0
2
4
6
8
10
12
0
0.02
0.04
0.06
0.08
0.1


T4S
Load (kips)
Displacement (in)
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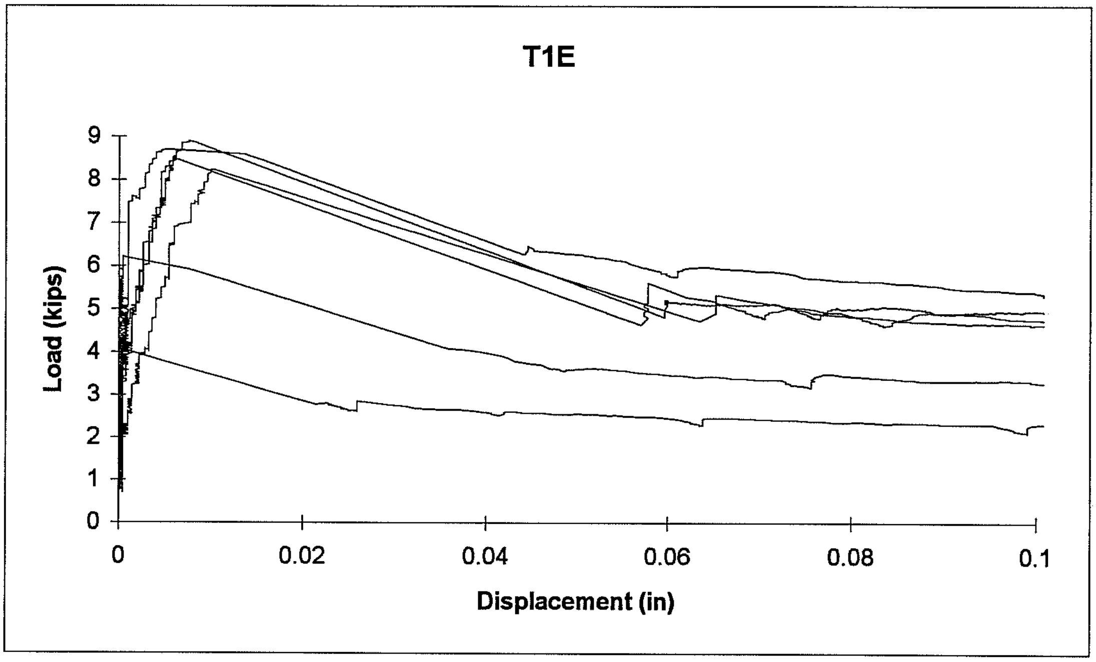
2
4
6
8
10
12
0
0.02
0.04
0.06
0.08
0.1


T1E
Load (kips)
Displacement (in)
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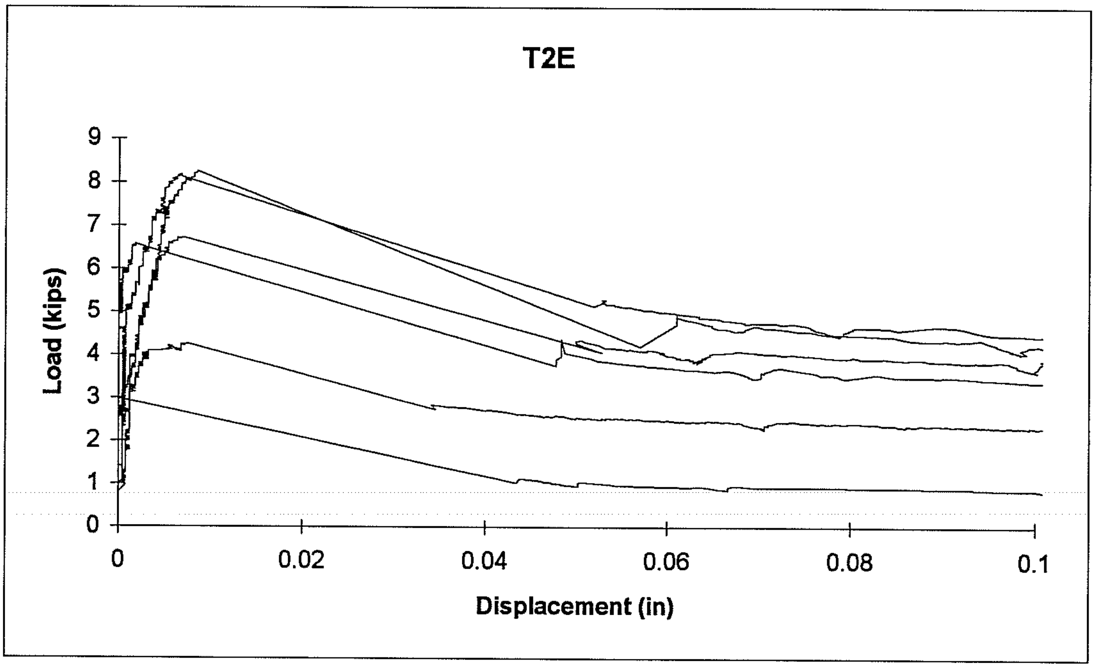
1
2
3
4
5
6
7
8
9
0
0.02
0.04
0.06
0.08
0.1


T2E
Load (kips)
Displacement (in)
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1
2
3
4
5
6
7
8
9
0
0.02
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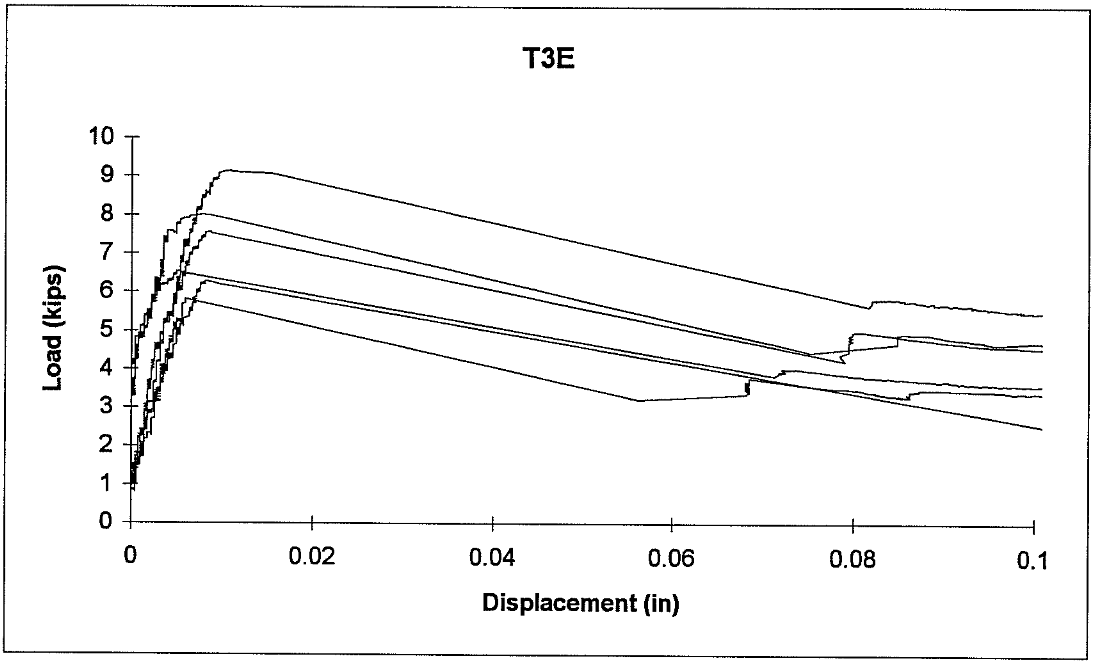
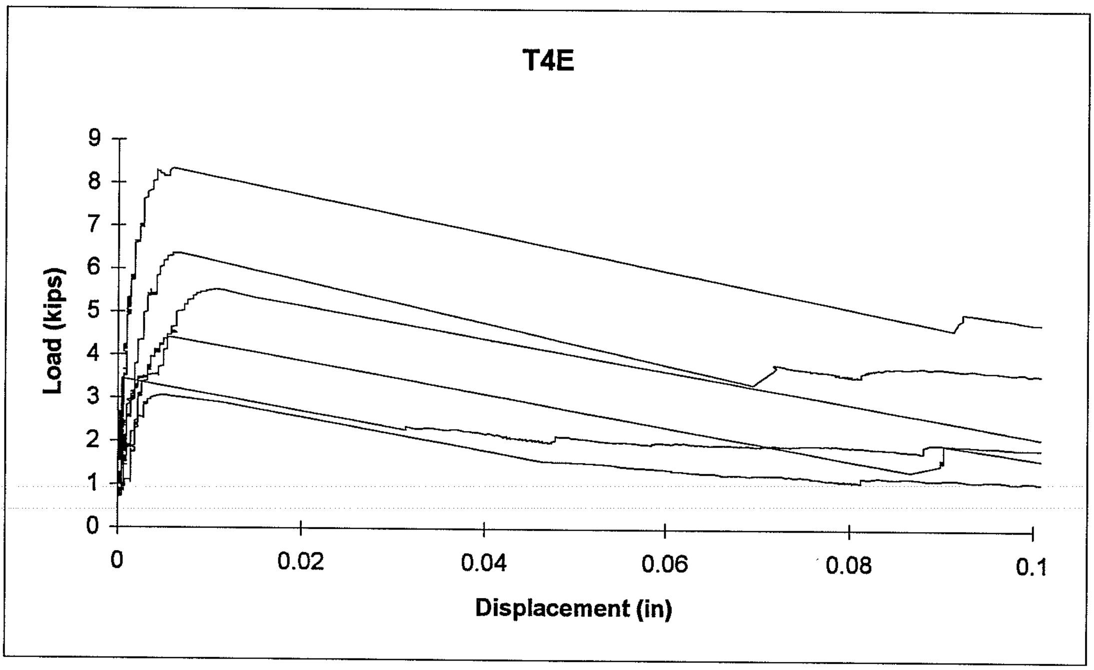
0.06
0.08
0.1


T3E
10
9
8
7
6
5
4
3
2
1
0
Load (kips)
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


T4E
9
8
7
6
5
4
3
2
1
0
Load (kips)
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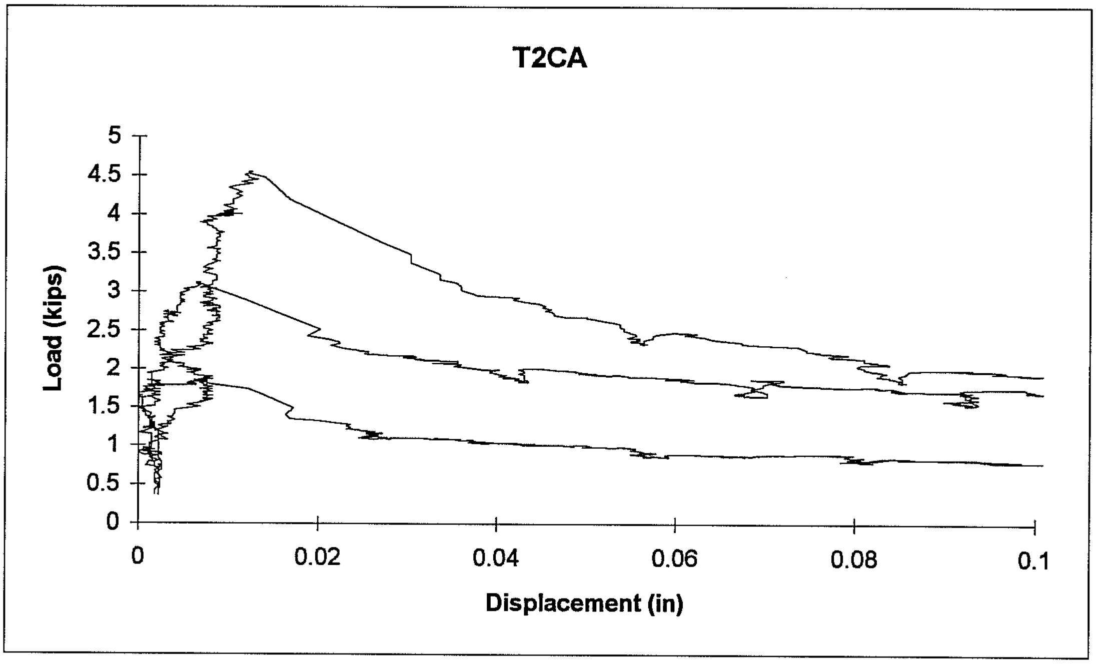
0.04
0.06
0.08
0.1
Displacement (in)


T2CA
Load (kips)
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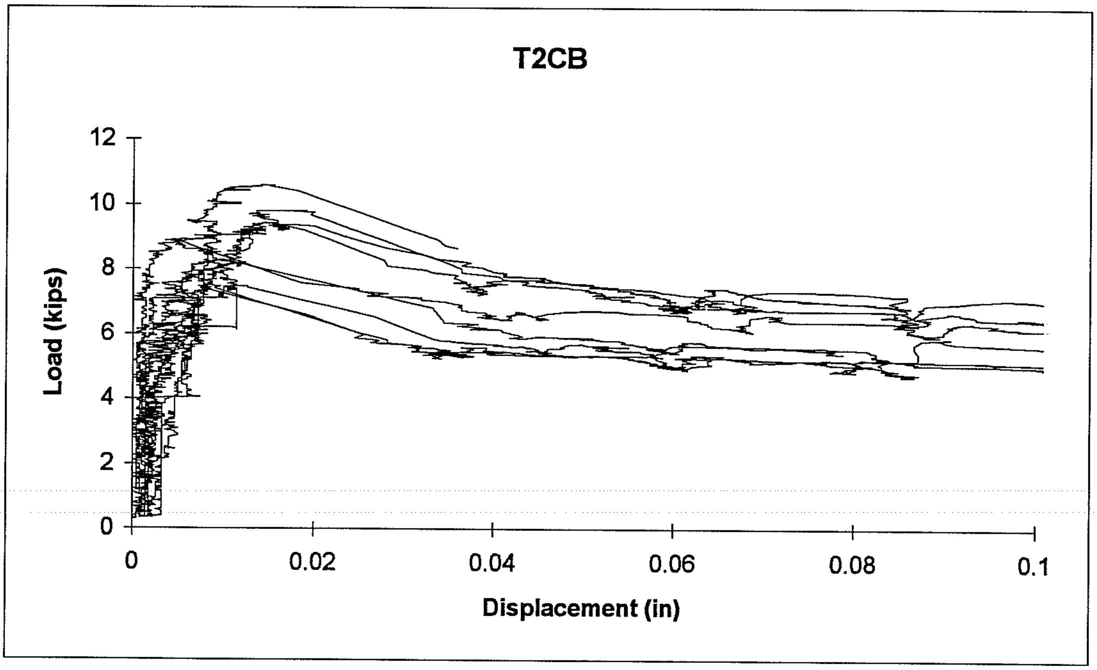
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


T2CB
Load (kips)
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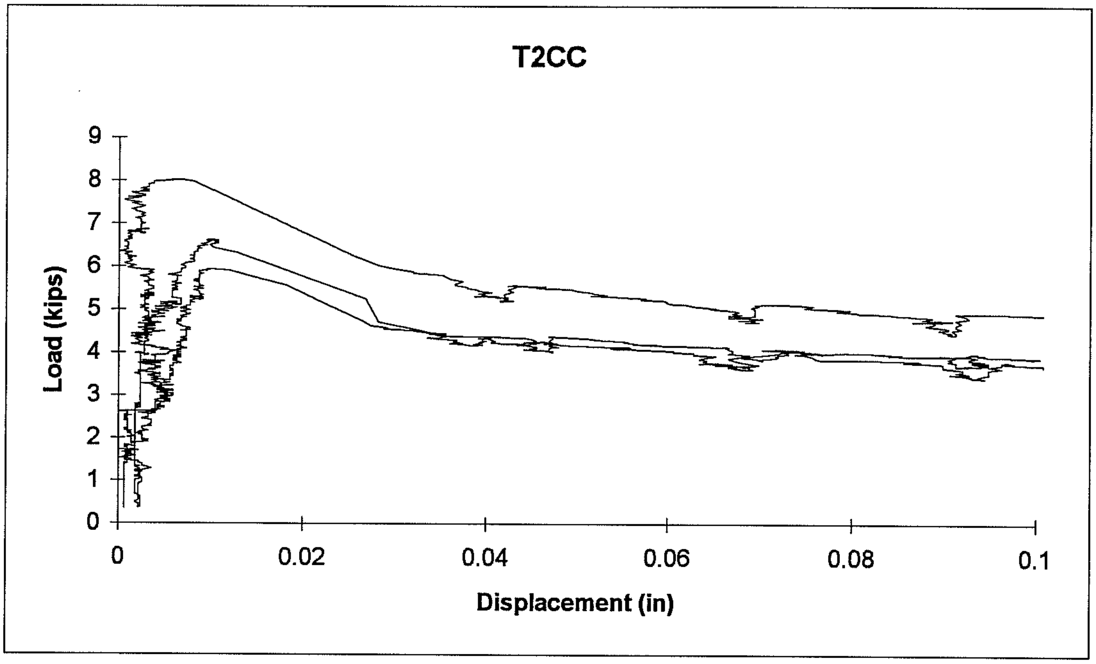
8
6
4
2
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


T2CC
Load (kips)
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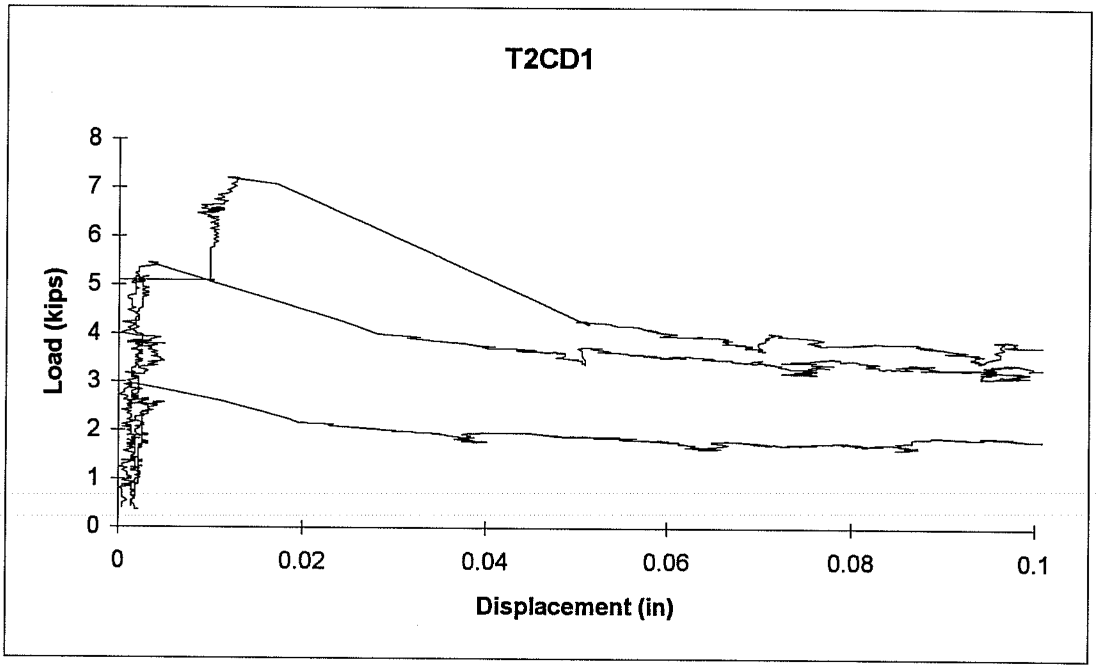
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


T2CD1
Load (kips)
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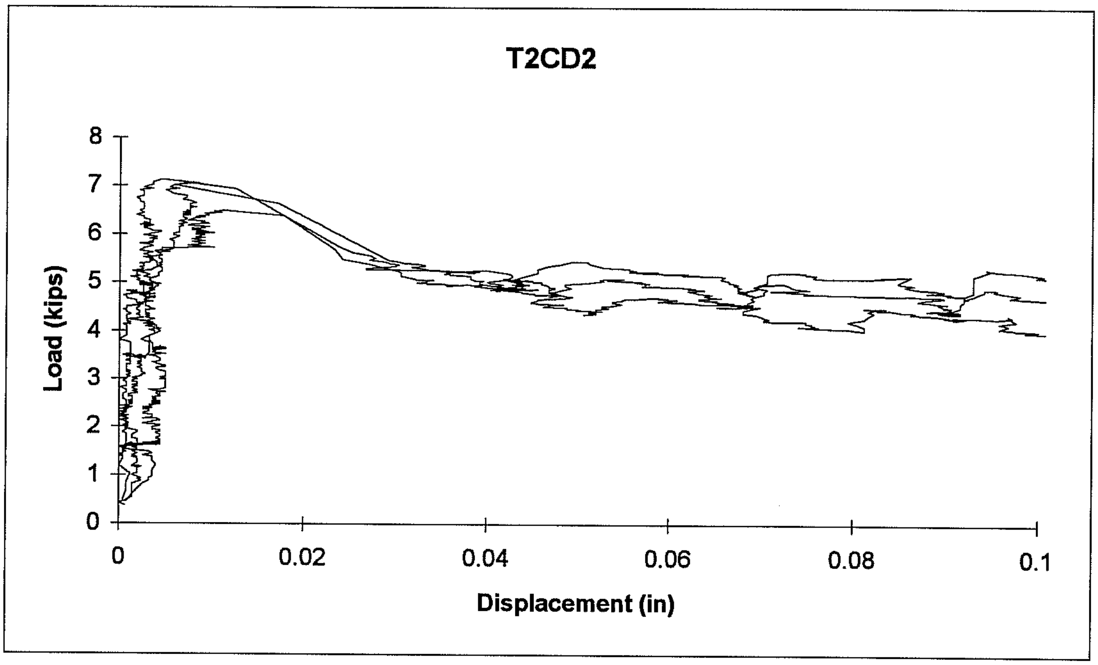
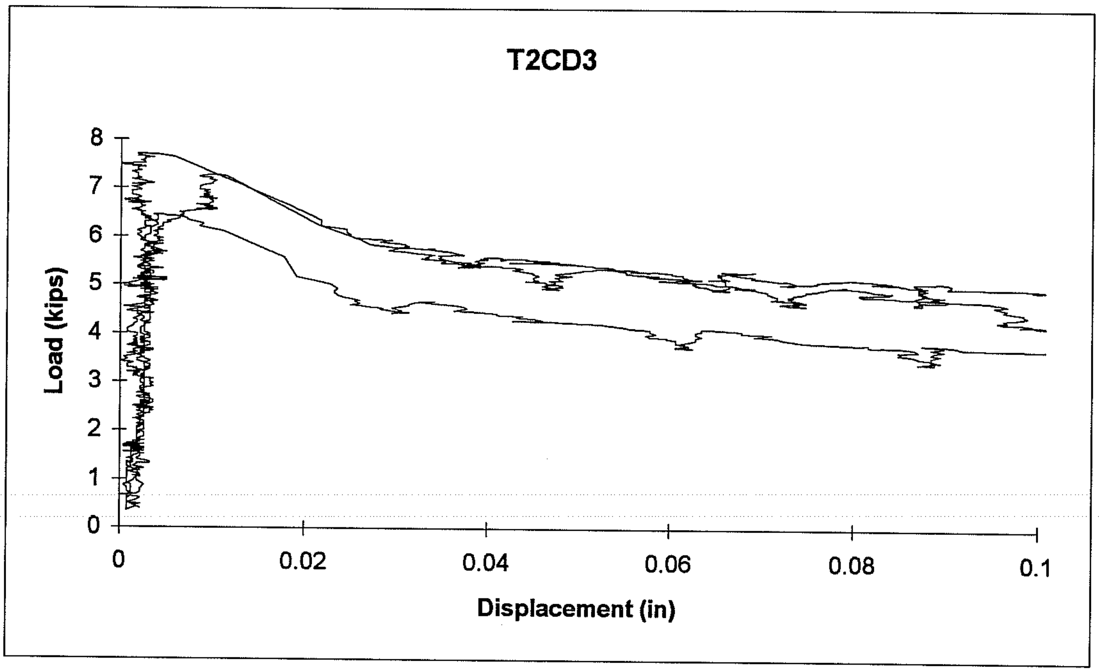
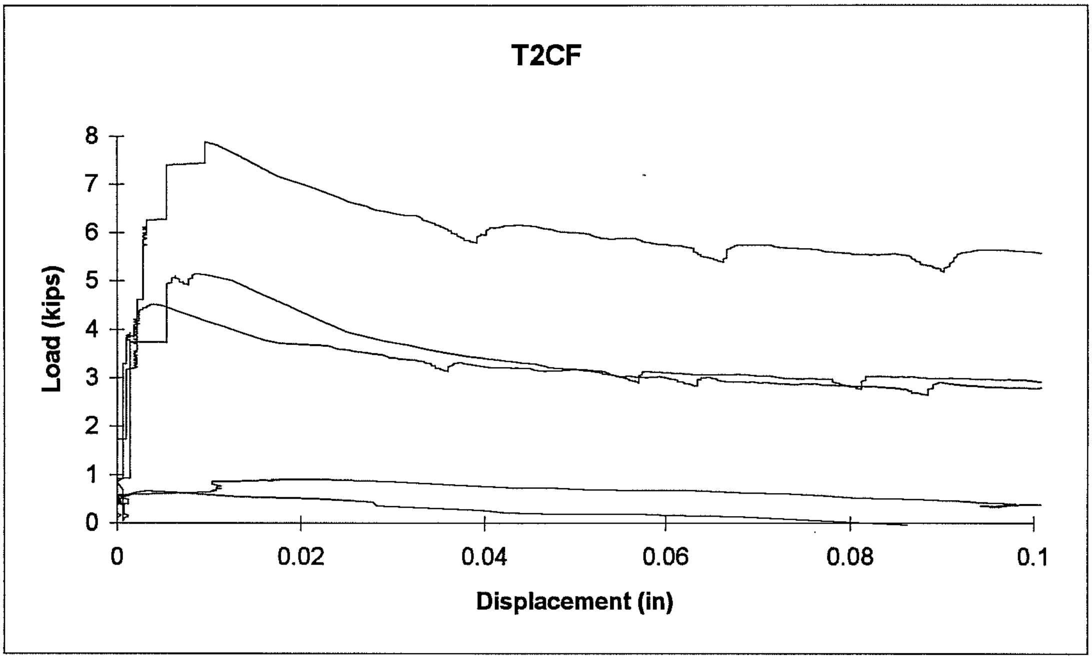
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)



T2CD2
Load (kips)
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)



T2CD3
Load (kips)
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


T2CF
Load (kips)
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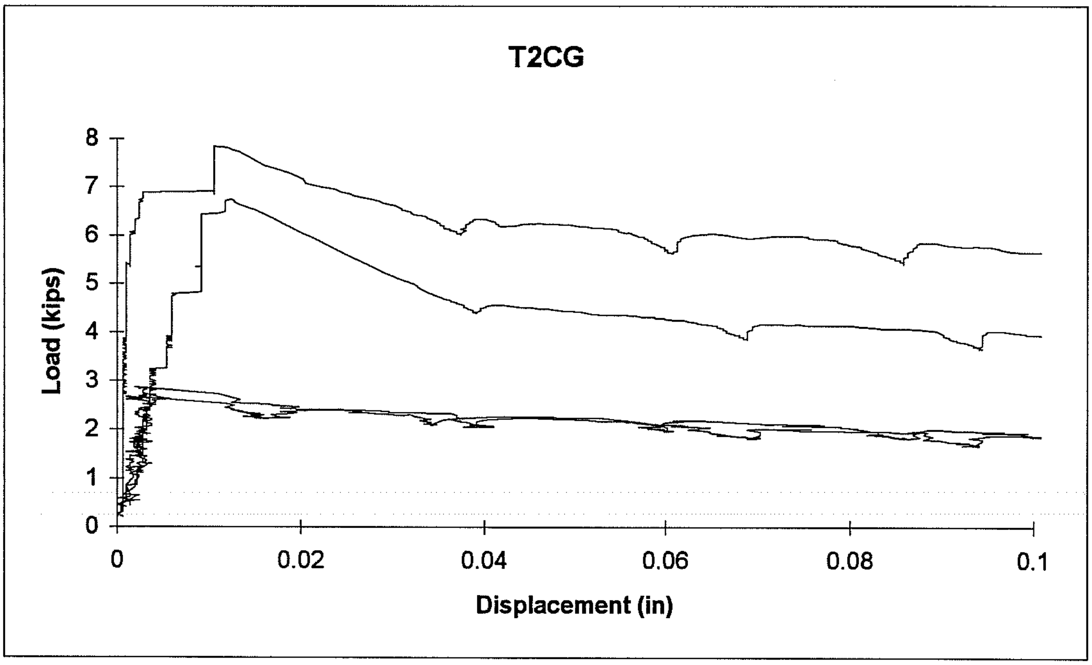
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)


T2CG
Load (kips)
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
Displacement (in)

Bibliography

1) Bagate, Moussa; McCullough, B. Frank; Fowler, David W.; "A Mechanistic Design for Thin-Bonded Concrete Overlay Pavements"; Research Report 457-3; Center for Transportation Research, The University of Texas at Austin; September 1987.

2) Choi, DongUk; Fowler, David W.; Wheat, Dan L.; Thermal Stresses in Polymer Concrete Overlays; Unpublished Master's Thesis; The University of Texas at Austin; 1992.

3) Chon, Carlos; Epoxies for Anchoring Dowels in Concrete; Unpublished Master's Thesis; The University of Texas at Austin; May 1984.

4) Hilti Corporation; Unpublished Research Reports.

5) Koesno, Koestomo; McCullough, B. Frank; "Evaluation of the Performance of the Bonded Concrete Overlay on Interstate Highway 610 North, Houston, Texas"; Research Report 920-2; Center for Transportation Research, The University of Texas at Austin; December 1987.

6) Luke, Philip Chi Chung; Strength and Behavior of Rebar Dowels Epoxy-Bonded in Hardened Concrete; Unpublished Master's Thesis; The University of Texas at Austin; May 1984.

7) Lundy, James Ray; McCullough, B. Frank; Fowler, David W.; "Delamination of Bonded Concrete Overlays at Early Ages"; Research Report 1205-2; Center for Transportation Research, The University of Texas at Austin; January 1991.

8) Menn, Christian; "Bonding of Old and New Concrete for Monolithic Behavior"; Unpublished Paper; Institute of Structural Engineering, Swiss Federal Institute of Technology; November 1991.

9) Seibel, F.; Latham, C. T.; "Analysis and Design Models for Structural Concrete Bridge Deck Overlays"; Journal of Structural Engineering; Vol. 116, No. 10; October 1990.

10) Seibel, F.; Latham, C. T.; "Horizontal Load Transfer in Structural Concrete Bridge Deck Overlays"; Journal of Structural Engineering; Vol. 116, No. 10; October 1990.

11) Solanki, Abdulrahman Ismail; Fowler, D. W.; McCullough, B. Frank; "A Study of the Effect of Construction Variables on the Bond Behavior of CRCP Overlays"; Research Report 457-4; Center for Transportation Research, The University of Texas at Austin; October 1987.

12) Suh, Young-Chan; Lundy, James R.; McCullough, B. Frank; Fowler, D. W.; "A Summary of Studies of Bonded Concrete Overlays"; Research Report 457-5F; Center for Transportation Research, The University of Texas at Austin; November 1988.

13) Teo, Kok Jin; Fowler, D. W.; McCullough, B. Frank; "Monitoring and Testing of the Bonded Concrete Overlay on Interstate Highway 610 North in Houston, Texas"; Research Report 920-3; Center for Transportation Research, The University of Texas at Austin; February 1989.

14) van Metzinger, Willem A.; McCullough, B. Frank; Fowler, David W.; "An Empirical-Mechanistic Design Method Using the Bonded Concrete Overlay for the Rehabilitation of Pavements"; Research Report 1205-1; Center for Transportation Research, The University of Texas at Austin; January 1991.

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