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A Report on Research Sponsored by

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Structural Engineering and Engineering Materials

SM Report No. 44

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THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.

2291 Irving Hill Drive - Campus West, Lawrence, Kansas 66045

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ABSTRACT

Research has been conducted by several investigators on a new, innovative type of reinforcement, referred to as the headed bar. The development of the headed bar resulted out of the need to reduce the development length of the bar and anchor the reinforcement in a shorter length. Construction in earthquake prone regions and designing for blast or impact conditions requires dense reinforcement configurations.. In these areas, designs call for connection details of major structural members that become congested with reinforcement. So much congestion occurs that standard 90° or 180° hooks, as prescribed by codes such as ACI, become unmanageable and are not feasible in complex reinforcement configurations. As the main focus of this present study, the anchorage behavior of a headed bar embedded in concrete in terms of development length and bond strength is investigated. In addition, further research will be proposed to evaluate the use of headed bars in lap splice applications.

This research includes a testing program consisting of concrete beam-end tests used to investigate the anchorage behavior of the headed bar. In order to form a basis for comparison, other beam-end specimens are tested using straight reinforcing bar, and still others using standard 180° hooked bars in addition to tests of the headed bar. Variables evaluated include the clear cover, bonded length, and transverse reinforcement.

The results of this program show the headed bar to provide almost immediate development of the bar provided that an adequate amount of confinement in terms of cover or transverse reinforcement is used. The results show the headed bar to be an adequate, if not an improved substitute, for the standard hooked bar as set forth by ACI. Based on these results and comparisons to previously developed expressions from past research, a design equation is proposed to describe the development length of headed reinforcement. From this equation, a set of design guidelines also is developed and presented to ACI for inclusion in a future version of the ACI Building Code.

Currently, there are no ACI code provisions that cover the use of the headed bar in structural design. Through this research, as well as studies being done at other institutions, a sufficient and accurate basis can be provided for the adoption of such standards into future editions of the ACI Building Code.

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Several other businesses also contributed to this research program. Bending of reinforcing steel was donated by Paul Turner at Sheffield Steel and Jon Knapp at Ambassador Steel Corporation. Concrete was supplied by John Pendry at Lawrence Ready Mix, Lawrence, Kansas. Additional support was furnished by Bob D. Campbell & Company Structural Engineers, Kansas City, Missouri.

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CHAPTER 1

INTRODUCTION

1.1 Background

The design of reinforced concrete structures require that the reinforcement must be anchored so as to fully develop the bar to its yield stress. For full development, a sufficient amount of bar surface area must be exposed to the concrete and through means of chemical adhesion, friction, and mechanical interlock via deformations or ribs on the bar, the steel-concrete compatibility must be insured. Therefore, a minimum development length of the reinforcing bar must be provided through anchorage to the concrete before this compatibility can be achieved. Along this development length, the bar force that can be achieved gradually increases to reach the full yield force in the bar. This development length can become quite long, especially with low confinement. Consequently, researchers have long since strived for ways in which to minimize the development length and in the process, save steel costs and eliminate detailing problems for the structural designer.

These challenges become even more daunting when designing structures in areas of high seismic activity or for blast loads. Here the reinforcing details for major structural members and connections can become very difficult due to high levels of steel congestion. Consequently, conventional hooked bar anchorages may become unfeasible or impractical. An alternative is the use of headed reinforcement, which allows for extremely small development lengths, that can reduce congestion without compromising the integrity of the structure. As a result, designing and detailing the structure are made easier and more efficient. These benefits have already been utilized in such major construction projects as the Hibernia and Troll offshore drilling platforms. In addition, headed reinforcement also has been evaluated for use in on-shore projects, especially in bridge applications.

What makes this technology so unique lies in the fact that the heads on the bar can provide a means to develop bond strength through a separate load path. This path is provided in the headed bar by means of the concrete bearing on the head itself. Exactly what proportion of load is taken through these mechanisms is still somewhat uncertain, however, research presented by Dahl (1995) provides some evidence that a minimum of approximately 75% of the load is taken through bearing of the head and the remaining 25% through conventional bond strength. As a result, many of the factors and expressions that describe the development length of straight deformed bars also may apply to headed reinforcement as well. While extensive research has already been conducted on headed bars, the research program described here focuses on gaining new insights to the anchorage behavior of these bars, as well as developing design expressions to describe its development length.

The development of design recommendations is important. No current codes, in the United States include provisions for the use of headed reinforcement in concrete structures, however, there are codes in Canada and Europe that contain some provisions. It is hoped that the findings of this study will provide a foundation for such code provisions to be considered for inclusion in a future ACI Building Code.

1.2 Previous Research

Previous research into the bond and development of reinforcement has been extensive. There have been many studies performed in the United States, Canada, Europe, and in Japan. As such, it is impossible to summarize all of the important work that has been performed around the world. For purposes of this study the relevant studies are those that have had a profound effect on the ACI Building Code provisions. Moreover, these studies provide a starting point for the development of design expressions and guidelines for use of headed bars in reinforced concrete structures.

1.2.1 Straight Bar Research

Some of the most renown work in the area of bar development and bond strength originated from studies by Orangun, Jirsa and Breen (1975, 1977). From analysis of test results of splice specimens, equations were formulated to describe the development lengths of steel reinforcing bar. The effects of bonded length, cover, bar spacing, bar diameter, compressive strength, transverse reinforcement, and moment gradient across the splice were investigated and comparisons of the results were made to the then existing equations set forth by AASHTO Interim Specifications for Bridges (1974). These comparisons showed that even under the worst of confinement conditions and configurations, the provisions were conservative (as much as 11%). Subsequently, with additional cover or transverse reinforcement, these same provisions may underestimate splice strengths by as much as 60%.

In addition to the work by Orangun et al.(1975, 1977), several other studies have been done in the past to investigate and improve the bond strength of deformed steel reinforcing bars. Over the past decade, extensive studies at the University of Kansas has been devoted to such a topic with primary focus on epoxy coating effects and bar deformation patterns. In some of the studies, improved development length or bond strength equations also were obtained.

Choi et al. (1990) used a series of beam-end specimens tests, along with nonlinear finite element modeling, to study the effects of epoxy coating thickness, bar deformation pattern, bar size, cover, and casting position, on the reduction in bond strength caused by epoxy coatings. Among the findings was the conclusion that epoxy coating decreased bond strength, however, the magnitude of the decrease was overestimated by the code provisions enforced at that time. Interestingly, the decreased bond strength that result from epoxy-coatings were not as significant if high relative rib area bars were used. Another finding demonstrated that coating thickness to had little effect on bond for No. 6 or larger bars, yet for No. 5 bars or smaller the increase in coating thickness provided for a greater reduction in bond strength due to the presence of epoxy coating. Lastly, the study concluded that the reduction in bond strength due to epoxy-coatings is independent of cover, even though increases in cover produce increases in bond strength for both uncoated and coated bars.

A continuation of the study by Choi et al. (1990), further research by Hadje-Ghaffari et al. (1991) investigated the effects of additional variables: concrete slump, consolidation, transverse reinforcement, concrete compressive strength, on the reduction of bond strength caused by epoxy coatings. Furthermore, this study also included several beam-splice tests in addition to beam-end tests. From this test program, it was observed that bottom cast bars performed increasingly better than top-cast bars when the concrete slump was increased, and when the slump is low, epoxy coatings had a negligible effect on either top or bottom cast bars. The study also found that when slump is increased, the bond strength reduction due to epoxy coatings is lower for top-cast bars than it is for similar bottom cast bars. Finally, this research also confirmed that the use of transverse reinforcement increases the bond strength of the bar and in fact, epoxy coated bars confined by transverse reinforcement have bond strength approximately equal to that of uncoated unconfined test bars.

The work of a separate study by Darwin et al.(1992) which detailed the efforts of a study aimed at finding an improved expression for describing development lengths of deformed steel reinforcing bars. The equation, similar to and based upon the work of

Orangun et al. (1975,1977) appears a more accurate expression for bond strength and provides a better indication of bond strength when significant differences between clear cover and half of the bar clear spacing are inherent in the test specimen. The study also concluded that development length equations, dictated by ACI at that time, were unconservative for No. 6 and smaller bars subjected to minimum cover conditions and/or close bar spacings. Furthermore, these equations were conservative for most all sizes of bars with large amounts of cover and/or large center-to-center bar spacings.

The study provided by Darwin et al. (1992) was somewhat limited in that only bars not confined by transverse reinforcement were evaluated. Therefore, a study was undertaken by Darwin and Graham (1993), and subsequently, Idun and Darwin (1995), to evaluate the effects of transverse reinforcement, deformation patterns, and epoxy effects in beam-end and splice specimens. From the latter study, it became apparent that while the bond strength equation proposed by Darwin et al. (1992) was adequate for normal strength concrete, it did not work well with higher strength concrete. Thus, modifications were made to this expression using the both the 1/2 power and 1/4 power of the concrete compressive strength, f'c. From dummy variable analysis of this variable it became clear that $f'c^{1/4}$ was a better reflection of the effects of concrete strength on the bond strength of bottom cast bars not confined by stirrups. Modifications to the equation by Darwin et al. (1992) also were made to account for additional confinement provided by transverse reinforcement, and was based upon the quantity of transverse reinforcement rather than the yield strength of the stirrups themselves.

As mentioned before, the study also investigated the effects of bar deformation patterns and epoxy-coatings. This report confirmed the findings by Choi et al.(1990) that with a higher relative rib area on the bar the smaller the amount of reduction due to the presence of epoxy coatings. A study by Darwin and Graham (1993), which preceded the study by Idun and Darwin (1995), determined that when conditions of low confinement are provided, bond strength is controlled by the splitting of the concrete and thus becomes independent of deformation patterns. By providing additional confinement via transverse reinforcement or clear cover, the bond strength of the bar will increase. Furthermore, the study by Idun and Darwin (1995) concurs with that of Darwin and Graham (1993) by concluding that increases in relative rib area produce higher bond strengths provided that transverse reinforcement is used. In summary, results of the study by Idun and Darwin (1995) indicate that development lengths can be reduced by 9-16% if bars with high relative rib areas are used and the bars are confined by transverse reinforcement.

1.2.2 Headed Bar Research

It is obvious that extensive research and study has been devoted to improving the development lengths of straight deformed steel reinforcing bars. However, a relatively small amount of study has been focused on headed reinforcement in part because of its recent development. Much of the early research was conducted outside the United States in Norway. This work was sponsored by Metalock Industries, the producer of headed bars in Norway, or by various oil companies or contractors. As such, much of the work is proprietary in nature and has not been published. There have been a number of studies published in Norway by Fynboe and Thorenfeldt (1986), Hole et al. (1989) and Thorenfeldt (1990) where the performance of headed bars under static conditions were evaluated.

In addition, two important articles were written for the US engineering community on headed bars based on tests performed at UC-Berkeley and other locations and drawing on the European and Canadian experience. Articles by Berner, Gerwick and Hoff (1991) and by Berner and Hoff (1994) illustrate the application of headed bars in large scale structures. Studies have been undertaken in the US to investigate the performance of headed bars in beam-column connections, shear walls, and other seismic related applications. A cyclic test of a bridge pier-beam bent was recently completed by Seqad Consulting Engineers (1995) and shows the promise of headed bars in seismic applications. Little study has been completed to effectively assess the development length and anchorage behavior of headed reinforcing bars. Studies are currently underway at the University of Texas, however, this research concentrates on headed test bars with smaller heads and test results from true pullout specimens. Recent work by Devries and Jirsa is in the process of being published. Therefore, the scope of this study is different than the scope of the test program presented here in this report. In addition, the "pullout" test is much different style of test than that of the beam-end style tests performed within this research. Comparisons and discussion of these test types are provided later in this report.

In summary, although significant amounts of research has been undertaken or is currently underway, relatively little has been done in comparison to the amount of research that has been performed on the topic of bond strength of straight deformed bars. Furthermore, past or present headed bar test programs are much different in scope than the research presented in this report.

1.3 Scope

In order to investigate the development characteristics of headed bars, a research program was devised at the University of Kansas that consisted of performing beam-end tests on specimens with headed bars, as well as hooked and straight bar specimens. These beam-end tests will be discussed in Chapter 2 of this report, and are based on the work over the past decade described in several studies on bond and development, including work by Choi et al (1990), Hadje-Ghaffari et al. (1991), Darwin and Graham (1993), and

Idun and Darwin (1995). In addition, the beam-end test provides a more realistic representation of an actual reinforcement application than the more conventional "pullout" tests. Because they are easier and more cost efficient than a large splice specimen, beam-end tests are the standard tests used for evaluating development applications.

A total of 70 beam-end tests are summarized in Chapter 3 of the report. The data includes tests of headed bars with and without transverse reinforcement, changes in cover and in the amount of bar exposed to the concrete for bond. An important element of the study is the effect of confinement, represented by study of the changes in performance from changes in cover and transverse steel. A second major point is the study of deformed headed bars versus a "smooth" headed bar where the deformations are covered with a PVC tube to make a smooth bar without deformations. In the smooth bar, the entire anchorage of the bar is provided by the head alone, thus allowing study of the efficiency of the head in anchoring the bar.

Several variables also are investigated in the testing program. While the effects of cover, bonded length and transverse reinforcement were evaluated for headed test bars, parameters such as concrete strength, bar size, and bar yield strength will remain constant throughout the course of the study. After evaluating the influence of the primary variables on headed bar anchorage, several conclusions and observations are made regarding the bond and development of headed reinforcing bars. These observations are made in the test data alone and in the overall performance of these systems.

Based on the results of the tests, Chapter 4 will contain comparisons made to bond strength and development equations previously developed. Using statistical evaluation of these comparisons along with analysis of strut-tie models, bond strength equations, such as that developed by Orangun et al. (1975, 1977) are evaluated for their merits as an adequate expression on which to base a design equation to describe the development of headed reinforcing bar. Using the comparisons made to various expressions, best-fit lines will be produced and plotted through the actual headed bar data. Subsequently, an equation of this line will be used to describe headed bar development length. Modifications to this line for the normalizations of concrete strength and bar yield strength are made and an alternate expression developed to also describe the development length of headed bars. Using these two expressions along with the test results, design guidelines are constructed in a context consistent with the ACI Building Code. The report concludes with a summary of observations and conclusions, as well as needs for future study.

CHAPTER 2

EXPERIMENTAL PROGRAM

2.1 General

A test program consisting of seventy beam-end tests was conducted to investigate the development length characteristics of headed reinforcement. While the majority of specimens involve Headed test bars, the remainder of the beam-end specimens consist of both straight bars and bars with 180° hooks at one end. Test configurations and procedures outlined herein were developed at the University of Kansas in previous work on bond (Brettmann et al. 1984, 1986, Donahey et al. 1983, 1985, Choi et al. 1990, Hadje-Ghaffari et al. 1991, Darwin et al. 1993), and are outlined in ASTM A944-95 (1996). Some modifications have been made to these procedures and will be discussed throughout this chapter.

This chapter will provide a description of the variables considered in the test program as well as explain test configurations for the beam-end tests. In addition, material properties, specimen fabrication, and testing procedures used in these tests also will be discussed.

2.2 Test Parameters

The test program is divided into four batches of beam-end tests. The first batch of tests served primarily as a basis for determining which parameters needed further investigation and to plan the remainder of the program. Consequently, batches #2, #3, and #4 comprise the majority of the testing program. Whenever material and logistics allowed, three specimens of each variable were fabricated and tested to increase the reliability of the test results.

Some aspects of the experiments remained constant throughout the duration of the program. These include a constant test bar size (No.25M [No.8]), embedment length of 305mm [12"], and a general concrete strength of 31-34.5MPa [4500-5000psi]. There were three primary variables that were investigated throughout the course of the test program:

Concrete Cover: Beam-end specimens with both two and three bar diameters (approximately 50mm and 70mm [2" and 3"] respectively, measured from the edge of the bar) of cover were investigated (Fig. 2.1).

Reinforcing Bar Exposure: The effects of allowing the test bar to bond to the concrete was observed in some of the tests. In other specimens, the test bar was covered with a polyvinyl chloride (PVC) tube, thus eliminating the bonding of concrete to the test bar. It is important to note that in tests of the former, at least 13mm [0.5"] of the test bar closest to the front (loaded-end) was covered with PVC. This is known as the "lead length" (Fig. 2.1), and is necessary to prevent a localized cone-type failure of the concrete at the loaded end portion of the specimen.

Transverse Reinforcement: Various quantities and spacing patterns of transverse reinforcement were provided as an additional means of confining the test bar in the specimen. A total of four stirrup spacing patterns were observed throughout the experimental program (Fig. 2.2).

2.3 Test Specimens

2.3.1 Materials

Concrete: Air-entrained concrete having nominal strengths of 31-34.5MPa [4500-5000psi] was supplied by a local ready-mix plant. Concrete mixes consisted of Type I Portland cement, Kansas river sand, and 19mm [0.75"] (maximum) nominal size crushed limestone aggregate. Concrete properties and mix proportions for each batch of tests are given in Table 2.1.

Steel Reinforcement: Principal test bars for the specimens were fabricated from Grade 75 ASTM A 615 (1992) steel with a metric size designation of No.25M [No. 8]. All other steel reinforcement used in each specimen was that of Grade 60 ASTM A 615 (1992). Some of this reinforcement required bending. This service was provided by Sheffield Steel and Ambassador Steel Corporation. Headed test bars were supplied by Headed Reinforcement Canada in Mt. Pearl, Newfoundland, Canada, and fabricated using friction welding procedures (Olsen, 1993) in conformance with the proposed ASTM specification for welded headed bar.

2.3.2 Specimen Fabrication

Forms were fabricated from 19mm [0.75"] plywood that consist of a "dry-strip" polymeric layer to protect and seal the wood from the concrete during placement. Formwork not constructed from this special grade of wood was given protective coats of polyurethane to provide the "dry strip" characteristic to those forms. All form edges and joints were caulked and sealed to prevent leakage during casting.

Formwork was fabricated such that specimens would have an overall size of 229mm x 457mm x 610mm [9" x 18" x 24"]. For specimens with three bar diameters of cover, the depth increased 25mm [1"] to accommodate the additional cover. The overall dimensions for these specimens are, therefore, 229mm x 483mm x 610mm [9" x 19" x 24"]. All test bars are a nominal 25mm [1"] in diameter and are cast 381mm [15"] up from the bottom of the specimen (Fig. 2.1). It is important to note that specimens are cast in an inverted position as compared to the position in which they are tested (Fig 2.3). The test specimens will be discussed with relation to their testing position throughout the remainder of this chapter.

Cast at the same height as the test bar, a section of 25mm [1"] diameter steel conduit was positioned adjacent to the test bar and continued to the back face of the specimen (Figs. 2.4a,b,c,d) to provide a means to access the unloaded portion of the test bar. In specimens with hooked test bars, the steel conduit was cut to fit the bend of the hook and sealed to the bar to prevent concrete seepage into the conduit during concrete placement. In specimens with headed test bars, a 45mm [1.75"] long piece of steel conduit 32mm [1.25"] in diameter was affixed to the back of the head itself using an epoxy bonding agent. The 25mm [1"] diameter piece of conduit was then fitted inside this piece and was allowed to juxtaposition the head. The outer piece of conduit was covered with clay to prevent its bonding to the concrete. This connection also was sealed to prevent seepage into the conduit. For specimens using straight test bars, the conduit was positioned and affixed in a manner set forth by previous tests and studies (Choi et al. 1990, Hadje-Ghaffarri et al. 1991, Darwin et al. 1993).

In the specimens with straight test bars and in specimens with headed test bars, the unloaded ends provided a flat vertical surface. This is needed for effectively measuring the "unloaded-end slip" using a single spring-loaded linear variable differential transformer (LVDT) to contact the test bar's unloaded end. The 180° hooked test bars did not provide this ability so consequently, some modification was made to these specimens. A 1mm [0.037"] diameter steel wire was epoxied to the point on the test bar that marked the hook's starting point. The wire was then fed through the steel conduit out the back end of the specimen and left for later connection to the LVDT (Orangun et al. 1975).

PVC bond breaking pipes had inside diameters equal to the test bar diameter and were used to control both the lead length and bonded length within the specimen (Fig. 2.1). These lengths varied among each of the specimens and are summarized in Table 3.1.

Several pieces of reinforcing bar make up the rest of the steel configuration. Four pieces of No. 6 reinforcing bar were positioned to prevent a flexure failure of the specimen (Fig 2.4a). The configuration used here is a slight modification from that used in previous studies (Choi et al. 1990, Hadje-Ghaffarri et al. 1991, Darwin et al. 1993) in which specimens only consisted of two auxiliary bars. Three #5 transverse bars also were provided in the specimen. One of these acted as a means to support the test bar and the other two were used to aide in moving the specimen (Fig. 2.4b). Four No. 3 double-legged closed loop stirrups were oriented parallel to the flexure steel and provided shear reinforcement for the specimen (Fig. 2.4c). Additional No. 3 closed-loop stirrups were used in various spacing patterns to provide transverse reinforcement and give further means of confinement. These stirrups are positioned between the flexure reinforcement and are looped around the test bar as shown in Fig. 2.4d.

2.3.3 Concrete Placement and Curing

Concrete was cast in the beam-end specimens in two separate lifts. Each lift was vibrated in six evenly spaced points. Once the concrete had set up, all specimens were covered with wet burlap and a 3 mil sheet of plastic. Specimens were cured in this fashion until concrete strengths reached at least 20.7 MPa [3000 psi]. Forms were then removed and the specimens were inverted to their test position. The test specimens were then left to cure until the concrete reached its designated test strength.

Standard test cylinders measuring 153mm x 305mm [6"x12"] were cast in a combination of steel and plastic molds, and cured in the same manner as the test specimens. Compressive strength was tested seven days after pouring and monitored until the strength asymptotically reached a value at which the test was to be performed.

2.4 Test Procedure

The beam-end specimens were tested using an apparatus developed by Donahey and Darwin (1983, 1985). This apparatus was modified by Brettman et al. (1984, 1986) and further developed by Darwin and Graham (1993) (Figs. 2.5 and 2.6). Both the specimen and test apparatus were secured to the structural floor using two wide-flange sections and four tie-down rods. Load was applied to the test bar by two sixty ton hollow-core jacks through two 25mm [1"] diameter load rods instrumented as load cells. The jacks were powered by an Amsler hydraulic pump and provided load to the test bar at a rate of 27kN [6 kips] per minute. Load was applied to yokes (via the load rods) and then transferred to the test bar through a steel wedge-grip assembly. As shown in Fig. 2.5, the tensile force acting on the test bar is equaled by an opposite compressive force applied by a bearing pad rigidly fixed to the frame of the apparatus. The bearing pad occupies the lower 90mm [3.5"] of the specimens front surface and measures 350mm [13.75"] from the center of the test bar to the center of the bearing pad.

To measure slip at the loaded end, two spring-loaded LVDTs with 25mm [1"] stroke range were attached to an aluminum block mounted to the test bar. A single LVDT, also having a 25mm [1"] stroke range, was inserted through the steel conduit on the back surface of the specimen to measure unloaded slip. This LVDT was butted up to the back of the test bar (or head) and attached to the end of the steel conduit. In cases where hooked specimen were tested, the protruding steel cable-wire was tied to the LVDT and the LVDT was attached to the end of the steel conduit. An additional LVDT with 127mm [5"] of stroke range was placed across the top surface, transverse to the test bar, to measure splitting crack widths that resulted from the tests. This LVDT was not used when headed specimens with no transverse reinforcement were tested. Data from the load cells and LVDTs were processed by a Hewlett Packard 3497A data acquisition device with a model #3455A digital voltmeter. The data was then fed into a computer program for later management and interpretation.

CHAPTER 3

TEST RESULTS AND OBSERVATIONS

3.1 General

This portion of the report consists of a discussion and examination of the test results obtained in a manner described in Chapter 2. Primary variables such as cover, bonded length, and transverse reinforcement will be analyzed. From an evaluation of test data, conclusions and observations will be made regarding these parameters. In addition, performance of the headed test bars will be compared with the results of 180° hooked test bars.

The concrete strength of tests performed in batch #1 are less than those of tests performed in batches #2,#3 and #4. To ensure an equal basis for comparison of the results, corrections are made to account for differences in concrete strengths among each specimen. Therefore, the ultimate axial load for each specimen is normalized to a specimen with a nominal concrete strength of 34.5 MPa [5000 psi]. Within the concrete strength range used in these tests, it is assumed that bond strength is a function of the concrete's tensile strength. It is also assumed that bond strength is proportional to the square root of the concrete's compressive strength. Consequently, ultimate axial loads are multiplied by a factor of $(5000/f'c)^{1/2}$ where f'c is measured in units of pounds per square inch (psi).

A summary of modified and original ultimate axial loads, along with other individual test data, can be found in Table 3.1. The specimen identification consists of six groups of characters and each group is separated by a hyphen. The identification defines batch number, specimen type and number, use or non-use of PVC around the bar, use or non-use of stirrups and stirrup spacing pattern, cover, and lead length (mm), in that order.

3.2 Headed Bar vs. 180° Hook (ACI 7.1-7.3, 1989)

Throughout the testing program, noticeable similarities became apparent between the 180° hooked bar tests and the headed bar tests. In order for this claim to have any validity, the specimens must be compared upon an equitable basis. As shown in Fig. 2.1, the centerline of the head is assumed to be equivalent to the centerline of the bar along the back portion of the hook. Using the centerline as a basis to determine embedment length, the hooked portion of the bar becomes representative of the head itself. That considered, when PVC is applied to hooked specimens, the PVC is terminated at a point projected vertically from the end of the hook's tail.

The most obvious similarity between the 180° hooked specimens and the headed tests can be seen in Table 3.2. Examination of this figure shows that in every case the headed tests failed at loads approximately equal to, or higher than, those of the hooked tests. In only one combination of variables did this trend not occur. In this particular case, headed tests that include PVC, stirrup pattern "3S1"(Fig. 2.2), and 3db of clear cover, show an average "modified ultimate axial load" approximately 22kN [5 kips] lower than in hooked tests with similar parameters. It is important to note, however, that the amount of scatter was large for headed tests of that group; with one test actually yielding the bar. Therefore, headed tests under these variables may actually have had as much axial capacity as its hooked counterpart, however, more data would be needed to determine this behavior.

Another similarity that can be observed is the way in which the headed and hooked tests react to changes in combinations of variables. In cases where PVC is provided and only 2db of cover is used, transverse reinforcement is instrumental in obtaining additional axial load from the specimen. Inclusion of #3 stirrups provided an additional 80kN [18 kips] capacity to the 180° hooked specimens and approximately 49kN [11 kips] additional strength to the headed tests. When the same conditions were applied with 3db of cover, the benefit of the stirrups was not quite as dramatic. While no real differences can be observed in the headed specimens, there was only a moderate increase in axial load capacity, 241kN to 264kN [54.2 kips to 59.4 kips], in the hooked specimens.

In instances where the bar was allowed to bond to the concrete and transverse reinforcement was provided, the benefits from an additional bar diameter of cover was similar for both hooked and headed specimens. Table 3.2 shows that the ultimate axial load increased almost 9kN [2 kips] with these parameters for hooked tests and approximately 15.5kN [3.5 kips] in the headed tests. The addition of cover did not appear to have much effect on the axial load in either hooked or headed tests when the bar was prevented from bonding to the concrete, even though transverse reinforcement was included. Here once again, changes in parameters effected the 180° hooked tests and headed tests in a like manner and further indicates a strong resemblance between these two methods of anchoring and developing reinforcing bar.

The amount of ductility shown in each of these two kinds of test bars is also an issue that demonstrates their parallel performance. Loaded slip data shown in Table 3.3 clearly indicates that the values between hooked and headed tests are approximately the same. In tests with 2db of cover, the average difference shown in the loaded end slip values for the two kinds of tests is 0.418mm [0.0165"]. The loaded slip data also shows that the ductility of the headed tests are effected by parameter changes in a similar fashion and magnitude as the way in which the hooked test specimens are effected. For example, in tests that have bars covered with PVC and 2db of clear cover, the addition of stirrups increases the ductility of the hooked test bar from 1.01mm [0.0398"] at failure to 3.14mm [0.1235"] at yield. Likewise, the ductility of the headed test bar also increases (from

1.4mm [0.055"] to 2.37mm [0.0932"]). Based upon the data shown for cases with 3db of cover, this increase in ductility is not as obvious. However one should be aware that in these cases, many of these tests either yielded the test bars, or failed the test specimen at, or near, the axial yielding load of the test bar. As one might expect, the data collected during this portion of the test is highly dependent upon the sampling rate of the data acquisition program and may not clearly indicate the exact point at which the test bar yielded.

Not all of the similarity between the hooked and headed tests are within the numerical data. Resemblance can also be seen in the extent and manner to which the specimens cracked during the tests. Headed tests which had no PVC as well as no stirrups (Fig. 3.1), showed cracking behavior that matched the degree to which its counterpart, hooked test "HK#3" (Fig. 3.3), cracked. Furthermore, the results of adding transverse reinforcement to these two tests (Fig. 3.2 and "HK#1" - Fig. 3.3), showed a significant increase in the amount of cracking in these specimens.

In summary, when headed test bars are configured with the same parameters as 180° hooked bars, the headed bars perform similarly, and in many cases, better than hooked test bars in terms of ultimate axial loads, ductility (loaded-end-slip), and degree of cracking. When analyzing data, one should consider the nature of the hooked test specimen. Due to imperfections inherent in bending and fabricating 180° hooks, a large scatter of data should be expected for such specimens. In addition, some parameters only tested one specimen for that group, so conclusions made on this limited amount of data should be made with caution. More data will be needed from future testing to better understand the headed bar - hooked bar comparison.

3.3 Bonded Length

Allowing the reinforcing bar to bond to the concrete appears to make a significant difference in the behavior of the "T"-headed test specimens. For tests with 2db of clear cover, the use of PVC provided an additional 50.5kN [11.4 kips] of ultimate axial load capacity in cases where no transverse reinforcement was used, but only as little as 19.1kN [4.3 kips] of additional load capacity when that group of specimens contained no stirrups (Table 3.4). When one bar diameter of cover is added and transverse reinforcing steel is used in the specimen, covering the bar with PVC produced tests with average ultimate axial loads of 241kN [54.14 kips]. However, as PVC is removed from this group of parameters, none of those tests appeared to yield the test bar even though the average ultimate axial loads were higher (256kN [57.52 kips]) than the 241kN [54.14 kips] of their PVC counterparts. Although the ultimate axial loads listed for this group (Table 3.4) appear to show that PVC decreases the capacity, in actuality it appears to have performed better by allowing for yielding to occur. As explained by the note in Table 3.4, data was highly variable for this group of parameters. It should be pointed out that one test in this group did, in fact, yield the bar at a reasonable load of 269kN [60.43 kips]. This indicates that a more indicative average for this group of parameters is more likely to be closer to 269kN [60.43 kips] than the mean of 241kN [54.14 kips] shown in Table 3.4.

The inclusion of PVC over the bar also effected the extent to which the specimen cracked at failure. Tests such as these differ from other headed tests in the manner that the top portion of the specimen appears to break off. This section of concrete remains relatively intact however, if the transverse reinforcement has been used in the specimen. Figs. 3.1 and 3.2 demonstrate the typical appearance of specimens that do not have any PVC covering the entire bar, both without and with stirrups, respectively. Results shown in Figs. 3.4 and 3.5 have the same parameters with the exception that they include the

PVC covering. A comparison of these two sets of figures show that when the bar is prevented from bonding to the concrete, the amount of overall cracking in the specimen is significantly less than in specimens that allow the bar to bond to the concrete regardless of the presence of transverse reinforcement. It is also apparent that headed specimens with PVC fail more suddenly than those without PVC. Those tests without PVC showed extensive cracking yet were still able to take on additional load. In essence, tests with these parameters allowed the specimen to soften and become more ductile. In contrast, headed bar specimens with PVC failed quite suddenly and displayed no significant preliminary cracking throughout the tests.

As discussed earlier, the presence of transverse reinforcement did nothing to effect the difference between specimens with and without PVC. The same behavior is noted for concrete clear cover. Just as stirrups did nothing to effect the "PVC vs. no PVC" relationship, so did the amount of cover. The observations explained above were made for specimens with both 2 and 3 bar diameters of cover. Therefore, differences in cracking behavior and physical appearance of the test specimen as a result of the inclusion or exclusion of PVC, is independent of both, the presence of transverse reinforcement, and the amount of cover provided in the headed test specimen.

3.4 Confinement Effects

Analysis of the results in Table 3.5 will show a couple of important characteristics of how the headed tests perform under 2 and 3 bar diameters of clear cover. The most obvious assumption one might make is that the ultimate axial load is directly proportional to the amount of clear cover provided. While the results of this test program prove this to be true, the extent to which one additional bar diameter of cover effects the capacity of the test specimen depends upon other factors.

In tests where PVC covered the test bar and no transverse reinforcement was included, the addition of one bar diameter of cover had a relatively dramatic effect on the ultimate axial load capacity of the specimen. These specimens with 2db of cover had an average axial load strength of 210kN [47.17 kips] and those with 3db of cover result in an average of 264kN [59.42 kips]. This increase of approximately 54.5kN [12.3 kips] provided enough additional capacity in the specimen to allow the test bars in that group to either yield or fail near to the yield load of the bar.

When transverse reinforcing steel was used to confine the test bar, the effects of additional cover were subdued. The differences in axial load capacity (as a result of increasing the cover from 2db to 3db) vary from 2.75kN to 16.7kN [0.62 kips to 3.76 kips], depending upon whether or not PVC was included in the specimen. In general, these differences are lowest when PVC was used. In groups where no PVC was used, the differences in ultimate axial load as a result of added cover seem to lessen as the number of stirrups increase. The difference is highest at 16.7kN [3.76 kips] when only 3 stirrups were provided. The difference is the lowest at 7.25kN [1.63 kips] in groups that provided 4 stirrups where the "4S2" spacing pattern (Fig. 2.2) was utilized. Even though Table 3.5 shows differences in axial load for 5 stirrups to be slightly higher (8.14kN [1.83 kips]) than the stirrup configuration "4S2", it is significantly lower than pattern "4S1". This may, in part, be due to the manner to which the transverse reinforcement was distributed throughout the embedment length. Considerable attention will be given to this topic in the section that follows.

As one might expect, the difference between tests with and without transverse reinforcement is significant. Table 3.6 shows that with 2db of cover, the addition of stirrups provided an increase in axial load capacity of as much as 80kN [18kips] when the bar was left uncovered and 55kN [12.5 kips] when the bar was covered with PVC.

Interestingly, in cases with 3db of cover, the presence of stirrups did not provide much, if any, additional load capacity for the specimen.

In summary, the use of stirrups to confine the headed test bar allows for a large increase in the ultimate axial load capacity of the specimen as compared to specimens without stirrups. If no transverse steel is provided and the bar is not allowed to bond to the concrete (PVC covering the bar), then the amount of cover provided also significantly increases the axial load capacity. However, when stirrups are provided, additional cover yields only small increases in the ultimate axial load of the headed specimen. Using PVC in these specimens only further minimizes these increases in capacity. Similarly, in groups with 3db of cover and PVC covering the test bar, adding transverse reinforcing steel to the specimen only provides negligible increases in axial load capacity.

3.5 Stirrup Spacing Patterns

One of the intentions of this testing program was to determine the effects of various transverse reinforcement spacing patterns. When comparing tests with these parameters only specimens that allowed the bar to bond to the concrete (no PVC) are considered. Not only will this ensure an equitable basis for comparison, but also will better simulate a manner in which the headed bar will be used in practice. There were four spacing patterns included in the testing program; specimens with 3 stirrups, 4 stirrups (all stirrups on the loaded side of head), 4 stirrups (one stirrup on the unloaded side of the head), and specimens with 5 stirrups (Fig. 2.2).

A comparison of all the patterns' results indicates that pattern #5S1 provided for the highest load capacity of the specimen both with 2db and 3db of cover (255kN [57.42 kips] and 264kN [59.24 kips], respectively). Pattern #4S1 took the least amount of load out of the four spacings with an average ultimate axial load of 231kN [51.87 kips] with

2db of cover and 242kN [54.43 kips] under 3db of cover. Careful analysis of these results, shown in Table 3.7, will reveal that spacing pattern #3S1 actually had a higher load capacity than pattern #4S1. Tests conducted using stirrup pattern #4S2 resulted ultimate axial loads of 246kN [55.20 kips] with 2db of cover and 253kN [56.83 kips] with 3db of cover. These results are very similar to the ultimate axial loads of stirrup pattern #3S1 under 3db of cover, but slightly higher than that pattern's performance with 2db of cover. In addition, the ultimate loads of spacing pattern #4S2 were higher than those of spacing pattern #4S1 for both 2 and 3 bar diameters of cover.

Other observations can be made that may help to explain the results of these stirrup spacing patterns. First of all, the closer a stirrup is placed to the head (on the loaded side of the head) the higher the ultimate axial load of the specimen. Notice that the spacing pattern that produced the lowest ultimate load, pattern #4S1, had its closest stirrup on the loaded side of the head just 50mm [2"] away (Table 3.7). The other 3 spacing patterns tested all have the closest loaded side stirrup 40mm [1.5"] or closer to the head. Secondly, a closer examination of Fig. 2.2 shows that the distribution of the transverse reinforcement is more evenly placed throughout the embedment length in all of the spacing patterns except pattern #4S1. With this pattern the stirrups seem to be concentrated more toward the head itself rather than evenly distributed through the embedment. Perhaps this may explain the loss of capacity in specimens with pattern #4S1.

It is apparent that a relationship exists between the proximity of the stirrups to the head and its effects upon the compression struts that result from applied test loads. Figure 3.6 demonstrates a way in which this relationship may be explained. The reasoning used here is based upon two important assumptions. First of all, the thickness of the compression strut is taken as 25mm [1"] to ease calculations. Second and more importantly, the bond force attained when the test bar is exposed to the concrete may be assumed as 0.25P. Studies done by Dahl (1995) show that in headed tests, approximately 75% of the applied is taken via the head itself while the remaining 25% may be attributed to the bond forces upon the test bar. This is important to note as an expression is developed for the strut angle "α" and how it relates to cover, the applied load, concrete strength, and stirrup placement (Fig. 3.6).

Development of the "α" equation offers insights and a way of explaining empirically the ramifications of the various parameters considered in this test program. It can clearly be shown that in cases where PVC has been used to cover the bar, the bond force is lost and the load is thus forced through the head and its ensuing compression struts. Because this loss of bond force has no effect on the strut capacity, an increase in load carried by the head can only result if the strut angle "α" is reduced. This allows for better utilization of the transverse reinforcing steel and thus may account for the overall increase in ultimate axial load capacity in the specimens that cover the bar with PVC. Another product of using PVC to cover the bar is the elimination of lateral "wedge" forces that act transverse to the specimen and, in essence, work to increase the "α" and reduce the axial load capacity of the specimen. Because the primary function of the stirrup is to impede this "wedging" action rather than reduce the strut angle, it should be expected that transverse reinforcement has more of an impact on specimens without PVC than those with PVC.

The simple presence of stirrups does, in fact, lower the strut angle "α" and increase the axial load capacity of the specimen. To show this effect, notice that group "P-NS-2DB-292" in Table 3.8 shows a compression strut angle of 56.95°. The addition of stirrups in group "P-3S1-2DB-292" reduces that angle to 55.4°. It is important to note that in both of these groups, PVC was used, therefore "wedging" action from an exposed bar's ribs was not a factor here in the ability of the transverse reinforcement to reduce "α".

Based upon this evidence, it would be reasonable that if more transverse reinforcement could be utilized within the embedment, a higher load capacity could be achieved in the headed specimen. Values listed for the variable "S" in Table 3.8 demonstrate how well the stirrups are utilized and help explain why some spacing patterns result in higher ultimate loads than do others. It was stated earlier that the distribution of the transverse reinforcement and proximity of a stirrup to the loaded side of the head, appeared to be a major factor affecting a stirrup pattern's axial load capacity. Notice that the horizontal projection onto the bar, "S" (Fig. 3.6, Table 3.8), is approximately equal to or larger than the closest distance of a loaded-side stirrup to the head (Table 3.7) for every spacing pattern except that of pattern #4S1. The larger the ratio of "S" to the "stirrup-to-head" distance, the more the amount of transverse reinforcing steel becomes involved in confining the headed test bar and the greater ability to which each stirrup is effective in confining the bar. Interestingly, in pattern #5S1, "S" exceeded the stirrup-to-head distance by the greatest amount, and consequently resulted in the highest average ultimate axial load of the four patterns tested. Conversely, pattern #4S1 had the lowest ultimate axial load resulting from its low ratios of "S" to the "stirrup-to-head" distance. While these observations only partially explain the spacing pattern's behavior in terms of ultimate axial load, it does not provide much insight into the ductility behavior of these headed tests. It is obvious that much more research is needed to provide a better understanding of spacing pattern effects in these areas.

CHAPTER 4

DESIGN AND CODE RECOMMENDATIONS

4.1 General

The research program at the University of Kansas, along with research at other public institutions, has been devoted to determining the behavior of, and obtaining a set of design equations for, the use of headed reinforcement in concrete structures. Already included in the Canadian reinforced concrete code, it is hoped that the design guidelines and code recommendations for headed bar presented in this chapter will provide a basis for the inclusion of headed reinforcement in the next issue of the American Concrete Institute Building Code (ACI-318).

In the previous chapter of this report, the results of this test program were presented with attention given to the effects of bonded length, clear cover, and transverse reinforcement. In addition, a comparison of headed bar test results against hooked bar test results were provided. In this chapter, those results will be compared with past research, expressions and current codes. From these evaluations, an expression to describe the required development length of a headed reinforcing bar will be obtained. Finally, this expression will be modified so that it fits within the current ACI Building Code philosophy structure and used as a basis for headed bar building code provisions.

4.2 Comparison to Previous Research and Expressions

As mentioned earlier, a study by Dahl (1995) indicates that the ultimate strength of a headed reinforcing bar is not entirely dependent upon the bearing capacity in the "headed" region. There also is a bond strength component that contributes to the overall capacity of the headed bar. Because of this fact, it is important that comparisons be made between the results obtained in this test program and the results predicted by expressions developed from past research. Another reason for comparing previous research equations is the reality that development length equations have long since been developed on the basis of bond strength. Consequently few, if any, development length expressions currently exist specifically for headed reinforcing bar due to the relative immaturity of this technology. Therefore, what follows is an observation of how the test results of this program compare to previous expressions for the development lengths of conventional straight and hooked reinforcing bars.

4.2.1 Headed Bar Specimens Without Transverse Reinforcement

4.2.1.1 Straight Bar Development Expressions

Studies by Mathey and Walstein (1961) and Ferguson and Thompson (1962) were used to derive an expression for the bond capacity of a straight bar. What resulted was as follows:

$$U = 35(f'c)^{1/2} \qquad (4\text{-}1)$$

where U is the average bond force per unit length and f'c equals the compressive strength of the concrete in psi.

Table 4.1 presents a summary of headed bar tests. The specimen identification code that appears in this table and others consists of a series of six terms (separated by a hyphen) and denotes the parameters involved in the tests. These terms are indicative of (in order): test group number (1,2,3 or 4), test specimen number (where SB, HK, and TH represent straight bar, hooked bar and headed bar tests, respectively), the use ("P") or absence ("NP") of PVC tubing to cover the reinforcing bar, stirrup pattern (Fig. 2.2) used for specimens with confining steel ("NS" denotes no transverse reinforcement present in the specimen), concrete clear cover (in bar diameters), and the test bar lead length (mm).

Shown in Table 4.1 headed bar specimens with 305mm [12"] of exposed bar have an average test/prediction ratio of 1.21 and a standard deviation of 0.0727. As expected, the equation loses its ability to predict the behavior of the headed bars where the bar is covered with PVC and the bond strength component is no longer a means to equate the axial test load. The average test/prediction ratios of 1.58 and 2.00 (σ = 0.0502, σ = 0.0337) for tests of 2db and 3db of cover, respectively, show an increased load capacity measured by testing specimens covered with PVC and demonstrate the expression's ineffectiveness in predicting the capacity of "smooth bar" headed reinforcement.

Some of the most recognized research in development length expressions came from work by Orangun, Jirsa, and Breen (1975, 1977). Using nonlinear regression analysis, an expression for average bond stress was developed and normalized with respect to the square root of the concrete strength, f'c. This equation:

$$u = [1.22 + 3.23(C_m/d_b) + 53(d_b/l_s)](f'c)^{1/2} \qquad (4\text{-}2)$$

was developed on a basis of 62 test specimens and later refined to obtain a more concise and conservative form:

$$u = [1.2 + 3(C_m/d_b) + 50(d_b/l_s)](f'c)^{1/2} \qquad (4\text{-}3)$$

where u = average bond stress (psi)
$f'c$ = concrete compressive strength (psi)
d_b = bar diameter (in.)
l_s = splice length or development length (in.)
C_m = the smaller of:
1) concrete bottom cover (in.)
2) concrete side cover (in)
3) one-half the clear spacing between spliced bars (in.)

Applying this expression to the test results, side cover is always taken as 102mm [4"]. Therefore, C_m , is always equivalent to the clear cover listed for the specimens in this test program. It also is assumed that l_s is equal to the length required to develop the reinforcing bar, or in the case of beam-end specimens compared here, the "bonded length".

Shown in Table 4.2, the comparison of test results to those predicted by this expression demonstrates a trend similar to the observations made in regard to Eq. 4-1. Tests in which PVC does not cover the bar, once again show a closer similarity to Eq. 4-2 with an average test/prediction ratio of 1.19 as opposed to those tests with PVC covering the bar.

In recent years, a substantial quantity of research has been conducted at the University of Kansas in the area of reinforcement bar bond strength and development. Some of this study can be attributed to a report by Darwin, McCabe, Idun, and Schoenekase (1992). Using linear regression techniques, the results from one hundred forty-seven splice and development tests were analyzed and used to derive a development length expression for each individual bar size included in the test program. Because only one bar size, No.25M [No.8], is discussed in this report, the corresponding equation for No.8 bars as determined by Darwin et al. (1992) takes the following form:

$$[A_b f_s/(f'c)^{1/2}] = 6.36 l_d [C + 0.5d_b][0.92 + 0.08(C_{max}/C_{min})] + 338.5 \qquad (4\text{-}4)$$

A the original study indicates, this expression was further modified to a more general and conservative form descriptive of all reinforcing bar sizes. Using a dummy variable method, the study concluded an expression that can be summarized as:

$$[A_b f_s/(f'c)^{1/2}] = 6.67 l_d [C + 0.5d_b][0.92 + 0.08(C_{max}/C_{min})] + 300A_b \qquad (4\text{-}5)$$

where the variables for Eqs. 4-4 and 4-5 are as follows:

A_b = average bond stress (psi)
$f'c$ = concrete compressive strength (psi)
f_s = bar yield stress (psi)
d_b = bar diameter (in.)
l_d = splice length or development length (in.)
C = C_{min} = the smaller of, and C_{max} = the larger of:
1)C_b:concrete bottom cover (in.)
2)C_s: defined as the smaller of: a)concrete side cover (in.)
b)one-half the clear spacing between spliced bars. (in.)

A comparison of the test results to the expressions set forth in Eqs. 4-4 and 4-5 can be summarized in Tables 4.3a and 4.3b, respectively. Notice again the ineffectiveness of the expressions for predicting the test results of specimens with test bars covered with PVC. Conversely, specimens that leave the test bar exposed to bond with the concrete exhibit test prediction ratios very close to 1.0. It is interesting to note that Eq. 4-4, on the average, predicts values that are slightly unconservative (ave. test/prediction ratio = 0.96) for specimens without PVC. Equation 4-5, which is a more general expression, does indeed produce an average test/prediction ratio greater than 1.0 (1.19) for the same specimens.

Additional studies by Idun and Darwin (1995) used Eq. 4-5 as a basis to develop bond strength equations that re-examine the variables for defining concrete strength and bar spacing. From their research, development length/bond strength equations were developed using the standard 1/2 power of f'c, as well as an improved 1/4 power. These expressions are as follows:

$$[A_b f_s/(f'c)^{1/4}] = [63l_d(C + 0.5d_b) + 2280A_b][0.918 + 0.082(C_{max}/C_{min})] \qquad (4\text{-}6)$$

$$[A_b f_s/(f'c)^{1/2}] = [8.8l_d(C + 0.5d_b) + 220A_b][0.907 + 0.093(C_{max}/C_{min})] \qquad (4\text{-}7)$$

The accuracy with which these equations predict the headed test results is presented in Tables 4.4a and 4.4b. A closer look at these tables show no noticeable differences in the average test/prediction ratios for "no PVC" test specimens between the two expressions. Both equations yield conservative ratios of 1.12. On the other hand, while specimens with test bars covered with PVC continue to produce high test/prediction ratios, the accuracy of Eq. 4-6 is better, at 2.69 and 3.71, with the 1/4 power than that of Eq. 4-7, at 3.38 and 4.44, for 2 and 3 bar diameters of cover, respectively. The significance of this difference is probably somewhat limited though due to the higher order of magnitude of the coefficients in Eq. 4-6 compared with the coefficients in Eq. 4-7.

Nonetheless, using the 1/4 power of f'c, Eq. 4-6 gives a more unconservative test/prediction ratio than using the 1/2 power of f'c.

In addition to evaluating the test results with regard to past research, comparisons also were made with existing equations set forth by ACI. Bond strength or development length equations presented in ACI 318-95 and ACI 408.1R-90 for both straight bar and hooked reinforcing bar are evaluated here in this report, and a summary of these comparisons can be found in Table 4.5. It should be noted, however, that due to the inability of these particular expressions to provide for capacity in the anchorage system when the bonded length is equal to zero, only results of specimens without PVC are compared.

As defined in section 12.2.3 of ACI 318-95, the development length for a straight deformed bar or wire is described by the following expression:

$$(l_d / d_b) = [3f_y / 40(f'c)^{1/2}][\alpha\beta\gamma\lambda / ((C + K_{tr})/d_b)] \qquad (4\text{-}8)$$

where the quantity $(C + K_{tr})/d_b$ is less than or equal to 2.5. After removing the factors α,β,γ, that account for location, surface coating, and size of the bar, respectively; as well as the factor, λ, for lightweight aggregate; Eq. 4-8 can be rearranged to express bond strength in terms of the bar area, A_b, similar to the previous expressions (Eqs. 4-2 thru 4-7). After rearrangement, Eq. 4-8 becomes:

$$[A_b f_s/(f'c)^{1/2}] = [(40 l_d A_b) / 3C] \qquad (4\text{-}9)$$

where (d_b / C) must be greater than or equal to 0.4, and A_b is the area of the bar (in.), f_s equals the yield stress of the bar (psi), f'c is the compressive strength of the concrete (psi), l_d equals the development length of the bar (in.), and C is the cover dimension (in.). It should be noted that in these comparisons, no transverse reinforcement is used and hence, $K_{tr} = 0$.

As pointed out in the previous sections of this report, headed reinforcing bars can develop the strength of the bar over a much shorter length than its straight bar counterpart. Based upon this knowledge, it is reasonable to expect that development length equations set forth by ACI for straight bar anchorages would be grossly conservative when compared with headed bar anchorages. Comparisons of Eq. 4-9 to the headed bar test results demonstrates the degree to which the ACI expression underestimates the strength of the headed bar, shown by a high 8.36 average test/prediction ratio (Table 4.5).

As recently as 1990, an ACI 408 committee report proposed an expression (section 1.1.2 and 1.1.3) describing the development length of bars sized No.7 and larger as:

$$l_d = 2200A_bf_y / 60000(f'c)^{1/2} \tag{4-10}$$

Rearranging this expression to fit the form of the previous equations, it can be written as:

$$A_bf_s/(f'c)^{1/2} = 27.27l_d \tag{4-11}$$

Although Eq. 4-11 continues to underestimate the strength of a headed test bar (ave. test/prediction ratio = 1.632), it is still more accurate than that of the average test/prediction ratio of Eq. 4-9 (Table 4.5).

4.2.1.2 Hooked Bar Development Expressions

One last comparison that can be drawn to this particular group of test results is to evaluate how they compare to equations for similar hooked anchorages with no transverse reinforcement. Described in section 12.5.2 and 12.5.3 of the ACI 318-95 code, the basic development length equation is presented as:

$$l_d = 1200d_bf_y / 60000(f'c)^{1/2} \tag{4-12}$$

After making the necessary modifications to present the equation in terms of bar area and applying a 0.7 reduction factor per section 12.5.3.2 to account for the degree of clear cover, the resulting expression is shown to be:

$$A_b f_s/(f'c)^{1/2} = 71.43 l_d A_b / d_b \qquad (4\text{-}13)$$

An evaluation of the test results against this equation (ave. test/prediction ratio = 0.806) summarized in Table 4.5, shows the expression to be an unconservative means of predicting the development length of a headed reinforcing bar.

One important point should be mentioned in regards to the comparisons presented above. Few tests were conducted in which specimens had no transverse reinforcement, and only a small number of these allowed the bar to be exposed to the concrete (as in a typical application). Consequently, conclusions and inferences about these test specimens must be made while keeping in mind the small amount of data. Still yet, standard deviations presented in all of the tables demonstrate a low scatter of the data and may show the reliability of these data points to be good, even though the data is somewhat limited in quantity.

4.2.2 Headed Bar Specimens With Transverse Reinforcement

4.2.2.1 Straight Bar Development Expressions

While a limited amount of data exists for specimens without transverse reinforcement, an extensive collection of data can be presented for tests that include transverse reinforcement. In some cases, the expressions presented above were extended to include the effects of additional confining steel. A comparison of these "modified" equations follows.

Presented in its original form, Eq. 4-3 was studied further to develop a term to express the effects of transverse reinforcement on bond strength. Orangun et al. (1975,

1977) suggested that an additional term be added to the right-side of Eq. 4-3 so that the expression reads:

$$\mathbf{u = \{1.2 + 3(C_m/d_b) + 50(d_b/l_s) + [(A_{tr}f_{ytr}) / 500sd_b]\}(f'c)^{1/2}} \qquad (4\text{-}14)$$

where the additional term $[(A_{tr}f_{ytr}) / 500sd_b]$ must be less than or equal to **3.0**, and A_{tr} equals the cross-sectional area of a single transverse stirrup (one leg), f_{ytr} is the yield stress of the confining steel, and s equals the maximum stirrup spacing. Putting this equation into a form compatible with the other expressions presented here, it can be described in the following manner:

$$\mathbf{[A_b f_s/(f'c)^{1/2}] = [3.23\pi l_d(C + 0.378d_b + (0.00062A_{tr}f_{ytr} / s)) + 212A_b} \qquad (4\text{-}14a)$$

The reasoning behind imposing the limit of 3.0 on this additional term is to prevent the equation from predicting a value of "u" higher than what is possible due to a pullout failure of the reinforcing bar. Because headed test bars react the applied load primarily through bearing rather than the steel-concrete bond (Dahl 1995), it is reasoned that this limit is not appropriate when used for headed reinforcement. Consequently, comparisons of the test results are made to Eq. 4-14a, both considering, and not considering, this limit.

Tables 4.6a and 4.6b both present a summary of these comparisons. It is interesting to note the effectiveness to which Eq. 4-14a predicts the test results when no limits are placed upon K_{tr}, as is demonstrated by the test/prediction ratios for cases with $3d_b$ of cover (1.23, 1.05, 1.12, 1.12 for stirrup patterns #3S1, #4S1, #4S2, and #5S1 respectively). When K_{tr} is limited, these cases show much higher test/prediction ratios (1.23, 1.13, 1.21, 1.26). Test/prediction ratios for cases with $2d_b$ of cover show an even more pronounced increase when the limit is imposed, going from 1.46, 1.23, 1.28, and 1.30, to 1.46, 1.35, 1.40, and 1.50 (Table 4.6a and 4.6b). Increases in ratios are more pronounced with $2d_b$ of cover due to the greater importance of confining steel when smaller amounts of cover are used. In instances where stirrup pattern #3S1 is used, there is no difference in test/prediction ratios when imposing or not imposing the limit. This result is because pattern #3S1 does not contain enough steel spaced over the bonded length such that the limit would be implemented. Therefore, the test/prediction ratios of 1.46 and 1.23 for 2 and 3 bar diameters of cover are the same in both Table 4.6a and 4.6b. In summary, by limiting the value attainable for K_{tr}, Eq. 4-14a will fail to accurately account for the benefits of additional confinement from transverse reinforcement on headed reinforcement.

From the expression presented in Eq. 4-6, modifications were made here to express the contribution of confining steel to the bond strength equation. The additional term accounting for this is expressed as a quantity describing the total cross-sectional area of the confining steel in the development region. Allowance also is made for the manner in which the specimen fails. This modified expression, developed using the 1/4 power of f'c, is presented as:

$$[A_b f_s/(f'c)^{1/4}] = \{[63l_d(C+0.5d_b)+2280A_b][0.918+0.082(C_{max}/C_{min})] +(2187NA_{tr} / n)+202\} \qquad (4\text{-}15)$$

where the additional term **($2187NA_{tr}$ / n)** uses a general constant to express the broad range of confining steel yield stresses, f_{ytr}, that may be used. As mentioned before, the manner of specimen failure can be shown in that when n equals 1, $C_b<C_s$, where a "top-side" splitting crack forms. When $C_s<C_b$, however, n becomes equal to the total number of bars being developed or spliced in the steel layer as side cracking predominates. Table 4.7a summarizes the comparisons of the test results made with Eq. 4-15. Table 4.7b presents the comparisons with specimens containing pattern #4S1, a transverse steel configuration in which a stirrup was placed directly behind the headed portion of the test bar (Fig. 2.2). It is, therefore, debatable whether to consider this stirrup in the development length region. Table 4.7a presents test/prediction ratios for these specimens

using a value for N equal to 3. Table 4.7b, on the other hand, uses a value of N equal to 4 and allows the expression to be slightly more effective in predicting the test results by lowering the test/prediction ratio by an average of 0.05 (1.29 to 1.23 for $2d_b$ of cover and 1.19 to 1.14 for $3d_b$ of cover).

Overall, test/prediction ratios appear to be higher for Eq. 4-15 than those displayed by Eq. 4-14a. Equation 4-15 can be contrasted with Eq. 4-14a in that there is no limitations placed upon the K_{tr} term as there is in the later. In addition, comparisons to Eq. 4-15 differ from the comparisons made to Eq. 4-14a, when evaluating how the expressions account for increases in the amount and distribution of confining steel. Table 4.7a exhibits nearly the same test/prediction ratios for specimens with patterns #4S1, #4S2, #5S1 when a given amount of cover is provided (1.29, 1.30, 1.31 for $2d_b$ of cover and 1.19, 1.22, 1.22 for $3d_b$ of cover). However, Eq. 4-14a showed noticeable differences in the test/prediction ratio when the amount of steel was changed or distributed differently. This behavior may be primarily due to the absence of a variable in Eq. 4-15 to measure the transverse steel spacing and the presence of such a variable ("s") in Eq. 4-14a.

Test specimens with stirrup pattern #3S1 continue to yield test/prediction ratios that are more conservative than other spacing patterns although the degree to which these ratios are more conservative is much less pronounced that the ratios for this pattern described by Eq. 4-14a. One may conclude from this that the axial load capacity of a headed test bar is greatly enhanced by confining steel, even if the quantity of that steel is somewhat minimal.

Problems again arise with respect to the transverse steel as expressions developed by ACI attempt to evaluate its contribution to the bond strength of the reinforcement. Recall that Eq. 4-9 contains a limiting value on the quantity (d_b / C). When confining steel is used to increase bond capacity of the specimen, this quantity becomes (d_b / ($C + K_{tr}$)), yet like the previous term this quantity also must be greater than or equal to 0.4. Keeping in mind this limitation, the new form of Eq. 4-9 can now be presented as:

$$[A_b f_s/(f'c)^{1/2}] = [(40 l_d A_b) / 3(C + K_{tr})] \tag{4-16}$$

The limitation, like before, is called into question on the basis of the headed test bar having a primarily bearing type behavior and an unlikely possibility of a pullout failure. Thus, test results are again compared to this equation using, and not using, the 0.4 limitation. Tables 4.8a and 4.8b illustrate the effects of the limit as all test/prediction ratios are curtailed to a range of approximately 15.0 - 18.0. Unfortunately, the extremely high test/prediction values show this fact to be somewhat irrelevant, and point out only that equations provided by section 12.2.3 of ACI 318-95 are conservative if applied to headed reinforcement.

These limitations are also a factor when investigating how well the test results compare to an expression described in section 1.1.2.2 of the ACI 408.1R-90 committee report. The basic development length expression using transverse steel given in that report is presented as the following:

$$l_d = 5500 A_b f_y / 60000 K (f'c)^{1/2} \tag{4-17}$$

where K is a confinement factor determined (with C as the smaller of C_s or C_b) by:

$$[0.5d_b + C + K_{tr}] < \text{ or } = 3d_b$$

The conditions and parameters that influence the results of this research dictate that the first of these two expressions be evaluated. Looking at this expression closely, one will see that once $2.5d_b$ of cover is provided, no additional benefit comes from adding transverse steel. Therefore, when the limitation of $3d_b$ on the confinement factor, K is imposed, specimens with 3 bar diameters of cover receive no additional capacity from this code equation for the transverse steel within the specimen. Similarly, those specimens with 2 bar diameters of cover only receive a fraction of the additional capacity provided by the transverse steel. This fact is evident by observing Tables 4.9a and 4.9b in which Eq. 4-17, rewritten into the form:

$$[A_b f_s/(f'c)^{1/2}] = 10.909\, l_d K \qquad (4\text{-}18)$$

becomes much more conservative (higher test/prediction ratios) when these limitations are placed upon the equation.

Similar to the comparisons made to Eq. 4-15, test/prediction ratios calculated with respect to Eq. 4-18 are consistent among the various stirrup patterns #4S1, #4S2, #5S1 (Table 4.9a). When limitations on the effects of confining steel are enforced (Table 4.9b), this trend is no longer evident.

4.2.2.2 Hooked Bar Development Expressions

Consideration also must be given to the code written for hooked reinforcing bars where attention is given to cases that include transverse reinforcement. As presented earlier in Eq. 4-12, the basic development length expression, as set forth in ACI section 12.5.2 can be multiplied by a factor of 0.7 for cover considerations explained in ACI section 12.5.3.2. Adding the effects of stirrups, the equation also must be multiplied by an additional factor of 0.8 After applying these factors and rearranging the equation such that it is presented in a form consistent with the other equations, the expression is given as:

$$[A_b f_s/(f'c)^{1/2}] = 102.04\, l_d A_b /d_b \qquad (4\text{-}19)$$

One should understand, however, that this expression only will apply to specimens with stirrup patterns #4S1, #4S2, #5S1. The spacing provided in pattern #3S1 of 125mm [5"] violates the criteria set forth in ACI318-95 section 12.5.3.3 in that the stirrups are spaced at greater than 3 bar diameters. Therefore, Eq. 4-13 applies to specimens with this spacing pattern. A summary of how the test results compare to this equation is presented in Table 4.10. Notice that with the exception of specimens with stirrup pattern #3S1, test/prediction ratios indicate that the relationship set forth by ACI for hooked bars would be somewhat unconservative if that same equation were applied to headed reinforcing bar. This expression, like the previous ones continue to underestimate the benefits of transverse steel to headed bars when only a minimal amount is used or spaced at large distances. This situation exists in specimens with stirrup pattern #3S1, which display average test/prediction ratios of 1.21 for cases with $2d_b$ of cover and 1.31 for cases with $3d_b$ of cover.

4.2.3 Comparisons to Straight Bar and Hooked Bar Specimens

Test results presented here in this report are not limited to specimens with headed test bars only. Specimens with straight and 180° hooked test bars also were evaluated. Thus, it is important to give some consideration to how the data generated from these tests compare to some previous research and existing code equations.

A total of three tests were conducted in which the straight bar test specimens include transverse reinforcement. In all three tests, the predicted values determined by Eq. 4-14a and 4-15 were less than 1.0 with test/prediction ratios according to Eq. 4-14a being the more unconservative of the two expressions (Table 4.11). Limited conclusions can be drawn from the small amount of data presented here, however, it is apparent that the data collected from these tests demonstrates reasonable test/prediction ratios when compared to either Eq. 4-14a or 4-15 despite being significantly less than 1.0. The unconservative nature of these ratios (<1.0) may be attributed to differences in test procedure and specimen configuration.

An evaluation of how the hooked test results obtained in this test program compare with existing ACI code can be summarized in Table 4.12. Specimens that do not contain a test bar sheathed with PVC exhibit test/prediction ratios very close to 1.0, showing a close correlation with section 12.5 of the ACI 318-95 code (Eq. 4-13). Note that most of the test results presented in this table are the results of specimens that do contain PVC over the test bar. Consequently, the test/prediction ratios are high and reflect the increased capacity of the specimen when the test bar is prevented from bonding to the concrete.

4.3 Basis For Headed Bar Development Expression

4.3.1 Further Examination of studies by Orangun et al. (1975, 1977) and Idun and Darwin (1995).

Over the course of this test program, it has become apparent that in absence of large amounts of clear cover, a necessary quantity of confining steel is required to achieve the yield strength of a headed reinforcing bar. For this reason, further investigation of the results of specimens that include transverse reinforcement is provided. In doing so, a closer look is given to comparisons made of the test results to Eqs. 4-14a and 4-15 -- two development length expressions with wide acceptance and recognition in the concrete design industry.

Using the abundance of results from specimens with transverse reinforcement, best-fit lines were plotted for $A_b f_s/(f'c)^{1/2}$ (obtained from test results) versus the quantity:

$$l_d[C + 0.378d_b + (0.00062A_{tr}f_{ytr} / s)]$$

extracted from Eq. 4-14a. This fit also was performed for the term $A_b f_s/(f'c)^{1/4}$ versus the quantity:

$$\{l_d[2(C_{max}/C_{min})(C + 0.5d_b) + 22.39C + 11.195d_b]\} + \{72.38A_b[(C_{max}/C_{min}) + 11.2]\} + \{846.69NA_{tr} / n\}$$

taken from Eq. 4-15. Using linear regression analysis, these best-fit lines were determined not only for the entire group of results but separate lines also were fit through data for 2 and 3 bar diameters of cover. These best-fit lines are graphically presented in Figs. 4.1a, 4.1b, 4.2a, and 4.2b along with each lines' corresponding coefficient of determination.

After careful study of these figures, some important observations can be made, First of all, the decision whether or not to restrict the contribution of transverse reinforcement to the bond capacity of the specimen significantly effects the scatter of the data. Notice that in Fig. 4.1b, when the value of $((A_{tr}f_{ytr}) / 500sd_b)$ is limited, the results are collated to two distinct groups. However, this data has virtually no effect on the value of the y-intercept when a line is fit through all of the data. Secondly, there is a noticeable difference in the slopes of lines fit through results of $2d_b$ and $3d_b$ cover specimens. This result may indicate that these two expressions do not accurately describe the effects of cover when applied to headed reinforcement. With each equation, however, the slopes of the lines fit through results of specimens with $3d_b$ of cover is always smaller than that of results of specimens with $2d_b$ of cover. It also is interesting to point out that when a line is fit through only data produced by specimens with $3d_b$ of cover for Eq. 4-14a, the corresponding y-intercept produces a value of $A_bf_s/(f'c)^{1/2}$ equal to 808.4. Because this value is higher than that required to yield a 75 ksi test bar confined in 5000 psi concrete (806.5), this infers that the head by itself is sufficient enough to effectively develop the bar and no additional development length is necessary.

As a calibration of the test results presented here, best-fit lines also were positioned among the results for specimens with straight test bars and transverse reinforcement. This plotting was done for both Eqs. 4-14a and 4-15, and is shown in Figs.

4.3 and 4.4. Notice the strong correlation to the equation developed by Idun and Darwin (1995), apparent in the similar slopes (Fig. 4.4). In contrast, Fig. 4.3 shows that the slope of the best fit line for this data is somewhat different than that predicted by Orangun et al. (1975, 1977). Again it is important to note that, by only presenting three data points, it is obvious that more data is needed for an accurate assessment of these trends.

4.3.2 Statistical Basis of Observations

During the course of analyzing the results of this test program, it became obvious that some statistical background should be provided so as to demonstrate the qualities and characteristics of the observations made within this section.

Note in Figs. 4.1-4.4 that r^2, the coefficient of determination, is presented for each best-fit line. This statistic is presented to give an indication of how strong the data is correlated to the line in question. The closer r^2 is to +1.0 or -1.0, the stronger the correlation. However values close to zero can infer something other than just a weak correlation. As Khazanie (1990) points out, a correlation coefficient (square root of r^2) near zero can mean one of two things. It may indicate no clear pattern of dependence between x and y and, therefore, the data is perhaps widely scattered resulting in a best fit line with a slope near or at zero. Secondly, a relationship among the data may in fact exist, although it may not be of a linear variety. Such an equation may be described by a higher order equation rather than a linear expression.

Values of r^2 presented in Figs. 4.1 and 4.2 are, in general, higher for the best fit lines determined from the expression by Idun and Darwin (1995). It also is apparent in either expression that as the cover is increased and the slope decreased, the values for r^2, and likewise r, diminish significantly. Because so little data is attributable to cases for 2 and 3 bar diameters of cover, the scatter of data may be significant enough to cause the lower values of r^2 , even though the standard deviation for these groups of data are small enough to suggest the scatter is not that severe. Conversely, in cases where a line is fit through all of the data points, low standard deviations of each test group would lead one to believe that the amount of scatter due to testing error is insignificant in its ability to effect the values of r^2 . Therefore, the relatively low r^2 values of 0.2372 and 0.4813 for lines fit through all of the data regarding Eq. 4-14a and 4-15, respectively, can most likely be explained by the fact that the average bond strength, $A_b f_s/(f'c)^{1/2}$ for headed reinforcement is related to these equations not by a linear fashion, but more likely, by a nonlinear, higher order function. In addition, it is possible that the dependence of "Y" ($A_b f_s/(f'c)^{1/2}$ or $A_b f_s/(f'c)^{1/4}$) on "X" (expression pulled from Eq. 4-14a and 4-15 discussed previously) may be minimal due to the fact that "X" is not a unique value, but is instead a function other variables (l_d ,d_b , C, A_{tr} , etc.). In summary, the statistic r^2 does not give a good indication of trends present in data when few data points are available or when chances that a nonlinear relationship among the data exists. In addition, the statistic has no ability to infer what is, or what is not, an acceptable correlation to a particular trend.

In efforts to present a solution to these faults, a "test for goodness of fit" is provided using the statistic X^2 . This test indicates whether or not enough evidence is present to prove the best fit lines (Figs. 4.1-4.4) to be unacceptable. It does not, however, demonstrate how good the lines are if they are deemed acceptable. The X^2 statistic can be described as follows:

$$\mathbf{X^2 = \Sigma_{i=1}(Observed\ Value_i - Expected\ Value_i)^2 / Expected\ Value_i} \qquad (4\text{-}20)$$

Values for X^2 were calculated for each best fit line presented in Figs. 4.1 thru 4.4. These X^2 results are presented along with the acceptable X^2 values in Table 4.13. Acceptable values of X^2 are determined at a 5% level of significance (95% level of confidence) according to "v" degrees of freedom where "v" is equal to the number of observations minus 1 (Table 4.14).

After observation of the results shown in Table 4.13, it is obvious that, for the most part, best fit lines plotted through data compared against Eq. 4-14a cannot be proven to be of unacceptable quality. In other words, the null hypothesis that the data is accurately described by its best fit line, cannot be rejected. Notice, however, that this null hypothesis is rejected for every line plotted in regards to Eq. 4-15. This result is more than likely due to the high orders of magnitude that the data takes on and therefore the chi-square test may perhaps be ineffective for these lines.

In attempts to investigate other statistics, "Analysis of Variance" (ANOVA) tables were prepared for each of the best fit lines and the data evaluated with regard to a F-distribution curve. In this form of hypothesis testing, the null hypothesis was assumed as the following: "The variance, σ^2_1 ,of the data with respect to the expression in question (Eq. 4-14a or Eq. 4-15) is equal to the variance, σ^2_2 , of a best-fit line through that data plotted with relation to that same expression" (i.e. $\sigma^2_1 = \sigma^2_2$). A summary of ANOVA results can be found in Table 4.15. Depicting the results of the F-distribution curves graphically, Fig. 4.5 indicates that the null hypothesis should be rejected for lines plotted through all of the data based on a 5% level of significance (95% level of confidence). Based on that same level of significance, most lines plotted through data for $2d_b$ or $3d_b$ of cover do not allow that null hypothesis to be rejected. In summary, it would require an extremely low significance level for the null hypothesis to not be rejected when considering lines plotted through all of the data points.

What do all of these statistics mean? Which equation, 4-14a or 4-15, describes the headed bar test results the best? Because each expression has positive and negative qualities (depending on the statistic evaluated), it cannot be clearly shown from these statistics either of the equations to be the superior. While best fit lines in regard to Eq. 4-14a seem to have poor r^2 and such values for Eq. 4-15 lines are somewhat higher than for Eq. 4-14a lines, tests of goodness of fit indicate a poor fit for each of the Eq. 4-15 lines. The statistics presented above once again point out the inability of these expression to accurately describe the effects of cover on headed reinforcing bar when transverse reinforcement is used. This behavior is not only evident in the dramatic change in r^2 values as the cover increases (slope of best-fit line decreases), but also by the large disparity in the levels of significance for each line (F-distribution curves) as the cover is varied.

Based on the uncertainty surrounding the coefficient of determination, indications of good correlations or fit of lines from chi-squared tests, lower test/prediction ratios, and higher significance levels among the "all data" lines (Fig. 4.5), Eq. 4-14a appears as a more qualified expression than Eq. 4-15 on which to base best-fit lines and subsequent expressions describing headed bar development lengths.

4.4 Presentation of Headed Bar Development Length Equation

Due to the reasons previously discussed, the best-fit line, plotted through all data compared to Eq. 4-14a, will serve as a template out of which to mold an expression for headed bar development length. Several modifications will need to be made to this equation before it can be presented in a useful design form and structure compatible with ACI code. Presented in original form, the equation of this best-fit line is as follows:

$$[A_b f_s/(f'c)^{1/2}] = \{2.595\, l_d[C + 0.378d_b + (0.00062A_{tr}f_{ytr} / s)]\} + 663.65 \qquad (4\text{-}21)$$

Rearranging the terms, the expression takes the form:

$$\{[(A_b f_s/(f'c)^{1/2}) - 663.65] / 2.595\} = l_d[C + 0.378d_b + (0.00062A_{tr}f_{ytr} / s)] \qquad (4\text{-}22)$$

After simplification the equation can be described as follows:

$$l_d = \{[(A_b f_s / 2.6(f'c)^{1/2}) - 255.68] / [C + 0.378 d_b + (0.00062 A_{tr} f_{ytr} / s)]\} \quad (4\text{-}23)$$

Assuming that the value of the Y-intercept is directly proportional to the area of the bar, similar to the assumption made by Orangun et al. (1975, 1977), 255.68 can be replaced by the value $336.24A_b$. Due to the dissimilar nature of headed reinforcement and straight deformed bar, this conjecture will require further research and investigation. Having said this, the equation now follows as:

$$l_d = \{[(A_b f_s / 2.6(f'c)^{1/2}) - 336.24 A_b] / [C + 0.378 d_b + (0.00062 A_{tr} f_{ytr} / s)]\} \quad (4\text{-}24)$$

In efforts to simplify this expression, minor adjustments were made. Among them, the numerator of the second term, $336.24A_b$, was modified to $340A_b$. To counteract the effects of this change on the development length, the term $0.378d_b$, within the denominator of the equation, was eliminated. As shown in Fig. 4.6, the expression can now be presented as:

$$l_d = \{[(A_b f_s / 2.6(f'c)^{1/2}) - 340 A_b] / [C + (0.00062 A_{tr} f_{ytr} / s)]\} \quad (4\text{-}25)$$

To demonstrate the negligible effects of these deviations, one needs only to look at Table 4.16 which provides a summary of development lengths for 75 ksi, No. 25M bar, and a f'c of 5000 psi, before and after the expression was modified.

Current format of ACI 318-95 - Chapter 12 presents development length equations in terms of bar diameter rather than bar area. Keeping this approach, an alternate expression based upon Eq. 4-25 was developed to express the headed bar development length in terms of bar diameter rather than bar area. In the process of determining this alternate equation, several parameters were normalized within the expression including concrete compressive strength, f'c, yield stress of the developing bar, f_y, and concrete clear cover. In addition, a correction factor was developed to allow this alternate expression to account for instances where an undeformed, smooth bar is being developed.

In efforts to explain how this alternate expression was obtained, the following modifications were made to Eq. 4-25. To account for various bar yield stresses, the best-fit line was shifted downward (Fig. 4.7), using the bar yield stress characteristic of these tests as a benchmark. Hence, the Y-intecept value of $340A_b$ was multiplied by a factor, $(f_y / 75000)$. Reworking Eq. 4-25 into an expression of bar diameters and noting that $(f_s = f_y)$, the equation can be shown as:

$$l_d = 0.302 d_b f_y [(1 / (f'c)^{1/2}) - 0.0118] [d_b / (C + (0.00062 A_{tr} f_{ytr} / s))] \qquad (4\text{-}26)$$

Normalizing the expression with respect to 3 bar diameters of cover, the equation then becomes:

$$l_d = 0.10 d_b f_y [(1 / (f'c)^{1/2}) - 0.0118] [3d_b / (C + (0.00062 A_{tr} f_{ytr} / s))] \qquad (4\text{-}27)$$

For purposes of clarity, the coefficient on the second term can be rounded from 0.0118 to 0.0125. After shifting the line once again to account for the concrete compressive strength, the Y-intercept coefficient, now 0.0125, is multiplied by the quantity, $(5000 / (f'c)^{1/2})$. The resulting expression after simplification reads:

$$l_d = [0.0116 d_b f_y / (f'c)^{1/2}] [3d_b / (C + (0.00062 A_{tr} f_{ytr} / s))] \qquad (4\text{-}28)$$

where typical development lengths from this equation can be seen in Table 4.17. Arranging this equation to express the ultimate bond strength, Fig. 4.8 presents a graph that includes a plot of a third line. It is this third line, predicted by Eq. 4-28, that represents the alternate equation mentioned earlier. This expression also can be written in a form consistent with the previously discussed equations and follows as:

$$[A_b f_y / (f'c)^{1/2}] = 22.5689\, l_d (C + (0.00062 A_{tr} f_{ytr} / s)) \qquad (4\text{-}29)$$

As mentioned earlier, a correction factor was developed to account for a smooth, undeformed headed bar. Instances such as this would apply to test specimens in which PVC sheathing was used to cover the test bar. To determine the value of this factor, three groups of specimens were analyzed, all of which contained no transverse confining steel.

The first group of results 2-TH07,08,09-NP-NS-2DB requires a development length equal to 19.78" based on the expression provided in Eq. 4-28. Because the configuration of this group of tests provides an embedment distance equal to 11.38", only a percentage (11.38 / 19.78) of the bar's yield strength is attained (34kips). Comparing this value to the group's average failure load, 35.37 kips, a test/prediction ratio very close to 1.0 is achieved (1.04). Similarly, the same procedure carried out for a second and third group of tests, 1-TH01, 02, 03-P-NS-2DB and 4-TH01, 02, 03,-P-NS-3DB (specimens that included PVC sheathing) test/prediction ratios of 1.44 and 1.18, respectively, are obtained. Assuming that the differences in average failure loads between the second and third group are directly and linearly related to the cover parameter, a simple relationship (Fig. 4.9) can then be presented to express the "smooth-bar" correction factor as a function of clear cover. Empirically this relationship can be described as ($l_{d\,hdbar} = \rho l_d$) where:

$$\rho = -0.23C + 1.8 \qquad (4\text{-}30)$$

and C expresses the clear cover in inches and ρ is the correction factor that must be greater than or equal to 1.0.

4.5 Presentation of Headed Bar Building Code Provisions

From the evidence, results, and previous discussion, it is apparent that two expressions, Eqs. 4-25 and 4-28, can be presented as a viable means to describe the development length of headed reinforcing bar. Presented in Table 4.18, a proposal is drafted to describe the necessary requirements for developing headed bars. The proposal is structured in such a way to be included in a future revision of the ACI building code.

Figure 4.10 shows obvious disparities between the development lengths described by Eqs. 4-25 and 4-28, especially when significantly high or drastically low amounts of confinement are used in the specimen. In addition, problems arise when using Eq. 4-25 to describe development lengths of bars with yield strengths less than 75 ksi. In these cases, Eq. 4-25 allows a development length, l_d, equal to zero for 60 ksi bars,, when in fact, the development length is more likely a small, but significant value. Therefore, it is possible that the best way of describing headed bar development may be using a combination of the two equations. Figure 4.10 shows areas for each equation in which development lengths predicted for 75 ksi headed bars would be conservative (within reason) or unconservative. This assumption is the premise behind the equations in section 12.x.2 (Table 4.18). Under this proposal, headed bars with yield strengths greater than 60ksi would have development length equal to that predicted by Eq. 4-25 or 4-28, whichever yields a greater value. In other words, the development length set forth under this set of code would be predicted by the conservative portions of each expression (Fig. 4.10).

For headed bars with yield stresses smaller than 75ksi (i.e. Grade 60 steel), development lengths would be described by Eq. 4-28 only. The portion of this expression labeled as unconservative (Fig. 4.10) most likely becomes conservative due to the lower loads required to attain yielding in the bar. It is imperative, however, because no data exists for bar sizes other than No.25 [No. 8] bar, that more research be performed to investigate this presumption before concluding that this portion of the expression is indeed conservative.

Since more study is needed on various sizes of headed bar, minimum development lengths, set forth in section 12.x.1 (Table 4.18), cannot be proved beyond doubt. However, the equation provided in section 12.x.2.1 of Table 4.18 provides justification for the minimums suggested. Simplification of this expression for bar yield strengths of 60,000 psi results in the quantity:

$$l_d = [700d_b/(f'c)^{1/2}] \quad (4\text{-}31)$$

This term does not include the modification factors necessary for cover or confining steel, and is similar in nature to the expression that describes hooked bar anchorages in section 12.5.2 of ACI 318-95. This section states that for a hooked bar with a yield strength of 60,000 psi, the basic development length for that bar shall be given by the equation:

$$l_d = [1200d_b/(f'c)^{1/2}] \quad (4\text{-}31)$$

Due to the fact that headed bars behave similarly and slightly better than hooked reinforcing bar and considering the comparison of Eqs. 4-31 and 4-32, these minimum development lengths prescribed by section 12.x.1 should be at least 58.3% of the minimums set for hooked reinforcement in section 12.5.1 of ACI 318-95. As a conservative approach, minimum headed bar development lengths of $6d_b$ (75% of hooked bar development lengths) are suggested. An additional 6 in. minimum is also recommended for logistical concerns of confinement around the head.

Other minimums presented in section 12.x.1 describe confinement requirements based upon the configurations of specimens whose results consistently demonstrated high failure loads or yielding of the bar (i.e. stirrup configuration pattern #5S1). These specimens included those with 3 bar diameters of cover and stirrup spacing patterns #4S1, #4S2, and #5S1. A three stirrup limitation is also included in section 12.x.1 to prevent a designer from using one or two stirrups that are large in diameter, to achieve the required value for the quantity $(A_{tr}f_{ytr} / s)$.

Keeping with the current code structure, modification factors are presented in section 12.x.3 to account for casting position, lightweight aggregate, epoxy-coated bar surfaces, excess reinforcement and undeformed (non-ribbed) bar. With the exception of the later, future research will be needed to develop these factors. The factor "ρ" is based completely on the expression developed in Eq. 4-30, and like the other factors, also will require further study to verify.

While parts of the code proposed in Table 4.18 requires future research to develop, it is hoped that what is presented here is a solid foundation on which to evolve a set of design guidelines for the development of headed reinforcing bar.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Summary

A research program, developed here at the University of Kansas has investigated the development characteristics of headed reinforcing bars. Over the course of this study, insights were gained into this new method of anchoring steel reinforcing bars. In addition, this research has provided the means to develop design guidelines for the development of headed bars, as well as recommended changes to the ACI Building Code.

The test program consisted of evaluating the performance of seventy beam-end test specimens. While most of these specimens included headed test bars, specimens also were tested using straight and 180° hooked test bars. Although concrete strengths were held constant at 31-34.5MPa [4500-5000psi] and tests bars were limited to 25mm [No.8] diameter bars of 517 MPa [75ksi] steel yield strengths, variables such as cover, bonded length and transverse reinforcement were carefully controlled and their effects on the test results investigated.

After careful evaluation of the test results, comparisons were then made to bond strength/development length expressions for straight deformed bars developed over the past several years. In particular, expressions by Orangun et al. (1975, 1977) and Idun and Darwin (1995) proved to be the most useful. Based on these comparisons, best-fit lines were developed and used to obtain design equations to describe the development length characteristics of headed bars. These expressions were then used as a basis, along with test results of this program, to propose headed bar development length criteria to be considered for inclusion in future issues of the ACI Building Code.

5.2 Observations and Conclusions

This section summarizes the important observations and conclusions from this research. The first section will contain a summary of the test results and overall behavior. The second section will summarize the design expressions and guidelines that were developed.

5.2.1 Beam-End Test Results

After evaluation of the results from beam-end tests on straight, hooked and headed bars, the following observations and conclusions can be made:

5.2.1.1 General Performance - Deformed Bars

Headed bar tests fail at approximately equal or higher loads than tests using hooked bars. In addition, hooked bars and headed bars exhibit similar behavior under load and are both affected by the inclusion of transverse reinforcement in a similar manner. Similarities also are apparent in the amount of ductility, measured as loaded-end slip, displayed during the test and also in the degree of cracking that is presented in a failed specimen.

5.2.1.2 Confinement Effects - Deformed Bars

1) Specimens with stirrup spacing pattern #3S1 display the largest increase in ultimate axial load capacity from an additional bar diameter of cover. The more transverse reinforcement provided in the specimen, the smaller the increase in ultimate axial load capacity due to additional cover.

2) Test specimens with deformed bars exhibit a 50% increase in ultimate load capacity (80kN [18kips]) by including transverse stirrups as a part of the steel configuration.

3) The presence of transverse stirrups appears to lower the strut angle "α", allowing for an increase in the axial load capacity of the specimens. In addition, a relationship exists between the proximity of the stirrup to the head and its effects upon the compression strut angle as well as its effects on the overall axial load capacity of the specimen.

4) For strut-tie models in which the compression strut is restricted to 35°, as suggested by previous research, it is interesting that stirrup pattern #5S1, the only pattern of the four tested to position two stirrups such that they intersect the strut, demonstrates the highest and most consistent ultimate axial loads among the headed bar test specimens. Consequently, the closer a stirrup is placed to the head on the loaded side, the higher the ultimate axial load of the specimen. The fact that stirrup configuration pattern #5S1 provided the highest average load capacity among all specimens with 2 and 3 bar diameters of cover is evidence of this behavior.

5.2.1.3 General Performance - Smooth Bars

1) The use of PVC sheathing on the test bar significantly effects the ultimate axial load of the headed bar specimen. The use of a PVC covering is most effective at providing additional capacity to the specimen when no transverse reinforcement is used, as shown by a 32% [50.5kN or 11.3 kip] increase among such specimens having 2 db of cover.

2) The use of PVC sheathing directly effects the manner and degree of cracking exhibited by a failed specimen. When PVC is used to cover the test bar and prevent the concrete bond to the steel, the amount of cracking shown in the specimen is significantly less than those specimens that do not include PVC

sheathing. The splitting forces on the concrete created by deformations on the bar result in bursting of the concrete where as these forces are eliminated when PVC is present. In addition, PVC covered specimens show little cracking before failure and fail more abruptly than those specimens without the PVC covering.

3) As is the case with most any structural application, increases in cover bring about increases in the ultimate axial load capacity of the specimen. In cases where no transverse reinforcement is provided and PVC is used to cover the bar, increased cover brings about a dramatic increase in capacity of approximately 32% (54.5kn [12.3 kips]).

5.2.1.4 Confinement Effects - Smooth Bars

1) If the test bar is covered with PVC, the additional capacity obtained by using transverse reinforcement in the steel configuration is approximately 26% (55kN [12.5 kips]).

2) When specimens contain a PVC sheathing over the bar and transverse reinforcing steel, the effects of additional cover on the ultimate load capacity of the specimen is minimal. Specimens with this configuration experienced only a 1% increase in ultimate load capacity (2.7kN [0.62 kips]) as a result of increasing the cover from 2 to 3 bar diameters.

5.2.2 Design Equation Evaluation

Once the test results were obtained and evaluated, comparisons of the results were made against previous bond strength and development length equations developed for straight deformed reinforcing bars. A headed bar development length expression was obtained and proposed code language and requirements to support this equation were developed. What follows are observations and conclusions that can be drawn from this portion of the study.

1) As expected, previously developed bond strength equations underestimate the ultimate load of smooth headed reinforcing bar and the head itself is, therefore, the primary mechanism for anchoring the bar; in other words, there is no bond component.

2) For headed specimens without transverse reinforcement, expressions recently developed by Darwin et. al. (1992), and Idun and Darwin (1995), show good ability to accurately predict ultimate axial loads of headed test bars with deformed bars, that is the test/prediction ration is approximately 1.0.

3) Ultimate load comparisons of headed bar tests without transverse reinforcement to those loads predicted by established equations presented in section 12.2.3 of ACI 318-95 and ACI 408.1R-90 for straight bar bond strengths, show these equations predict conservative ultimate loads by an average of 12% of the bond strength values obtained from tests. However, predictions given by the 408 report generate test/prediction ratios that are lower than the ACI 318-95 predictions and are thus closer to 1.0. This result is as expected since the ACI 318 expressions are code equations and by intent are conservative. Ultimate loads predicted for hooked bar anchorages in section 12.5 of ACI 318-95 are, on the other hand, somewhat unconservative (average test/prediction ratio 0.806). All of these observations also are evident in the results of specimens that include transverse reinforcement regardless of whether or not limits are imposed upon the amount of transverse reinforcement accounted for in the expression.

4) In general, test/prediction ratios are lower and more unconservative for Eq. 4-14a than those ratios yielded by the more conservative Eq. 4-15.

5) Limitations placed upon the value of K_{tr} dramatically effect test/prediction ratios of Eq. 4-14a. Test/prediction ratios are lower when the restrictions are lifted, and because a pullout failure is not a realistic concern with a headed bar, these limits on K_{tr} appear not to be necessary for developing this style of reinforcing bar.

6) Test/prediction ratios of Eq. 4-15 demonstrate no significant changes when transverse reinforcement configurations are varied among specimens with 2 or 3 d_b of cover. This trend manifests itself because of the absence of a transverse stirrup spacing term in Eq. 4-15 to address the concentration of stirrups in the specimen.

7) Chi-Square tests on best-fit lines for headed bar results compared against Eqs. 4-14a and 4-15 indicate that the comparisons made to Eq. 4-14a provide a better set of data on which to base best-fit lines and hence, design equations for headed bar development lengths. However, ANOVA results do not provide conclusive evidence as to which of the two expressions is a more reliable basis.

8) Low values of r^2, the coefficient of determination, indicate that headed bar development lengths may more accurately be described by a non-linear equation rather than a linear variety such as proposed by Eq. 4-25 and 4-28. In addition, large disparities in F-values (ANOVA tables) between data lines of 2 and $3d_b$ of cover may show cover to be more influential in dictating the development length of a headed bar than the proposed equations allow.

9) Strut-tie models demonstrate the effectiveness of transverse reinforcement to provide a clamping force on the test bar, dissipate the applied load, and the degree to which the capacity of a stirrup (yield strength) can effect the model outcome. Consequently, equations used as a basis for headed reinforcing bar

development lengths need to account for the yield strength of the stirrup as well as its area. Equation 4-14a fulfills such requirements.

10) Based upon comparisons of headed bar results to Eq. 4-14a, two expressions are developed in Eq. 4-25 and 4-28 to describe the development length of headed reinforcing bar. The latter expression, however, is merely a derivative of the former with modifications for normalizing concrete strength, clear cover and test bar yield strength.

11) Using the equations developed in Eq. 4-25 and 4-28, a set of design guidelines and code propositions are presented in Fig. 4.12 that include suggested minimum development lengths and a development length modification factor for smooth, non-deformed bars developed from test results of headed bars sheathed with PVC.

(12) Applying Eq. 4-28 to Grade 60 [420] reinforcing steel with no confinement, the development length for a headed reinforcing bar expression follows as: $l_d = [\ 700d_b / (f'c^{1/2})]$ and thus, is 58% of the development length for a similar hooked anchorage under the same conditions as described by the expression: $l_d = [\ 1200d_b / (f'c^{1/2})]$ Additional cover or confinement will further reduce the development of the headed bar and as the headed bar becomes more confined, the development length of that bar will approach zero.

5.3 Issues For Future Study

Because the technology of headed reinforcing bar is new, there are several questions to be answered and aspects of headed bar performance to be investigated. Some of these issues have been answered by this research program and are summarized within this report. A number of topics have been left unanswered and will require future investigation. In addition, some observations and conclusions have been made on a small quantity of data and as a result, future studies also should concentrate on verifying these observations. Some issues that show the need for additional research include the following:

1) Concrete Strength, Bar Size, and Test Bar Yield Strength are factors that may influence the development length of headed bar. However, these parameters were not included as variables in this testing program. Future research should extend this study to investigate the effects of these elements on headed bar development lengths.

2) Although this program investigates the effects of transverse reinforcing steel on the development length of a headed bar, it does nothing to evaluate whether or not these effects are due to the size of the stirrups (A_{tr}), their stiffness, or the mere quantity of stirrups (n) within the development length region.

3) Study is needed to investigate the role of stirrups and their location, as well as their spacing pattern across the development length.

4) Research should be undertaken to determine the modification factors for casting position, lightweight aggregate, epoxy-coated bar, and excess reinforcement, as it applies to the development length of headed reinforcement.

5.4 Final Conclusions

During the course of this research program, a total of seventy beam-end specimens were tested. These specimens were comprised of headed deformed bars, headed smooth bars, straight deformed bars and hooked bars both smooth and deformed. The overall picture that emerges is that a headed bar anchorage performs almost identically to a hooked bar. Both anchorages are able to develop a reinforcing bar in a significantly shorter distance than a straight deformed bar.

A second overall trend is that confinement, either in the form of stirrups or additional cover, act to assist the anchorage of both hooks and headed bars. The confinement is so efficient that a headed bar can be effectively developed entirely by the head with no assistance from the deformations on the bar. Thus, a designer using cover or a small number of stirrups, would be able to anchor a reinforcing bar by the action of the head alone and be able to have the bar participate in carrying loads.

Lastly, design expressions were developed and a set of design guidelines were developed. The overall conclusion is that the development length of a standard Grade 60 [420] headed bar with two bar diameters of cover can be predicted by the equation:

$$[\, l_d / d_b \,] = [\, 700 / (f'c^{1/2})] \qquad (5\text{-}1)$$

This result can be compared to a coefficient of $[1200 / (f'c^{1/2})]$ for a hooked anchorage. Thus a headed bar can be developed in 7/12 the distance of a hooked bar. If stirrups or additional cover is provided, the development length is reduced and approaches zero for a fully confined headed bar.

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Table 2.1 Mix Proportions and Concrete Properties.

Mix Proportions

Batch No.	Nominal Strength MPa	Nominal Strength psi	w/c Ratio	Cement Content Kg~	Cement Content Lbs.~	Water Content Kg~	Water Content Lbs.~	Fine Aggregate* Kg~	Fine Aggregate* Lbs.~	Coarse Aggregate** Kg~	Coarse Aggregate** Lbs.~
1 thru 4	34.5	5000	0.44	232	511	102	225	709	1564	753	1661

~ Values provide are per cubic yard

* Kansas River Sand - Lawrence Sand Co., Lawrence, Kansas.
Bulk Specific Gravity (SSD) = 2.62; Absorption = 0.5%; Fineness Modulus = 2.89.

** Crushed Limestone - Fogel's Quarry, Ottawa, Kansas.
Bulk Specific Gravity (SSD) = 2.58; Absorption = 2.7%; Maximum Size = 19mm [0.75"];
Unit Weight = 1450 Kg/cu. meter [90.5 Lbs./cu. ft.]

Concrete Properties

Batch No.	Date of Pour	Air Temperature deg. C	Air Temperature deg. F	Concrete Temp deg. C	Concrete Temp deg. F	Slump mm	Slump inches	air content %	Age at test (days)	Ave. Comp. Strength MPa	Ave. Comp. Strength psi
1	6/22/95	35	95	36	97	102	4	2.6	25	28.5	4128
2***	8/29/95	33	91	32	90	121	4.75	3.2	9	33.6	4878
3a	1/9/96	9	49	4	40	108	4.25	4.5	15	33.2	4812
3b	1/9/96	9	49	4	40	108	4.25	4.5	16	33.4	4850
3c	1/9/96	9	49	4	40	108	4.25	4.5	18	33.4	4851
4a***	2/29/96	1	33	8	46	76	3	3	17	34.5	5003
4b***	2/29/96	1	33	8	46	76	3	3	18	34.7	5027

*** Superplasticizer added to increase workability during pour.

Table 3.1a Test Results Summary

Specimen Identification	Clear Cov.		Ultimate Axial Load		Modified Ultimate Axial Load		Loaded End Slip at Ult. Axial Load		Unloaded End Slip at Ult. Axial Load		Crack Width at Ult. Axial Load		Concrete Strength f'c	
	mm	in.	KN	Kips	KN	Kips	mm	inches	mm	inches	mm	inches	MPa	psi
Straight Bar Tests														
1-SB01-NP-NS-2DB-13	40.69	1.602	109.29	24.57	120.28	27.041	0.4648	0.0183	0.1092	0.0043	0.0965	0.0038	28.46	4128
1-SB03-NP-NS-2DB-19	40.44	1.592	102.57	23.06	112.89	25.379	0.4547	0.0179	0.1753	0.0069	0.0813	0.0032	28.46	4128
1-SB04-NP-NS-2DB-19	40.36	1.589	100.52	22.6	110.63	24.873	0.2235	0.0088	0.0889	0.0035	0.1321	0.0052	28.46	4128
+ + 1-SB05-NP-NS-2DB-25	40.61	1.599	96.833	21.77	106.57	23.959	0.3531	0.0139	0.1016	0.004	0.0508	0.002	28.46	4128
2-SB02-NP-NS-2DB-19	45.47	1.79	125.57	28.23	127.13	28.581	0.6401	0.0252	0.1499	0.0059	0.0991	0.0039	33.63	4878
Group Mean	41.51	1.634	106.96	24.046	115.5	25.967	0.4272	0.0168	0.125	0.0049	0.0919	0.0036		
2-SB01-NP-3S1-2DB-13	48.06	1.892	144.92	32.58	146.72	32.985	1.2675	0.0499	0.1727	0.0068	0.2057	0.0081	33.63	4878
3-SB01-NP-3S1-3DB-19	83.54	3.289	162.62	36.56	165.77	37.267	0.1016	0.004	0.1854	0.0073	0.3886	0.0153	33.18	4812
3-SB02-NP-3S1-3DB-19	82.3	3.24	181.26	40.75	184.76	41.538	0.5563	0.0219	0.1499	0.0059	0.2184	0.0086	33.18	4812
Group Mean	82.92	3.265	171.94	38.655	175.26	39.403	0.3289	0.013	0.1676	0.0066	0.3035	0.012		
4-SB01-NP-NS-3DB-19	80.59	3.173	158.08	35.54	158.03	35.529	0.602	0.0237	0.1067	0.0042	0.1727	0.0068	34.49	5003
4-SB02-NP-NS-3DB-19	81.43	3.206	117.25	26.36	117.21	26.352	0.7772	0.0306	0.193	0.0076	0	0	34.49	5003
Group Mean	81.01	3.19	137.67	30.95	137.62	30.941	0.6896	0.0272	0.1499	0.0059	0.0864	0.0034		

** Indicates bar yielded test stopped
~ Failure at or just before bar yielded
+ + Indicates #8, fy = 60ksi test bar used
^^ Problems with apparatus test
terminated before failure occurred.

Table 3.1a Test Results Summary (cont.)

Specimen Identification	Clear Cov.		Ultimate Axial Load		Modified Ultimate Axial Load		Loaded End Slip at Ult. Axial Load		Unloaded End Slip at Ult. Axial Load		Crack Width at Ult. Axial Load		Concrete Strength f'c	
	mm	in.	KN	Kips	KN	Kips	mm	inches	mm	inches	mm	inches	MPa	psi
Hooked Bar Tests														
1-HK01-P-NS-2DB-108	45.31	1.784	160.08	35.99	176.18	39.609	0.8407	0.0331	0.2261	0.0089	0.0127	0.0005	28.46	4128
1-HK02-P-NS-2DB-108	45.95	1.809	182.23	40.97	200.56	45.09	1.0617	0.0418	0.3835	0.0151	0.0229	0.0009	28.46	4128
1-HK03-P-NS-2DB-108	43.43	1.71	149.19	33.54	164.19	36.913	1.1278	0.0444	0.0381	0.0015	0.0432	0.0017	28.46	4128
Group Mean	44.9	1.768	163.83	36.833	180.31	40.537	1.0101	0.0398	0.2159	0.0085	0.0262	0.001		
**2-HK02-P-3S1-2DB-108	41.1	1.618	258.74	58.17	261.96	58.893	3.1369	0.1235	0.0533	0.0021	0	0	33.63	4878
2-HK03-NP-NS-2DB-19	56.46	2.223	154.57	34.75	156.49	35.182	0.7188	0.0283	0.0889	0.0035	0.4953	0.0195	33.63	4878
2-HK01-NP-3S1-2DB-19	47.83	1.883	202.83	45.6	205.35	46.167	1.1786	0.0464	0.0889	0.0035	0	0	33.63	4878
3-HK01-P-3S1-3DB-114	74.7	2.941	242.02	54.41	245.73	55.245	1.8771	0.0739	0.4394	0.0173	0.0406	0.0016	33.44	4850
**3-HK02-P-3S1-3DB-102	74.09	2.917	275.2	61.87	280.52	63.067	2.3165	0.0912	0.3175	0.0125	0	0	33.18	4812
**3-HK03-P-3S1-3DB-121	72.97	2.873	262.03	58.91	266.05	59.814	1.745	0.0687	0.2769	0.0109	0	0	33.44	4850
Group Mean	73.92	2.91	259.75	58.397	264.1	59.375	1.9795	0.0779	0.3446	0.0136	0.0135	0.0005		
3-HK04-P-NS-3DB-114	71.07	2.798	240.01	53.96	243.7	54.788	1.3437	0.0529	0.2616	0.0103	0	0	33.44	4850
3-HK05-P-NS-3DB-114	70.59	2.779	245.17	55.12	248.94	55.966	1.3538	0.0533	0.381	0.015	0	0	33.44	4850
3-HK06-P-NS-3DB-114	69.88	2.751	227.07	51.05	230.56	51.833	0.9068	0.0357	0.1676	0.0066	0	0	33.44	4850
Group Mean	70.51	2.776	237.42	53.377	241.06	54.196	1.2014	0.0473	0.2701	0.0106	0	0		
3-HK07-NP-3S1-3DB-19	75.21	2.961	210.26	47.27	213.48	47.995	1.1354	0.0447	0.0025	0.0001	0.6807	0.0268	33.44	4850
3-HK08-NP-3S1-3DB-19	78.13	3.076	205.76	46.26	208.92	46.97	0.9449	0.0372	0	0	0.7188	0.0283	33.44	4850
3-HK09-NP-3S1-3DB-19	88.67	3.491	216.17	48.6	219.49	49.346	0.8814	0.0347	0.1397	0.0055	0.4445	0.0175	33.44	4850
Group Mean	80.67	3.176	210.73	47.377	213.97	48.104	0.9872	0.0389	0.0474	0.0019	0.6147	0.0242		

** Indicates bar yielded test stopped
~ Failure at or just before bar yielded
+ + Indicates #8, fy=60ksi test bar used
^^ Problems with apparatus test
terminated before failure occurred.

Table 3.1a Test Results Summary (cont.)

Specimen Identification	Clear Cov.		Ultimate Axial Load		Modified Ultimate Axial Load		Loaded End Slip at Ult. Axial Load		Unloaded End Slip at Ult. Axial Load		Crack Width at Ult. Axial Load		Concrete Strength f'c	
	mm	in.	KN	Kips	KN	Kips	mm	inches	mm	inches	mm	inches	MPa	psi
Headed Bar Tests														
1-TH01-P-NS-2DB-292	45.47	1.79	190.6	42.85	209.76	47.159	1.6383	0.0645	0.7493	0.0295	0	0	28.46	4128
1-TH02-P-NS-2DB-292	45.39	1.787	196.74	44.23	216.52	48.678	1.2116	0.0477	0.6274	0.0247	0	0	28.46	4128
1-TH03-P-NS-2DB-292	47.12	1.855	184.68	41.52	203.25	45.695	1.3386	0.0527	0.7163	0.0282	0	0	28.46	4128
Group Mean	45.99	1.811	190.67	42.867	209.85	47.177	1.3962	0.055	0.6977	0.0275	0	0		
~2-TH01-P-3S1-2DB-292	47.02	1.851	253.54	57	256.69	57.708	2.3927	0.0942	0.7264	0.0286	0	0	33.63	4878
~2-TH02-P-3S1-2DB-292	47.93	1.887	259.5	58.34	262.72	59.065	2.9058	0.1144	1.082	0.0426	0	0	33.63	4878
2-TH03-P-3S1-2DB-292	45.77	1.802	252.11	56.68	255.25	57.384	1.8059	0.0711	0.6756	0.0266	0	0	33.63	4878
Group Mean	46.91	1.847	255.05	57.34	258.22	58.053	2.3681	0.0932	0.828	0.0326	0	0		
2-TH04-NP-3S1-2DB-19	47.96	1.888	244.28	54.92	247.32	55.603	1.2598	0.0496	0.5359	0.0211	0	0	33.63	4878
2-TH05-NP-3S1-2DB-19	50.8	2	234.45	52.71	237.37	53.365	0	0	0.475	0.0187	0	0	33.63	4878
2-TH06-NP-3S1-2DB-13	47.73	1.879	229.78	51.66	232.64	52.302	1.303	0.0513	0.4064	0.016	0	0	33.63	4878
Group Mean	48.83	1.922	236.17	53.097	239.11	53.757	0.8543	0.0336	0.4724	0.0186	0	0		
2-TH07-NP-NS-2DB-16	47.68	1.877	148.74	33.44	150.59	33.856	1.2319	0.0485	0.7137	0.0281	0	0	33.63	4878
2-TH08-NP-NS-2DB-16	47.88	1.885	155.72	35.01	157.66	35.445	0.7671	0.0302	0.221	0.0087	0	0	33.63	4878
2-TH09-NP-NS-2DB-16	49.48	1.948	167.51	37.66	169.59	38.128	0.7341	0.0289	0.2591	0.0102	0	0	33.63	4878
Group Mean	48.34	1.903	157.33	35.37	159.28	35.81	0.911	0.0359	0.3979	0.0157	0	0		
~3-TH01-P-4S1-3DB-292	75.11	2.957	259.81	58.41	263.79	59.306	2.1107	0.0831	0.7849	0.0309	0	0	33.44	4850
~3-TH02-P-4S1-3DB-292	81.38	3.204	259.32	58.3	263.3	59.195	1.5773	0.0621	0.6756	0.0266	0	0	33.44	4850
**3-TH03-P-4S1-3DB-292	75.18	2.96	272.4	61.24	276.58	62.18	2.3851	0.0939	0.6553	0.0258	0	0	33.44	4850
Group Mean	77.22	3.04	263.84	59.317	267.89	60.227	2.0244	0.0797	0.7053	0.0278	0	0		

** Indicates bar yielded test stopped

~ Failure at or just before bar yielded

++ Indicates #8, fy=60ksi test bar used

^^ Problems with apparatus test terminated before failure occurred.

Table 3.1a Test Results Summary (cont.)

Specimen Identification	Clear Cov.		Ultimate Axial Load		Modified Ultimate Axial Load		Loaded End Slip at Ult. Axial Load		Unloaded End Slip at Ult. Axial Load		Crack Width at Ult. Axial Load		Concrete Strength f'c	
	mm	in.	KN	Kips	KN	Kips	mm	inches	mm	inches	mm	inches	MPa	psi
Headed Bar Tests (cont.)														
3-TH04-NP-4S1-3DB-19	82.19	3.236	243.35	54.71	247.08	55.55	1.4503	0.0571	0.4445	0.0175	1.143	0.045	33.44	4850
3-TH05-NP-4S1-3DB-19	83.24	3.277	246.33	55.38	250.11	56.23	1.2014	0.0473	0.4445	0.0175	1.209	0.0476	33.44	4850
3-TH06-NP-4S1-3DB-19	81.69	3.216	225.65	50.73	229.11	51.509	1.5519	0.0611	0.4775	0.0188	1.6256	0.064	33.44	4850
Group Mean	82.37	3.243	238.44	53.607	242.1	54.429	1.4012	0.0552	0.4555	0.0179	1.3259	0.0522		
~3-TH07-P-4S1-2DB-292	48.49	1.909	263.68	59.28	267.7	60.184	0.7036	0.0277	0.696	0.0274	0	0	33.44	4851
**3-TH08-P-4S1-2DB-292	51.16	2.014	270.88	60.9	275.01	61.828	2.1209	0.0835	0.6147	0.0242	0	0	33.44	4851
3-TH09-P-4S1-2DB-292	48.77	1.92	248.87	55.95	252.66	56.803	1.8745	0.0738	0.7112	0.028	0.0635	0.0025	33.44	4851
Group Mean	49.47	1.948	261.14	58.71	265.12	59.605	1.5663	0.0617	0.6739	0.0265	0.0212	0.0008		
3-TH10-NP-4S1-2DB-19	53.72	2.115	228.81	51.44	232.29	52.224	1.0947	0.0431	0.5207	0.0205	1.2878	0.0507	33.44	4851
3-TH11-NP-4S1-2DB-19	51.33	2.021	226.27	50.87	229.72	51.645	1.2852	0.0506	0.4597	0.0181	0.8763	0.0345	33.44	4851
3-TH12-NP-4S1-2DB-19	52.65	2.073	226.71	50.97	230.17	51.747	1.397	0.055	0.3937	0.0155	0.7239	0.0285	33.44	4851
Group Mean	52.57	2.07	227.26	51.093	230.73	51.872	1.259	0.0496	0.458	0.018	0.9627	0.0379		
~4-TH01-P-NS-3DB-292	73.46	2.892	270.13	60.73	269.4	60.567	2.4816	0.0977	0.9271	0.0365	0	0	34.66	5027
**4-TH02-P-NS-3DB-292	68.86	2.711	262.79	59.08	262.08	58.921	3.0201	0.1189	0.5994	0.0236	0	0	34.66	5027
~4-TH03-P-NS-3DB-292	69.16	2.723	262.08	58.92	261.37	58.762	1.397	0.055	0.8153	0.0321	0	0	34.66	5027
Group Mean	70.49	2.775	265	59.577	264.28	59.416	2.2995	0.0905	0.7806	0.0307	0	0		
^^4-TH04-P-3S1-3DB-292	70.28	2.767	211.55	47.56	211.48	47.546	1.4326	0.0564	0.4064	0.016	0	0	34.49	5003
**4-TH05-P-3S1-3DB-292	76.76	3.022	242.24	54.46	242.17	54.444	2.4155	0.0951	0.7264	0.0286	0	0	34.49	5003
**4-TH06-P-3S1-3DB-292	72.24	2.844	268.88	60.45	268.8	60.432	2.4689	0.0972	0.6299	0.0248	0	0	34.49	5003
Group Mean	73.09	2.878	240.89	54.157	240.82	54.14	2.1057	0.0829	0.5876	0.0231	0	0		

** Indicates bar yielded test stopped

~ Failure at or just before bar yielded

+ + Indicates #8, fy = 60ksi test bar used

^^ Problems with apparatus test terminated before failure occurred.

Table 3.1a Test Results Summary (cont.)

Specimen Identification	Clear Cov.		Ultimate Axial Load		Modified Ultimate Axial Load		Loaded End Slip at Ult. Axial Load		Unloaded End Slip at Ult. Axial Load		Crack Width at Ult. Axial Load		Concrete Strength f'c	
	mm	in.	KN	Kips	KN	Kips	mm	inches	mm	inches	mm	inches	MPa	psi
Headed Bar Tests (cont.)														
~4-TH07-NP-3S1-3DB-19	81.97	3.227	265.95	59.79	265.87	59.772	2.3038	0.0907	0.4902	0.0193	1.2243	0.0482	34.49	5003
4-TH08-NP-3S1-3DB-19	80.06	3.152	255.8	57.51	255.73	57.493	2.0752	0.0817	0.6071	0.0239	1.4326	0.0564	34.49	5003
4-TH09-NP-3S1-3DB-19	82.4	3.244	246.02	55.31	245.95	55.293	1.3335	0.0525	0.447	0.0176	1.1989	0.0472	34.49	5003
Group Mean	81.47	3.208	255.92	57.537	255.85	57.519	1.9042	0.075	0.5148	0.0203	1.2852	0.0506		
4-TH10-NP-4S2-3DB-19	76.86	3.026	258.56	58.13	257.87	57.974	1.5545	0.0612	0.447	0.0176	0	0	34.66	5027
4-TH11-NP-4S2-3DB-19	80.19	3.157	253.27	56.94	252.59	56.787	2.3089	0.0909	0.4826	0.019	0	0	34.66	5027
4-TH12-NP-4S2-3DB-19	82.22	3.237	248.6	55.89	247.93	55.74	2.0523	0.0808	0.4267	0.0168	1.0795	0.0425	34.66	5027
Group Mean	79.76	3.14	253.48	56.987	252.8	56.833	1.9719	0.0776	0.4521	0.0178	0.3598	0.0142		
4-TH13-NP-4S2-2DB-19	55.45	2.183	249.62	56.12	248.95	55.969	1.4072	0.0554	0.5055	0.0199	1.2649	0.0498	34.66	5027
4-TH14-NP-4S2-2DB-19	55.7	2.193	231.87	52.13	231.25	51.99	1.3843	0.0545	0.3861	0.0152	0.7163	0.0282	34.66	5027
4-TH15-NP-4S2-2DB-19	56.57	2.227	257.14	57.81	256.45	57.655	1.7551	0.0691	0.442	0.0174	0.729	0.0287	34.66	5027
Group Mean	55.91	2.201	246.21	55.353	245.55	55.204	1.5155	0.0597	0.4445	0.0175	0.9034	0.0356		
~4-TH16-NP-5S1-3DB-19	78.97	3.109	261.45	58.78	260.75	58.622	2.6619	0.1048	0.508	0.02	1.2624	0.0497	34.66	5027
~4-TH17-NP-5S1-3DB-19	78.79	3.102	263.9	59.33	263.19	59.17	1.7958	0.0707	0.4064	0.016	0.9017	0.0355	34.66	5027
**4-TH18-NP-5S1-3DB-19	79.32	3.123	267.24	60.08	266.52	59.918	2.2606	0.089	0.3099	0.0122	0.5791	0.0228	34.66	5027
Group Mean	79.03	3.111	264.2	59.397	263.49	59.237	2.2394	0.0882	0.4081	0.0161	0.9144	0.036		
~4-TH19-NP-5S1-2DB-19	49.56	1.951	248.64	55.9	247.97	55.75	2.6213	0.1032	0.4267	0.0168	0.6858	0.027	34.66	5027
4-TH20-NP-5S1-2DB-19	55.37	2.18	254.51	57.22	253.83	57.066	1.7577	0.0692	0.3835	0.0151	0.7772	0.0306	34.66	5027
~4-TH21-NP-5S1-2DB-19	51.69	2.035	265.15	59.61	264.43	59.45	1.7602	0.0693	0.3454	0.0136	0.5029	0.0198	34.66	5027
Group Mean	52.21	2.055	256.1	57.577	255.41	57.422	2.0464	0.0806	0.3852	0.0152	0.6553	0.0258		

** Indicates bar yielded test stopped

~ Failure at or just before bar yielded

+ + Indicates #8, fy = 60ksi test bar used

^^ Problems with apparatus test terminated before failure occurred.

Table 3.2 180 Degree Hook vs. Head - Ultimate Load

180 Degree Hook vs. Headed Bar
Average Ultimate Axial Load Capacity*

Group Parameters	180 Degree Hook		Headed Bar		Difference		Ratio
	kN	Kips	kN	Kips	kN	Kips	Head/Hook
PVC - No Stirrups - 2db	180.32	40.54	209.81	47.17	29.49	6.63	1.164
PVC - Stirrups #3S1 - 2db	261.94	58.89	258.21	58.05	-3.74	-0.84	0.986
No PVC - No Stirrups - 2db	156.48	35.18	159.28	35.81	2.80	0.63	1.018
No PVC - Stirrups #3S1 - 2db	205.36	46.17	239.08	53.75	33.72	7.58	1.164
PVC - No Stirrups - 3db	241.08	54.2	264.30	59.42	23.22	5.22	1.096
PVC - Stirrups #3S1 - 3db	264.12	59.38	240.81**	54.14**	-23.31**	-5.24**	0.911**
No PVC - Stirrups #3S1 - 3db	213.95	48.1	255.85	57.52	41.90	9.42	1.196

* Values listed here are modified for differences in concrete strength f 'c.

** Test #4-TH06 yielded at 269kN [60.43 kips]. Other tests in this group experienced problems during testing.

Table 3.3 180 Degree Hook vs Head - Ductility

180 Degree Hook vs. Headed Bar
Ductility Comparison using "Loaded-End-Slip"

Group Parameters	180 Degree Hook mm	180 Degree Hook inches	"T"-Headed Bar mm	"T"-Headed Bar inches	Difference mm	Difference inches	Ratio Head/Hook
PVC - No Stirrups - 2db	1.0109	0.0398	1.3970	0.0550	0.3861	0.0152	1.382
PVC - Stirrups #3S1 - 2db	3.1369	0.1235	2.3673	0.0932	-0.7696	-0.0303	0.755
No PVC - No Stirrups - 2db	0.7188	0.0283	0.9119	0.0359	0.1930	0.0076	1.269
No PVC - Stirrups #3S1 - 2db	1.1786	0.0464	0.8534	0.0336	-0.3251	-0.0128	0.724
PVC - No Stirrups - 3db	1.2014	0.0473	2.2987	0.0905	1.0973	0.0432	1.913
PVC - Stirrups #3S1 - 3db	1.9787	0.0779	2.1057**	.0829**	.1270**	.0050**	1.064**
No PVC - Stirrups #3S1 - 3db	0.9881	0.0389	1.9050	0.0750	0.9169	0.0361	1.928

** Test #4-TH06 yielded at 2.4689mm [0.0972 inches]. Other tests in this group experienced problems during testing.

Table 3.4 Bonded Length Effects

Effects of Bonded Length on Headed Tests
Average Ultimate Axial Load Capacity*

Group Parameters	Bar Exposed		Bar Covered w/PVC		Difference		Ratio
	kN	Kips	kN	Kips	kN	Kips	PVC/NPVC
No Stirrups - 2db	159.28	35.81	209.81	47.17	50.53	11.36	1.317
Stirrups Pattern #3S1 - 2db	239.08	53.75	258.21	58.05	19.13	4.30	1.080
Stirrups Pattern #3S1 - 3db	255.85	57.52	240.81**	54.14**	-15.03**	-3.08**	0.941**
Stirrups Pattern #4S1 - 2db	230.72	51.87	265.15	59.61	34.43	7.74	1.149
Stirrups Pattern #4S1 - 3db	242.10	54.43	267.90	60.23	25.80	5.80	1.107

* Values listed here are modified for differences in concrete strength f 'c.

** Test #4-TH06 yielded at 269kN [60.43 kips]. Other tests in this group experienced problems during testing.

Table 3.5 Effects of Concrete Cover

Effects of Concrete Cover; 2db & 3db
Average Ultimate Axial Load Capacity*

Group Parameters	2 Bar Diameters		3 Bar Diameters		Difference		Ratio
	kN	Kips	kN	Kips	kN	Kips	3db / 2db
PVC - No Stirrups	209.81	47.17	264.30	59.42	54.49	12.25	1.260
PVC - Stirrups #3S1	258.21	58.05	240.81**	54.14**	-17.39**	-3.91**	0.933**
No PVC - Stirrups #3S1	239.12	53.76	255.85	57.52	16.72	3.76	1.070
PVC - Stirrups #4S1	265.15	59.61	267.90	60.23	2.76	0.62	1.010
No PVC - Stirrups #4S1	230.72	51.87	242.10	54.43	11.39	2.56	1.049
No PVC - Stirrups #4S2	245.53	55.20	252.78	56.83	7.25	1.63	1.030
No PVC - Stirrups #5S1	255.40	57.42	263.50	59.24	8.10	1.82	1.032

* Values listed here are modified for differences in concrete strength f 'c.

** Test #4-TH06 yielded at 269kN [60.43 kips]. Other tests in this group experienced problems during testing.

Table 3.6 Stirrup Effects on Load Capacity

No Stirrups vs. Stirrups
Average Ultimate Axial Load Capacity*

Group Parameters	No Stirrups		Stirrup Pattern #3S1		Ratio	Stirrup Pattern #4S1		Ratio	Maximum Difference	
	kN	Kips	kN	Kips	Strp./NStrp.	kN	Kips	Strp./NStrp.	kN	Kips
No PVC - 2db Cover	159.28	35.81	239.08	53.75	1.501	230.72	51.87	1.448	79.80	17.94
PVC - 2db Cover	209.86	47.18	258.21	58.05	1.230	265.15	59.61	1.263	55.29	12.43
PVC - 3db Cover	264.30	59.42	240.81*	54.14**	0.911**	267.90	60.23	1.014	3.60	0.81

* Values listed here are modified for differences in concrete strength f 'c.

** Test #4-TH06 yielded at 269kN [60.43 kips]. Other tests in this group experienced problems during testing.

Table 3.7 Effects of Stirrup Spacing

	Stirrup Spacing Patterns Average Ultimate Axial Load Capacity*						
	Concrete Cover 2 Bar Diameters		Concrete Cover 3 Bar Diameters		Ratio	Closest Stirrup to Head Distance (Loaded Side)**	
Group Parameters	kN	Kips	kN	Kips	3db/2db	mm	inches
Stirrup Pattern #3S1	239.12	53.76	255.85	57.52	1.070	25	1.0
Stirrup Pattern #4S1	230.72	51.87	242.10	54.43	1.049	50	2.0
Stirrup Pattern #4S2	245.53	55.20	252.78	56.83	1.030	38	1.5
Stirrup Pattern #5S1	255.40	57.42	263.50	59.24	1.032	13	0.5

NOTE: All groups listed here allow the reinforcing bar to bond to the concrete (no PVC used).

* Values listed here are modified for differences in concrete strength f 'c.

** Measured from the centerline of the stirrup to the centerline of the head (Figure 2.2).

Table 3.8 Alpha and "S" Values for Headed Tests

Headed Tests
Compression Strut Observations

Specimen Identification	Ultimate Axial Load*		Concrete Strength f 'c		Compression Strut Angle	Horizontal Projection to bar "S"	
	kN	Kips	MPa	psi	Degrees	mm	inches
P-NS-2DB-292	209.85	47.18	28.46	4128	56.95	41.36	1.63
P-NS-3DB-292	264.28	59.42	34.66	5027	66.26	39.15	1.54
NP-NS-2DB-16	159.28	35.81	33.63	4878	69.51	23.77	0.94
P-3S1-2DB-292	258.22	58.05	33.63	4878	55.40	43.85	1.73
NP-3S1-2DB-19	239.11	53.76	33.63	4878	58.28	39.30	1.55
P-3S1-3DB-292**	240.82	54.14	34.49	5003	68.38	35.30	1.39
NP-3S1-3DB-19	255.85	57.52	34.49	5003	66.95	37.89	1.49
P-4S1-2DB-292	265.12	59.61	33.44	4851	54.10	46.01	1.81
NP-4S1-2DB-19	230.73	51.87	33.44	4851	59.33	37.71	1.48
P-4S1-3DB-292	267.89	60.23	33.44	4850	64.98	41.56	1.64
NP-4S1-3DB-19	242.10	54.43	33.44	4850	67.53	36.82	1.45
NP-4S2-2DB-19	245.55	55.20	34.66	5027	58.41	39.10	1.54
NP-4S2-3DB-19	252.80	56.83	34.66	5027	67.36	37.14	1.46
NP-5S1-2DB-19	255.41	57.42	34.66	5027	56.98	41.32	1.63
NP-5S1-3DB-19	263.49	59.24	34.66	5027	66.34	39.01	1.54

* Values listed here are modified for differences in concrete strength f 'c.

** Only one test provided reliable data showing yield at 269kN [60.43 kips]. This test is more indicative of the group than is the mean value listed here.

Table 4.1 Comparison of Headed Results (w/o stirrups) to Eq. 4-1

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	P/le*(f'c)^1/2	Test/Prediction Ratio	Average	Standard Deviation
1-TH01-P-NS-2DB-292	42.85	4128	55.58	1.588		
1-TH02-P-NS-2DB-292	44.23	4128	57.37	1.639		
1-TH03-P-NS-2DB-292	41.52	4128	53.85	1.539		
					1.589	0.050
2-TH07-NP-NS-2DB-292	33.44	4878	39.90	1.140		
2-TH08-NP-NS-2DB-292	35.01	4878	41.77	1.193		
2-TH09-NP-NS-2DB-292	37.66	4878	44.93	1.284		
					1.206	0.073
4-TH01-P-NS-3DB-292	60.73	5027	71.38	2.039		
4-TH02-P-NS-3DB-292	59.08	5027	69.44	1.984		
4-TH03-P-NS-3DB-292	58.92	5027	69.25	1.979		
					2.001	0.034

Table 4.2 Comparison of Headed Results (w/o stirrups) to Eq. 4-2

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Test Results Abfs / (f'c)^1/2 (in.^2)	Eq. 4-2 Prediction Abfs / (f'c)^1/2 (in.^2)	X* (in.^2)	Test / Prediction Ratio	Average	Standard Deviation
2-THO7-NP-NS-2DB-292	33.44	4878	1.877	11.38	478.79	420.91	25.593	1.138		
2-THO8-NP-NS-2DB-292	35.01	4878	1.885	11.38	501.27	421.83	25.684	1.188		
2-THO9-NP-NS-2DB-292	37.66	4878	1.948	11.38	539.21	429.11	26.401	1.257	1.194	0.060
1-THO1-P-NS-2DB-292	42.85	4128	1.790	0.50	666.93	172.17	1.081	3.874		
1-THO2-P-NS-2DB-292	44.23	4128	1.787	0.50	688.41	172.16	1.079	3.999		
1-THO3-P-NS-2DB-292	41.52	4128	1.855	0.50	646.23	172.50	1.113	3.746	3.873	0.126
4-THO1-P-NS-3DB-292	60.73	5027	2.892	0.50	856.54	177.77	1.632	4.818		
4-THO2-P-NS-3DB-292	59.08	5027	2.711	0.50	833.27	176.85	1.541	4.712		
4-THO3-P-NS-3DB-292	58.92	5027	2.723	0.50	831.01	176.91	1.547	4.697	4.743	0.066

* X = Ld (C + 0.378Db)

Table 4.3a Comparison of Headed Results (w/o stirrups) to Eq. 4-4.

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Test Results Abfs / (f'c)^1/2 (in.^2)	Eq. 4-4 Prediction Abfs / (f'c)^1/2 (in.^2)	X* (in.^2)	Test / Prediction Ratio	Average	Standard Deviation
2-TH07-NP-NS-2DB-292	33.44	4878	1.877	11.38	478.79	525.53	29.408	0.911		
2-TH08-NP-NS-2DB-292	35.01	4878	1.885	11.38	501.27	526.04	29.488	0.953		
2-TH09-NP-NS-2DB-292	37.66	4878	1.948	11.38	539.21	530.04	30.116	1.017	0.960	0.054
1-TH01-P-NS-2DB-292	42.85	4128	1.790	0.50	666.93	346.48	1.254	1.925		
1-TH02-P-NS-2DB-292	44.23	4128	1.787	0.50	688.41	346.47	1.253	1.987		
1-TH03-P-NS-2DB-292	41.52	4128	1.855	0.50	646.23	346.66	1.282	1.864	1.925	0.061
4-TH01-P-NS-3DB-292	60.73	5027	2.892	0.50	856.54	349.59	1.744	2.450		
4-TH02-P-NS-3DB-292	59.08	5027	2.711	0.50	833.27	349.08	1.663	2.387		
4-TH03-P-NS-3DB-292	58.92	5027	2.723	0.50	831.01	349.11	1.668	2.380	2.406	0.038

* X = Ld [C + 0.5Db] [0.92 + 0.08 (Cmax / Cmin)]

Table 4.3b Comparisons of Headed Results (w/o stirrups) to Eq. 4-5

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Test Results Abfs (f'c)^1/2 (in.^2)	Eq. 4-5 Prediction Abfs (f'c)^1/2 (in.^2)	X* (in.^2)	Test / Prediction Ratio	Average	Standard Deviation
2-THO7-NP-NS-2DB-292	33.44	4878	1.877	11.38	478.79	424.27	29.408	1.129		
2-THO8-NP-NS-2DB-292	35.01	4878	1.885	11.38	501.27	424.80	29.488	1.180		
2-THO9-NP-NS-2DB-292	37.66	4878	1.948	11.38	539.21	429.00	30.116	1.257	1.188	0.065
1-THO1-P-NS-2DB-292	42.85	4128	1.790	0.50	666.93	236.48	1.254	2.820		
1-THO2-P-NS-2DB-292	44.23	4128	1.787	0.50	688.41	236.48	1.253	2.911		
1-THO3-P-NS-2DB-292	41.52	4128	1.855	0.50	646.23	236.67	1.282	2.730	2.821	0.090
4-THO1-P-NS-3DB-292	60.73	5027	2.892	0.50	856.54	239.75	1.744	3.573		
4-THO2-P-NS-3DB-292	59.08	5027	2.711	0.50	833.27	239.21	1.663	3.483		
4-THO3-P-NS-3DB-292	58.92	5027	2.723	0.50	831.01	239.25	1.668	3.473	3.510	0.055

* X = Ld [C + 0.5Db] [0.92 + 0.08 (Cmax / Cmin)]

Table 4.4a Comparison of Headed Results (w/o stirrups) to Eq. 4-6.

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Test Results Abfs / (f'c)^1/4 (in.^2)	Eq. 4-6 Prediction Abfs / (f'c)^1/4 (in.^2)	X* (in.^2)	Test / Prediction Ratio	Average	Standard Deviation
2-TH07-NP-NS-2DB-292	33.44	4878	1.877	11.38	4001.34	3751.65	836.28	1.067		
2-TH08-NP-NS-2DB-292	35.01	4878	1.885	11.38	4189.21	3755.36	837.71	1.116		
2-TH09-NP-NS-2DB-292	37.66	4878	1.948	11.38	4506.30	3785.06	849.21	1.191	1.124	0.062
1-TH01-P-NS-2DB-292	42.85	4128	1.790	0.50	5345.84	1989.06	153.89	2.688		
1-TH02-P-NS-2DB-292	44.23	4128	1.787	0.50	5518.00	1989.51	154.07	2.774		
1-TH03-P-NS-2DB-292	41.52	4128	1.855	0.50	5179.91	1979.68	150.26	2.617	2.693	0.079
4-TH01-P-NS-3DB-292	60.73	5027	2.892	0.50	7212.34	1898.54	118.85	3.799		
4-TH02-P-NS-3DB-292	59.08	5027	2.711	0.50	7016.38	1906.58	121.96	3.680		
4-TH03-P-NS-3DB-292	58.92	5027	2.723	0.50	6997.38	1905.99	121.74	3.671	3.717	0.071

* X = [2CLd (Cmax / Cmin)] + [LdDb (Cmax / Cmin)] + [72.381Ab (Cmax / Cmin)] + [22.39CLd] +[11.2LdDb]

Table 4.4b Comparison of Headed Results (w/o stirrups) to Eq. 4-7.

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Test Results Abfs (f'c)^1/2 (in.^2)	Eq. 4-7 Prediction Abfs (f'c)^1/2 (in.^2)	X* (in.^2)	Test / Prediction Ratio	Average	Standard Deviation
2-TH07-NP-NS-2DB-292	33.44	4878	1.877	11.38	478.79	447.24	74.049	1.071		
2-TH08-NP-NS-2DB-292	35.01	4878	1.885	11.38	501.27	447.79	74.185	1.119		
2-TH09-NP-NS-2DB-292	37.66	4878	1.948	11.38	539.21	452.13	75.272	1.193	1.128	0.061
1-TH01-P-NS-2DB-292	42.85	4128	1.790	0.50	666.93	197.77	11.535	3.372		
1-TH02-P-NS-2DB-292	44.23	4128	1.787	0.50	688.41	197.81	11.547	3.480		
1-TH03-P-NS-2DB-292	41.52	4128	1.855	0.50	646.23	196.79	11.290	3.284	3.379	0.098
4-TH01-P-NS-3DB-292	60.73	5027	2.892	0.50	856.54	188.72	9.268	4.539		
4-TH02-P-NS-3DB-292	59.08	5027	2.711	0.50	833.27	189.45	9.452	4.398		
4-TH03-P-NS-3DB-292	58.92	5027	2.723	0.50	831.01	189.40	9.439	4.388	4.442	0.084

* X = {[0.1025 (Cmax / Cmin)] [(2CLd) + (LdDb) + (50Ab)]} + {2CLd} + {LdDb}

Table 4.5 Comparison of Headed Results (w/o stirrups) to Eqs. 4-8 thru 4-13.

ACI 12.2.3 (1995) [EQ. 12-1]

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Test Results Abfs / (f'c)^1/2 (in.^2)	Eq. 4-9 Prediction Abfs / (f'c)^1/2 (in.^2)	X* (in.^2)	Test Prediction Ratio
2-TH07-NP-NS-2DB-16	33.44	4878	1.877	11.38	478.79	61.47	4.610	7.789
2-TH08-NP-NS-2DB-16	35.01	4878	1.885	11.38	501.27	61.21	4.591	8.190
2-TH09-NP-NS-2DB-16	37.66	4878	1.948	11.38	539.21	59.23	4.442	9.104

Average	Standard Deviation
8.361	0.674

ACI 12.5.2 & 12.5.3 (1995)

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Test Results Abfs / (f'c)^1/2 (in.^2)	Eq. 4-11 Prediction Abfs / (f'c)^1/2 (in.^2)	X** (in.^2)	Test Prediction Ratio
2-TH07-NP-NS-2DB-16	33.44	4878	1.877	11.38	478.79	628.16	8.794	0.762
2-TH08-NP-NS-2DB-16	35.01	4878	1.885	11.38	501.27	628.16	8.794	0.798
2-TH09-NP-NS-2DB-16	37.66	4878	1.948	11.38	539.21	628.16	8.794	0.858

Average	Standard Deviation
0.806	0.049

ACI 408 Committee Report Sect. 1.1.2 & 1.1.3

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Test Results Abfs / (f'c)^1/2 (in.^2)	Eq. 4-13 Prediction Abfs / (f'c)^1/2 (in.^2)	X*** (in.^2)	Test Prediction Ratio
2-TH07-NP-NS-2DB-16	33.44	4878	1.877	11.38	478.79	310.33	11.380	1.543
2-TH08-NP-NS-2DB-16	35.01	4878	1.885	11.38	501.27	310.33	11.380	1.615
2-TH09-NP-NS-2DB-16	37.66	4878	1.948	11.38	539.21	310.33	11.380	1.738

Average	Standard Deviation
1.632	0.098

* X = (AbLd) / C Where (Db / C)must be greater than or equal to 0.4

** X = (AbLd) / Db

*** X = Ld

Table 4.6a Comparison of Headed Results (WITH stirrups) to Eq. 4-14a.
Confinement Limit NOT imposed.

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Stirrup Spacing (in.)	Test Results Abfs / (f'c)^1/2 (in.^2)	Eq.4-14a Prediction Abfs / (f'c)^1/2 (in.^2)	X* (in.^2)	Test / Prediction Ratio	Average	Standard Deviation
2-TH04-NP-3S1-2DB-19	54.92	4878	1.888	11.25	5.0	786.34	512.73	34.631	1.534		
2-TH05-NP-3S1-2DB-19	52.71	4878	2.000	11.25	5.0	754.70	525.51	35.891	1.436		
2-TH06-NP-3S1-2DB-13	51.66	4878	1.879	11.50	5.0	739.66	519.49	35.298	1.424	1.465	0.060
4-TH07-NP-3S1-3DB-19	59.79	5003	3.227	11.25	5.0	845.30	665.59	49.695	1.270		
4-TH08-NP-3S1-3DB-19	57.51	5003	3.152	11.25	5.0	813.07	657.02	48.851	1.238		
4-TH09-NP-3S1-3DB-19	55.31	5003	3.244	11.25	5.0	781.97	667.53	49.886	1.171	1.226	0.050
3-TH10-NP-4S1-2DB-19	51.44	4851	2.115	11.25	3.0	738.56	600.93	43.323	1.229		
3-TH11-NP-4S1-2DB-19	50.87	4851	2.021	11.25	3.0	730.38	590.20	42.266	1.238		
3-TH12-NP-4S1-2DB-19	50.97	4851	2.073	11.25	3.0	731.81	596.13	42.851	1.228	1.231	0.005
3-TH04-NP-4S1-3DB-19	54.71	4850	3.236	11.25	3.0	785.59	728.90	55.934	1.078		
3-TH05-NP-4S1-3DB-19	55.38	4850	3.277	11.25	3.0	795.21	733.58	56.396	1.084		
3-TH06-NP-4S1-3DB-19	50.73	4850	3.216	11.25	3.0	728.44	726.61	55.709	1.003	1.055	0.045
4-TH13-NP-4S2-2DB-19	56.12	5027	2.183	11.25	3.0	791.52	608.69	44.088	1.300		
4-TH14-NP-4S2-2DB-19	52.13	5027	2.193	11.25	3.0	735.25	609.83	44.201	1.206		
4-TH15-NP-4S2-2DB-19	57.81	5027	2.227	11.25	3.0	815.36	613.71	44.583	1.329	1.278	0.064
4-TH10-NP-4S2-3DB-19	58.13	5027	3.026	11.25	3.0	819.87	704.92	53.572	1.163		
4-TH11-NP-4S2-3DB-19	56.94	5027	3.157	11.25	3.0	803.09	719.88	55.046	1.116		
4-TH12-NP-4S2-3DB-19	55.89	5027	3.237	11.25	3.0	788.28	729.01	55.946	1.081	1.120	0.041
4-TH19-NP-5S1-2DB-19	55.90	5027	1.951	11.25	2.5	788.42	613.35	44.547	1.285		
4-TH20-NP-5S1-2DB-19	57.22	5027	2.180	11.25	2.5	807.04	639.49	47.123	1.262		
4-TH21-NP-5S1-2DB-19	59.61	5027	2.035	11.25	2.5	840.75	622.94	45.492	1.350	1.299	0.045
4-TH16-NP-5S1-3DB-19	58.78	5027	3.109	11.25	2.5	829.04	745.54	57.575	1.112		
4-TH17-NP-5S1-3DB-19	59.33	5027	3.102	11.25	2.5	836.80	744.74	57.496	1.124		
4-TH18-NP-5S1-3DB-19	60.08	5027	3.123	11.25	2.5	847.37	747.14	57.732	1.134	1.123	0.011

* X = Ld [C + (0.378Db) + (0.00062AtrFytr/s)]

Table 4.6b Comparison of Headed Results (WITH stirrups) to Eq. 4-14a.
Confinement Limit IS imposed.

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Stirrup Spacing (in.)	Test Results Abfs (f'c)^1/2 (in.^2)	Eq.4-14a Prediction Abfs (f'c)^1/2 (in.^2)	X* (in.^2)	Test / Prediction Ratio	Average	Standard Deviation
2-TH04-NP-3S1-2DB-19	54.92	4878	1.888	11.25	5.0	786.34	512.73	34.631	1.534		
2-TH05-NP-3S1-2DB-19	52.71	4878	2.000	11.25	5.0	754.70	525.51	35.891	1.436		
2-TH06-NP-3S1-2DB-13	51.66	4878	1.879	11.50	5.0	739.66	519.49	35.298	1.424	1.465	0.060
4-TH07-NP-3S1-3DB-19	59.79	5003	3.227	11.25	5.0	845.30	665.59	49.695	1.270		
4-TH08-NP-3S1-3DB-19	57.51	5003	3.152	11.25	5.0	813.07	657.02	48.851	1.238		
4-TH09-NP-3S1-3DB-19	55.31	5003	3.244	11.25	5.0	781.97	667.53	49.886	1.171	1.226	0.050
3-TH10-NP-4S1-2DB-19	51.44	4851	2.115	11.25	3.0	738.56	549.68	38.273	1.344		
3-TH11-NP-4S1-2DB-19	50.87	4851	2.021	11.25	3.0	730.38	538.95	37.216	1.355		
3-TH12-NP-4S1-2DB-19	50.97	4851	2.073	11.25	3.0	731.81	544.89	37.801	1.343	1.347	0.007
3-TH04-NP-4S1-3DB-19	54.71	4850	3.236	11.25	3.0	785.59	677.65	50.885	1.159		
3-TH05-NP-4S1-3DB-19	55.38	4850	3.277	11.25	3.0	795.21	682.33	51.346	1.165		
3-TH06-NP-4S1-3DB-19	50.73	4850	3.216	11.25	3.0	728.44	675.37	50.660	1.079	1.134	0.048
4-TH13-NP-4S2-2DB-19	56.12	5027	2.183	11.25	3.0	791.52	557.45	39.038	1.420		
4-TH14-NP-4S2-2DB-19	52.13	5027	2.193	11.25	3.0	735.25	558.59	39.151	1.316		
4-TH15-NP-4S2-2DB-19	57.81	5027	2.227	11.25	3.0	815.36	562.47	39.533	1.450	1.395	0.070
4-TH10-NP-4S2-3DB-19	58.13	5027	3.026	11.25	3.0	819.87	653.68	48.522	1.254		
4-TH11-NP-4S2-3DB-19	56.94	5027	3.157	11.25	3.0	803.09	668.64	49.996	1.201		
4-TH12-NP-4S2-3DB-19	55.89	5027	3.237	11.25	3.0	788.28	677.77	50.896	1.163	1.206	0.046
4-TH19-NP-5S1-2DB-19	55.90	5027	1.951	11.25	2.5	788.42	530.96	36.428	1.485		
4-TH20-NP-5S1-2DB-19	57.22	5027	2.180	11.25	2.5	807.04	557.10	39.005	1.449		
4-TH21-NP-5S1-2DB-19	59.61	5027	2.035	11.25	2.5	840.75	540.55	37.373	1.555	1.496	0.054
4-TH16-NP-5S1-3DB-19	58.78	5027	3.109	11.25	2.5	829.04	663.16	49.456	1.250		
4-TH17-NP-5S1-3DB-19	59.33	5027	3.102	11.25	2.5	836.80	662.36	49.377	1.263		
4-TH18-NP-5S1-3DB-19	60.08	5027	3.123	11.25	2.5	847.37	664.75	49.613	1.275	1.263	0.012

* X = Ld [C + (0.378Db) + (0.00062AtrFytr/s)] where (0.00062AtrFytr/s) is less than or equal to (0.93LdDb)

Table 4.7a Comparison of Headed Results (WITH stirrups) to Eq. 4-15.
For Pattern #4S1 N=3

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Stirrup Spacing (in.)	Test Results Abfs / (f'c)^1/4 (in.^2)	Eq. 4-15 Prediction Abfs / (f'c)^1/4 (in.^2)	X* (in.^2)	N Stir.	Test / Prediction Ratio	Average	Standard Deviation
2-TH04-NP-3S1-2DB-19	54.92	4878	1.888	11.25	5.0	6571.58	4660.42	1726.06	3	1.410		
2-TH05-NP-3S1-2DB-19	52.71	4878	2.000	11.25	5.0	6307.14	4712.98	1746.41	3	1.338		
2-TH06-NP-3S1-2DB-13	51.66	4878	1.879	11.50	5.0	6181.50	4697.11	1740.27	3	1.316	1.355	0.049
4-TH07-NP-3S1-3DB-19	59.79	5003	3.227	11.25	5.0	7109.20	5381.11	2005.08	3	1.321		
4-TH08-NP-3S1-3DB-19	57.51	5003	3.152	11.25	5.0	6838.10	5337.36	1988.14	3	1.281		
4-TH09-NP-3S1-3DB-19	55.31	5003	3.244	11.25	5.0	6576.52	5391.06	2008.93	3	1.220	1.274	0.051
3-TH10-NP-4S1-2DB-19	51.44	4851	2.115	11.25	3.0	6163.72	4769.18	1768.17	3	1.292		
3-TH11-NP-4S1-2DB-19	50.87	4851	2.021	11.25	3.0	6095.42	4723.08	1750.32	3	1.291		
3-TH12-NP-4S1-2DB-19	50.97	4851	2.073	11.25	3.0	6107.41	4748.42	1760.13	3	1.286	1.290	0.003
3-TH04-NP-4S1-3DB-19	54.71	4850	3.236	11.25	3.0	6555.88	5386.37	2007.11	3	1.217		
3-TH05-NP-4S1-3DB-19	55.38	4850	3.277	11.25	3.0	6636.17	5410.40	2016.42	3	1.227		
3-TH06-NP-4S1-3DB-19	50.73	4850	3.216	11.25	3.0	6078.96	5374.68	2002.59	3	1.131	1.192	0.053
4-TH13-NP-4S2-2DB-19	56.12	5027	2.183	11.25	3.0	6664.85	5043.91	1874.53	4	1.321		
4-TH14-NP-4S2-2DB-19	52.13	5027	2.193	11.25	3.0	6191.00	5048.99	1876.49	4	1.226		
4-TH15-NP-4S2-2DB-19	57.81	5027	2.227	11.25	3.0	6865.56	5066.34	1883.21	4	1.355	1.301	0.067
4-TH10-NP-4S2-3DB-19	58.13	5027	3.026	11.25	3.0	6903.56	5505.00	2053.04	4	1.254		
4-TH11-NP-4S2-3DB-19	56.94	5027	3.157	11.25	3.0	6762.23	5580.84	2082.40	4	1.212		
4-TH12-NP-4S2-3DB-19	55.89	5027	3.237	11.25	3.0	6637.54	5627.53	2100.48	4	1.179	1.215	0.037
4-TH19-NP-5S1-2DB-19	55.90	5027	1.951	11.25	2.5	6638.72	5170.84	1923.67	5	1.284		
4-TH20-NP-5S1-2DB-19	57.22	5027	2.180	11.25	2.5	6795.49	5282.96	1967.08	5	1.286		
4-TH21-NP-5S1-2DB-19	59.61	5027	2.035	11.25	2.5	7079.33	5211.00	1939.22	5	1.359	1.310	0.042
4-TH16-NP-5S1-3DB-19	58.78	5027	3.109	11.25	2.5	6980.75	5793.53	2164.74	5	1.205		
4-TH17-NP-5S1-3DB-19	59.33	5027	3.102	11.25	2.5	7046.07	5789.47	2163.17	5	1.217		
4-TH18-NP-5S1-3DB-19	60.08	5027	3.123	11.25	2.5	7135.14	5801.65	2167.89	5	1.230	1.217	0.012

* X = Ld {[2 (Cmax / Cmin)(C + 0.5Db)] + 22.4C + 11.2Db} + { 72.4Ab [(Cmax / Cmin) + 11.2]} + {846.7NAtr/n}

Table 4.7b Comparison of Headed Results (WITH stirrups) to Eq. 4-15.
For Pattern #4S1 N=4

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Stirrup Spacing (in.)	Test Results Abfs / (f'c)^1/2 (in.^2)	Eq.4-15 Prediction Abfs / (f'c)^1/2 (in.^2)	X* (in.^2)	N Stir.	Test / Prediction Ratio
3-TH10-NP-4S1-2DB-19	51.44	4851	2.12	11.25	3.0	6163.72	5009.75	1861.31	4	1.230
3-TH11-NP-4S1-2DB-19	50.87	4851	2.02	11.25	3.0	6095.42	4963.65	1843.46	4	1.228
3-TH12-NP-4S1-2DB-19	50.97	4851	2.07	11.25	3.0	6107.41	4988.99	1853.27	4	1.224
3-TH04-NP-4S1-3DB-19	54.71	4850	3.24	11.25	3.0	6555.88	5626.94	2100.25	4	1.165
3-TH05-NP-4S1-3DB-19	55.38	4850	3.28	11.25	3.0	6636.17	5650.97	2109.55	4	1.174
3-TH06-NP-4S1-3DB-19	50.73	4850	3.22	11.25	3.0	6078.96	5615.25	2095.72	4	1.083

Average	Standard Deviation
1.227511	0.003114

Average	Standard Deviation
1.14067	0.050519

* X = Ld {[2 (Cmax / Cmin)(C + 0.5Db)] + 22.4C + 11.2Db} + { 72.4Ab [(Cmax / Cmin) +11.2]} + {846.7NAtr/n}

Table 4.8a Comparison of Headed Results (WITH stirrups) to Eq. 4-16.
Confinement Limits NOT Imposed.

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Stirrup Spacing (in.)	Test Results Abfs / (f'c)^1/2 (in.^2)	Eq. 4-16 Prediction Abfs / (f'c)^1/2 (in.^2)	X* (in.^2)	Test / Prediction Ratio	Average	Standard Deviation
2-TH04-NP-3S1-2DB-19	54.92	4878	1.888	11.25	5.0	786.34	41.23	3.093	19.070		
2-TH05-NP-3S1-2DB-19	52.71	4878	2.000	11.25	5.0	754.70	39.63	2.972	19.043		
2-TH06-NP-3S1-2DB-13	51.66	4878	1.879	11.50	5.0	739.66	42.29	3.172	17.491	18.535	0.904
4-TH07-NP-3S1-3DB-19	59.79	5003	3.227	11.25	5.0	845.30	27.79	2.084	30.417		
4-TH08-NP-3S1-3DB-19	57.51	5003	3.152	11.25	5.0	813.07	28.31	2.123	28.723		
4-TH09-NP-3S1-3DB-19	55.31	5003	3.244	11.25	5.0	781.97	27.68	2.076	28.255	29.132	1.138
3-TH10-NP-4S1-2DB-19	51.44	4851	2.115	11.25	3.0	738.56	31.87	2.390	23.177		
3-TH11-NP-4S1-2DB-19	50.87	4851	2.021	11.25	3.0	730.38	32.73	2.454	22.318		
3-TH12-NP-4S1-2DB-19	50.97	4851	2.073	11.25	3.0	731.81	32.24	2.418	22.696	22.730	0.430
3-TH04-NP-4S1-3DB-19	54.71	4850	3.236	11.25	3.0	785.59	24.27	1.820	32.368		
3-TH05-NP-4S1-3DB-19	55.38	4850	3.277	11.25	3.0	795.21	24.06	1.805	33.050		
3-TH06-NP-4S1-3DB-19	50.73	4850	3.216	11.25	3.0	728.44	24.37	1.828	29.886	31.768	1.665
4-TH13-NP-4S2-2DB-19	56.12	5027	2.183	11.25	3.0	791.52	31.27	2.345	25.310		
4-TH14-NP-4S2-2DB-19	52.13	5027	2.193	11.25	3.0	735.25	31.19	2.339	23.575		
4-TH15-NP-4S2-2DB-19	57.81	5027	2.227	11.25	3.0	815.36	30.90	2.318	26.387	25.091	1.419
4-TH10-NP-4S2-3DB-19	58.13	5027	3.026	11.25	3.0	819.87	25.40	1.905	32.272		
4-TH11-NP-4S2-3DB-19	56.94	5027	3.157	11.25	3.0	803.09	24.68	1.851	32.533		
4-TH12-NP-4S2-3DB-19	55.89	5027	3.237	11.25	3.0	788.28	24.27	1.820	32.486	32.431	0.139
4-TH19-NP-5S1-2DB-19	55.90	5027	1.951	11.25	2.5	788.42	30.76	2.307	25.635		
4-TH20-NP-5S1-2DB-19	57.22	5027	2.180	11.25	2.5	807.04	28.97	2.173	27.859		
4-TH21-NP-5S1-2DB-19	59.61	5027	2.035	11.25	2.5	840.75	30.08	2.256	27.955	27.150	1.313
4-TH16-NP-5S1-3DB-19	58.78	5027	3.109	11.25	2.5	829.04	23.44	1.758	35.367		
4-TH17-NP-5S1-3DB-19	59.33	5027	3.102	11.25	2.5	836.80	23.47	1.761	35.646		
4-TH18-NP-5S1-3DB-19	60.08	5027	3.123	11.25	2.5	847.37	23.37	1.753	36.253	35.755	0.453

* X = [LdAb / (C + Ktr)]

Table 4.8b Comparison of Headed Results (WITH stirrups) to Eq. 4-16.
Confinement Limit IS Imposed.

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Stirrup Spacing (in.)	Test Results Abfs / (f'c)^1/2 (in.^2)	Eq. 4-16 Prediction Abfs / (f'c)^1/2 (in.^2)	X* (in.^2)	Test / Prediction Ratio	Average	Standard Deviation
2-TH04-NP-3S1-2DB-19	54.92	4878	1.888	11.25	5.0	786.34	46.40	8.699	16.948		
2-TH05-NP-3S1-2DB-19	52.71	4878	2.000	11.25	5.0	754.70	46.40	8.699	16.266		
2-TH06-NP-3S1-2DB-13	51.66	4878	1.879	11.50	5.0	739.66	47.43	8.893	15.596	16.270	0.676
4-TH07-NP-3S1-3DB-19	59.79	5003	3.227	11.25	5.0	845.30	46.40	8.699	18.219		
4-TH08-NP-3S1-3DB-19	57.51	5003	3.152	11.25	5.0	813.07	46.40	8.699	17.524		
4-TH09-NP-3S1-3DB-19	55.31	5003	3.244	11.25	5.0	781.97	46.40	8.699	16.854	17.533	0.683
3-TH10-NP-4S1-2DB-19	51.44	4851	2.115	11.25	3.0	738.56	46.40	8.699	15.918		
3-TH11-NP-4S1-2DB-19	50.87	4851	2.021	11.25	3.0	730.38	46.40	8.699	15.742		
3-TH12-NP-4S1-2DB-19	50.97	4851	2.073	11.25	3.0	731.81	46.40	8.699	15.773	15.811	0.094
3-TH04-NP-4S1-3DB-19	54.71	4850	3.236	11.25	3.0	785.59	46.40	8.699	16.932		
3-TH05-NP-4S1-3DB-19	55.38	4850	3.277	11.25	3.0	795.21	46.40	8.699	17.140		
3-TH06-NP-4S1-3DB-19	50.73	4850	3.216	11.25	3.0	728.44	46.40	8.699	15.700	16.591	0.778
4-TH13-NP-4S2-2DB-19	56.12	5027	2.183	11.25	3.0	791.52	46.40	8.699	17.060		
4-TH14-NP-4S2-2DB-19	52.13	5027	2.193	11.25	3.0	735.25	46.40	8.699	15.847		
4-TH15-NP-4S2-2DB-19	57.81	5027	2.227	11.25	3.0	815.36	46.40	8.699	17.574	16.827	0.887
4-TH10-NP-4S2-3DB-19	58.13	5027	3.026	11.25	3.0	819.87	46.40	8.699	17.671		
4-TH11-NP-4S2-3DB-19	56.94	5027	3.157	11.25	3.0	803.09	46.40	8.699	17.309		
4-TH12-NP-4S2-3DB-19	55.89	5027	3.237	11.25	3.0	788.28	46.40	8.699	16.990	17.323	0.341
4-TH19-NP-5S1-2DB-19	55.90	5027	1.951	11.25	2.5	788.42	46.40	8.699	16.993		
4-TH20-NP-5S1-2DB-19	57.22	5027	2.180	11.25	2.5	807.04	46.40	8.699	17.394		
4-TH21-NP-5S1-2DB-19	59.61	5027	2.035	11.25	2.5	840.75	46.40	8.699	18.121	17.503	0.572
4-TH16-NP-5S1-3DB-19	58.78	5027	3.109	11.25	2.5	829.04	46.40	8.699	17.869		
4-TH17-NP-5S1-3DB-19	59.33	5027	3.102	11.25	2.5	836.80	46.40	8.699	18.036		
4-TH18-NP-5S1-3DB-19	60.08	5027	3.123	11.25	2.5	847.37	46.40	8.699	18.264	18.056	0.198

* X = [LdAb / (C + Ktr)] where (Db / C + Ktr) is greater than or equal to 0.4

Table 4.9a Comparsion of Headed Results (WITH stirrups) to Eq. 4-18.
Confinement Limit NOT Imposed.

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Stirrup Spacing (in.)	Test Results Abfs / (f'c)^1/2 (in.^2)	Eq. 4-18 Prediction Abfs / (f'c)^1/2 (in.^2)	X* (in.^2)	Test / Prediction Ratio	Average	Standard Deviation
2-THO4-NP-3S1-2DB-19	54.92	4878	1.888	11.25	5.0	786.34	400.09	36.675	1.965		
2-THO5-NP-3S1-2DB-19	52.71	4878	2.000	11.25	5.0	754.70	413.83	37.935	1.824		
2-THO6-NP-3S1-2DB-13	51.66	4878	1.879	11.50	5.0	739.66	407.85	37.387	1.814	1.868	0.081
4-THO7-NP-3S1-3DB-19	59.79	5003	3.227	11.25	5.0	845.30	564.42	51.739	1.498		
4-THO8-NP-3S1-3DB-19	57.51	5003	3.152	11.25	5.0	813.07	555.21	50.895	1.464		
4-THO9-NP-3S1-3DB-19	55.31	5003	3.244	11.25	5.0	781.97	566.50	51.930	1.380	1.447	0.057
3-TH10-NP-4S1-2DB-19	51.44	4851	2.115	11.25	3.0	738.56	499.95	45.829	1.477		
3-TH11-NP-4S1-2DB-19	50.87	4851	2.021	11.25	3.0	730.38	488.41	44.771	1.495		
3-TH12-NP-4S1-2DB-19	50.97	4851	2.073	11.25	3.0	731.81	494.79	45.356	1.479	1.484	0.010
3-THO4-NP-4S1-3DB-19	54.71	4850	3.236	11.25	3.0	785.59	637.52	58.440	1.232		
3-THO5-NP-4S1-3DB-19	55.38	4850	3.277	11.25	3.0	795.21	642.55	58.901	1.238		
3-THO6-NP-4S1-3DB-19	50.73	4850	3.216	11.25	3.0	728.44	635.07	58.215	1.147	1.206	0.048
4-TH13-NP-4S2-2DB-19	56.12	5027	2.183	11.25	3.0	791.52	508.29	46.594	1.557		
4-TH14-NP-4S2-2DB-19	52.13	5027	2.193	11.25	3.0	735.25	509.52	46.706	1.443		
4-TH15-NP-4S2-2DB-19	57.81	5027	2.227	11.25	3.0	815.36	513.69	47.089	1.587	1.529	0.072
4-TH10-NP-4S2-3DB-19	58.13	5027	3.026	11.25	3.0	819.87	611.75	56.078	1.340		
4-TH11-NP-4S2-3DB-19	56.94	5027	3.157	11.25	3.0	803.09	627.83	57.551	1.279		
4-TH12-NP-4S2-3DB-19	55.89	5027	3.237	11.25	3.0	788.28	637.64	58.451	1.236	1.285	0.050
4-TH19-NP-5S1-2DB-19	55.90	5027	1.951	11.25	2.5	788.42	515.82	47.284	1.528		
4-TH20-NP-5S1-2DB-19	57.22	5027	2.180	11.25	2.5	807.04	543.92	49.860	1.484		
4-TH21-NP-5S1-2DB-19	59.61	5027	2.035	11.25	2.5	840.75	526.13	48.229	1.598	1.537	0.055
4-TH16-NP-5S1-3DB-19	58.78	5027	3.109	11.25	2.5	829.04	657.94	60.311	1.260		
4-TH17-NP-5S1-3DB-19	59.33	5027	3.102	11.25	2.5	836.80	657.08	60.233	1.274		
4-TH18-NP-5S1-3DB-19	60.08	5027	3.123	11.25	2.5	847.37	659.65	60.469	1.285	1.273	0.012

* X = Ld K

Table 4.9b Comparison of Headed Results (WITH stirrups) to Eq. 4-18. Confinement Limit IS Imposed.

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Stirrup Spacing (in.)	Test Results Abfs / (f'c)^1/2 (in.^2)	Eq. 4-18 Prediction Abfs / (f'c)^1/2 (in.^2)	X* (in.^2)	Test / Prediction Ratio	Average	Standard Deviation
2-TH04-NP-3S1-2DB-19	54.92	4878	1.888	11.25	5.0	786.34	362.29	33.21	2.170		
2-TH05-NP-3S1-2DB-19	52.71	4878	2.000	11.25	5.0	754.70	362.29	33.21	2.083		
2-TH06-NP-3S1-2DB-13	51.66	4878	1.879	11.50	5.0	739.66	370.34	33.95	1.997	2.084	0.082
4-TH07-NP-3S1-3DB-19	59.79	5003	3.227	11.25	5.0	845.30	362.29	33.21	2.333		
4-TH08-NP-3S1-3DB-19	57.51	5003	3.152	11.25	5.0	813.07	362.29	33.21	2.244		
4-TH09-NP-3S1-3DB-19	55.31	5003	3.244	11.25	5.0	781.97	362.29	33.21	2.158	2.245	0.083
3-TH10-NP-4S1-2DB-19	51.44	4851	2.115	11.25	3.0	738.56	362.29	33.21	2.039		
3-TH11-NP-4S1-2DB-19	50.87	4851	2.021	11.25	3.0	730.38	362.29	33.21	2.016		
3-TH12-NP-4S1-2DB-19	50.97	4851	2.073	11.25	3.0	731.81	362.29	33.21	2.020	2.025	0.011
3-TH04-NP-4S1-3DB-19	54.71	4850	3.236	11.25	3.0	785.59	362.29	33.21	2.168		
3-TH05-NP-4S1-3DB-19	55.38	4850	3.277	11.25	3.0	795.21	362.29	33.21	2.195		
3-TH06-NP-4S1-3DB-19	50.73	4850	3.216	11.25	3.0	728.44	362.29	33.21	2.011	2.125	0.095
4-TH13-NP-4S2-2DB-19	56.12	5027	2.183	11.25	3.0	791.52	362.29	33.21	2.185		
4-TH14-NP-4S2-2DB-19	52.13	5027	2.193	11.25	3.0	735.25	362.29	33.21	2.029		
4-TH15-NP-4S2-2DB-19	57.81	5027	2.227	11.25	3.0	815.36	362.29	33.21	2.251	2.155	0.108
4-TH10-NP-4S2-3DB-19	58.13	5027	3.026	11.25	3.0	819.87	362.29	33.21	2.263		
4-TH11-NP-4S2-3DB-19	56.94	5027	3.157	11.25	3.0	803.09	362.29	33.21	2.217		
4-TH12-NP-4S2-3DB-19	55.89	5027	3.237	11.25	3.0	788.28	362.29	33.21	2.176	2.219	0.041
4-TH19-NP-5S1-2DB-19	55.90	5027	1.951	11.25	2.5	788.42	362.29	33.21	2.176		
4-TH20-NP-5S1-2DB-19	57.22	5027	2.180	11.25	2.5	807.04	362.29	33.21	2.228		
4-TH21-NP-5S1-2DB-19	59.61	5027	2.035	11.25	2.5	840.75	362.29	33.21	2.321	2.241	0.070
4-TH16-NP-5S1-3DB-19	58.78	5027	3.109	11.25	2.5	829.04	362.29	33.21	2.288		
4-TH17-NP-5S1-3DB-19	59.33	5027	3.102	11.25	2.5	836.80	362.29	33.21	2.310		
4-TH18-NP-5S1-3DB-19	60.08	5027	3.123	11.25	2.5	847.37	362.29	33.21	2.339	2.312	0.024

* X = Ld K where K = 3Db

Table 4.10 Comparison of Headed Results (WITH stirrups) to Eq. 4-19.

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Stirrup Spacing (in.)	Test Results Abfs / (f'c)^1/2 (in.^2)	Eq. 4-19 Prediction Abfs / (f'c)^1/2 (in.^2)	X* (in.^2)	Test / Prediction Ratio	Average	Standard Deviation
2-TH04-NP-3S1-2DB-19	54.92	4878	1.888	11.25	5.0	786.34	621.39	8.699	1.265		
2-TH05-NP-3S1-2DB-19	52.71	4878	2.000	11.25	5.0	754.70	621.39	8.699	1.215		
2-TH06-NP-3S1-2DB-13	51.66	4878	1.879	11.50	5.0	739.66	635.20	8.893	1.164	1.215	0.050
4-TH07-NP-3S1-3DB-19	59.79	5003	3.227	11.25	5.0	845.30	621.39	8.699	1.360		
4-TH08-NP-3S1-3DB-19	57.51	5003	3.152	11.25	5.0	813.07	621.39	8.699	1.308		
4-TH09-NP-3S1-3DB-19	55.31	5003	3.244	11.25	5.0	781.97	621.39	8.699	1.258	1.309	0.051
3-TH10-NP-4S1-2DB-19	51.44	4851	2.115	11.25	3.0	738.56	887.68	8.699	0.832		
3-TH11-NP-4S1-2DB-19	50.87	4851	2.021	11.25	3.0	730.38	887.68	8.699	0.823		
3-TH12-NP-4S1-2DB-19	50.97	4851	2.073	11.25	3.0	731.81	887.68	8.699	0.824	0.826	0.005
3-TH04-NP-4S1-3DB-19	54.71	4850	3.236	11.25	3.0	785.59	887.68	8.699	0.885		
3-TH05-NP-4S1-3DB-19	55.38	4850	3.277	11.25	3.0	795.21	887.68	8.699	0.896		
3-TH06-NP-4S1-3DB-19	50.73	4850	3.216	11.25	3.0	728.44	887.68	8.699	0.821	0.867	0.041
4-TH13-NP-4S2-2DB-19	56.12	5027	2.183	11.25	3.0	791.52	887.68	8.699	0.892		
4-TH14-NP-4S2-2DB-19	52.13	5027	2.193	11.25	3.0	735.25	887.68	8.699	0.828		
4-TH15-NP-4S2-2DB-19	57.81	5027	2.227	11.25	3.0	815.36	887.68	8.699	0.919	0.879	0.046
4-TH10-NP-4S2-3DB-19	58.13	5027	3.026	11.25	3.0	819.87	887.68	8.699	0.924		
4-TH11-NP-4S2-3DB-19	56.94	5027	3.157	11.25	3.0	803.09	887.68	8.699	0.905		
4-TH12-NP-4S2-3DB-19	55.89	5027	3.237	11.25	3.0	788.28	887.68	8.699	0.888	0.905	0.018
4-TH19-NP-5S1-2DB-19	55.90	5027	1.951	11.25	2.5	788.42	887.68	8.699	0.888		
4-TH20-NP-5S1-2DB-19	57.22	5027	2.180	11.25	2.5	807.04	887.68	8.699	0.909		
4-TH21-NP-5S1-2DB-19	59.61	5027	2.035	11.25	2.5	840.75	887.68	8.699	0.947	0.915	0.030
4-TH16-NP-5S1-3DB-19	58.78	5027	3.109	11.25	2.5	829.04	887.68	8.699	0.934		
4-TH17-NP-5S1-3DB-19	59.33	5027	3.102	11.25	2.5	836.80	887.68	8.699	0.943		
4-TH18-NP-5S1-3DB-19	60.08	5027	3.123	11.25	2.5	847.37	887.68	8.699	0.955	0.944	0.010

* X = (LdAb/Db)

Table 4.11 Comparison of Straight Bar Results (WITH stirrups) to Eq. 4-14a and 4-15.

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Stirrup Spacing (in.)	Test Results Abfs (f'c)^1/2 (in.^2)	Eq. 4-14a Predictions Abfs (f'c)^1/2 (in.^2)	X* (in.^2)	Test / Prediction Ratio
Predicted Values Determined by Eq. 4-14a									
2-SB01-NP-3S1-2DB-13	32.58	4878	1.892	11.50	5.0	466.48	521.00	35.447	0.895
3-SB01-NP-3S1-3DB-19	36.56	4812	3.289	11.25	5.0	527.04	672.66	50.393	0.784
3-SB02-NP-3S1-3DB-19	40.75	4812	3.240	11.25	5.0	587.44	667.07	49.841	0.881

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Stirrup Spacing (in.)	Test Results Abfs (f'c)^1/4 (in.^2)	Eq. 4-15 Predictions Abfs (f'c)^1/4 (in.^2)	X** (in.^2)	Test / Prediction Ratio	N***
Predicted Values Determined by Eq. 4-15										
2-SB01-NP-3S1-2DB-13	32.58	4878	1.892	11.50	5.0	3898.44	4703.25	1742.642	0.829	3
3-SB01-NP-3S1-3DB-19	36.56	4812	3.289	11.25	5.0	4389.60	5417.45	2019.144	0.810	3
3-SB02-NP-3S1-3DB-19	40.75	4812	3.240	11.25	5.0	4892.67	5388.72	2008.020	0.908	3

* X = Ld [C + (0.378Db) + (0.00062AtrFytr/s)]

** X = Ld {[2 (Cmax / Cmin)(C + 0.5Db)] + 22.4C + 11.2Db} + { 72.4Ab [(Cmax / Cmin) +11.2]} + {846.7NAtr/n}

*** N is the number of stirrups that cross the potential splitting failure plane for the bar being developed.

Table 4.12 Comparison of Hooked Bar Results to Eq. 4-13.

Test Identification	Ultimate Axial Load (kips)	Concrete Strength (psi)	Clear Cover (in.)	Bonded Length (in.)	Test Results Abfs (f'c)^1/2 (in.^2)	Eq. 4-13 Prediction Abfs (f'c)^1/2 (in.^2)	X* (in.^2)	Test / Prediction Ratio	Average	Standard Deviation
1-HK01-P-NS-2DB-108	35.99	4128	1.784	7.75	560.16	428.07	5.993	1.309		
1-HK02-P-NS-2DB-108	40.97	4128	1.809	7.75	637.67	428.07	5.993	1.490		
1-HK03-P-NS-2DB-108	33.54	4128	1.710	7.75	522.03	428.07	5.993	1.219		
									1.339	0.138
3-HK04-P-NS-3DB-114	53.96	4850	2.798	7.50	774.82	414.26	5.800	1.870		
3-HK05-P-NS-3DB-114	55.12	4850	2.779	7.50	791.48	414.26	5.800	1.911		
3-HK06-P-NS-3DB-114	51.05	4850	2.751	7.50	733.04	414.26	5.800	1.769		
									1.850	0.073
2-HK03-NP-NS-2DB-19	34.75	4878	2.223	11.25	497.55	621.39	8.699	0.801		
2-HK02-P-3S1-2DB-108	58.17	4878	1.618	7.25	832.87	400.45	5.606	2.080		
3-HK01-P-3S1-3DB-114	54.41	4850	2.941	7.50	781.28	414.26	5.800	1.886		
3-HK02-P-3S1-3DB-102	61.87	4812	2.917	8.00	891.90	441.88	6.186	2.018		
3-HK03-P-3S1-3DB-121	58.91	4850	2.873	7.25	845.90	400.45	5.606	2.112		
									2.006	0.114
2-HK01-NP-3S1-2DB-19	45.60	4878	1.883	11.25	652.90	621.39	8.699	1.051		
3-HK07-NP-3S1-3DB-19	47.27	4850	2.961	11.25	678.76	621.39	8.699	1.092		
3-HK08-NP-3S1-3DB-19	46.26	4850	3.076	11.25	664.25	621.39	8.699	1.069		
3-HK09-NP-3S1-3DB-19	48.60	4850	3.491	11.25	697.86	621.39	8.699	1.123		
									1.095	0.027

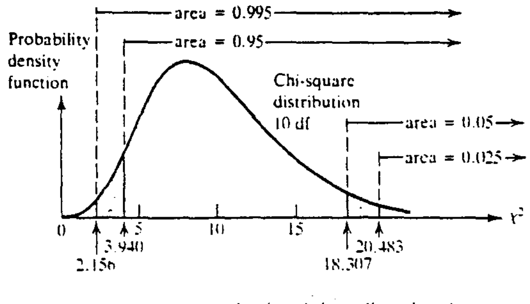
* X = (LdAb/Db)

Table 4.13 Chi-Square Analysis - A Test For Goodness of Fit

Null Hypothesis: The data is accurately described by its "best-fit" line.

	Chi-Squared (X^2)	Comparison	Acceptable Chi-Squared Stat	Conclusion
Best-Fit Line With Respect to Eq. 4-14a				
Confinment Limit NOT Imposed				
All Data Line	34.221	Less Than	35.172	DO NOT Reject
2db Data Line	17.643	Less Than	19.675	DO NOT Reject
3db Data LIne	15.415	Less Than	19.675	DO NOT Reject
Confinment Limit IS Imposed				
All Data Line	36.689	Greater Than	35.172	Reject Hypothesis
2db Data Line	19.917	Greater Than	19.675	Reject Hypothesis
3db Data LIne	10.310	Less Than	19.675	DO NOT Reject
Best-Fit Line With Respect to Eq. 4-15				
Pattern #4S1: N=3				
All Data Line	219.102	Greater Than	35.172	Reject Hypothesis
2db Data Line	87.557	Greater Than	19.675	Reject Hypothesis
3db Data LIne	103.852	Greater Than	19.675	Reject Hypothesis
Best-Fit Line With Respect to Eq. 4-15				
Pattern #4S1: N=4				
All Data Line	297.674	Greater Than	35.172	Reject Hypothesis
2db Data Line	144.440	Greater Than	19.675	Reject Hypothesis
3db Data LIne	142.880	Greater Than	19.675	Reject Hypothesis
Best-Fit Line With Respect to Eq. 4-14a				
Straight Test Bar Data Only				
All Data Line	3.654	Less Than	5.991	DO NOT Reject
Best-Fit Line With Respect to Eq. 4-15				
Straight Test Bar Data Only				
All Data Line	30.677	Greater Than	5.991	Reject Hypothesis

Table 4.14 Chi-Square Distribution Table Khazanie (1990).



Degrees of Freedom	α, area in the right tail under the curve							
	0.995	0.99	0.975	0.95	0.05	0.025	0.01	0.005
v	$\chi^2_{v,0.995}$	$\chi^2_{v,0.99}$	$\chi^2_{v,0.975}$	$\chi^2_{v,0.95}$	$\chi^2_{v,0.05}$	$\chi^2_{v,0.025}$	$\chi^2_{v,0.01}$	$\chi^2_{v,0.005}$
1	0.0^4393	0.0^3157	0.0^3982	0.0^2393	3.841	5.024	6.635	7.879
2	0.0100	0.0201	0.0506	0.103	5.991	7.378	9.210	10.597
3	0.0717	0.115	0.216	0.352	7.815	9.348	11.345	12.838
4	0.207	0.297	0.484	0.711	9.488	11.143	13.277	14.860
5	0.412	0.554	0.831	1.145	11.070	12.832	15.086	16.750
6	0.676	0.872	1.237	1.635	12.592	14.449	16.812	18.548
7	0.989	1.239	1.690	2.167	14.067	16.013	18.475	20.278
8	1.344	1.646	2.180	2.733	15.507	17.535	20.090	21.955
9	1.735	2.088	2.700	3.325	16.919	19.023	21.666	23.589
10	2.156	2.558	3.247	3.940	18.307	20.483	23.209	25.188
11	2.603	3.053	3.816	4.575	19.675	21.920	24.725	26.757
12	3.074	3.571	4.404	5.226	21.026	23.337	26.217	28.300
13	3.565	4.107	5.009	5.892	22.362	24.736	27.688	29.819
14	4.075	4.660	5.629	6.571	23.685	26.119	29.141	31.319
15	4.601	5.229	6.262	7.261	24.996	27.488	30.578	32.801
16	5.142	5.812	6.908	7.962	26.296	28.845	32.000	34.267
17	5.697	6.408	7.564	8.672	27.587	30.191	33.409	35.718
18	6.265	7.015	8.231	9.390	28.869	31.526	34.805	37.156
19	6.844	7.633	8.907	10.117	30.144	32.852	36.191	38.582
20	7.434	8.260	9.591	10.851	31.410	34.170	37.566	39.997
21	8.034	8.897	10.283	11.591	32.671	35.479	38.932	41.401
22	8.643	9.542	10.982	12.338	33.924	36.781	40.289	42.796
23	9.260	10.196	11.689	13.091	35.172	38.076	41.638	44.181
24	9.886	10.856	12.401	13.848	36.415	39.364	42.980	45.558
25	10.520	11.524	13.120	14.611	37.652	40.646	44.314	46.928
26	11.160	12.198	13.844	15.379	38.885	41.923	45.652	48.290
27	11.808	12.879	14.573	16.151	40.113	43.194	46.963	49.645
28	12.461	13.565	15.308	16.928	41.337	44.461	48.278	50.993
29	13.121	14.256	16.047	17.708	42.557	45.722	49.588	52.336
30	13.787	14.953	16.791	18.493	43.773	46.979	50.892	53.672

Abridged from Table 8 of *Biometrika Tables for Statisticians*, Vol. 1, by permission of the Biometrika Trustees.

Table 4.15 Analysis of Variance (ANOVA) Results for Best-Fit Lines

Best-Fit Line With Respect to Eq. 4-14a

Confinement Limit NOT Imposed

All Data Line

	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	Significance Level	
Regression	1	8402.716443	8402.716443	6.840408	0.015796178	
Residual	22	27024.66793	1228.393997			
Total	23	35427.38437				
	Coefficients	Standard Error	t - Statistic	P - Value	Lower 95%	Upper 95%
Intercept	663.6553	48.42176378	13.70572307	1.49E-12	563.23459	764.07599
x1	2.595621	0.992430839	2.615417416	0.015466	0.5374431	4.6537987

2db Data Line

	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	Significance Level	
Regression	1	2183.861523	2183.861523	1.597972	0.234860939	
Residual	10	13666.45838	1366.645838			
Total	11	15850.3199				
	Coefficients	Standard Error	t - Statistic	P - Value	Lower 95%	Upper 95%
Intercept	632.7387	110.4038918	5.731126721	0.000132	386.74345	878.73394
x1	3.305423	2.61482385	1.264109097	0.232321	-2.520769	9.1316142

3db Data Line

	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	Significance Level	
Regression	1	0.188536167	0.188536167	0.000152	0.990414558	
Residual	10	12426.45793	1242.645793			
Total	11	12426.64646				
	Coefficients	Standard Error	t - Statistic	P - Value	Lower 95%	Upper 95%
Intercept	808.3705	178.9977417	4.516093351	0.000878	409.53862	1207.2024
x1	-0.0404	3.279857739	-0.012317531	0.990393	-7.348379	7.26758

Table 4.15 Analysis of Variance (ANOVA) Results for Best-Fit Lines (cont.)

Best-Fit Line With Respect to Eq. 4-14a

Confinement Limit IS Imposed

All Data Line

	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	Significance Level	
Regression	1	6510.277326	6510.277326	4.952989	0.036609072	
Residual	22	28917.10705	1314.413957			
Total	23	35427.38437				
	Coefficients	Standard Error	t - Statistic	P - Value	Lower 95%	Upper 95%
Intercept	675.6411	51.42976095	13.13716283	3.55E-12	568.98223	782.30006
x1	2.591876	1.164610177	2.22553108	0.036133	0.1766199	5.0071324

2db Data Line

	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	Significance Level	
Regression	1	459.6078344	459.6078344	0.298627	0.596725687	
Residual	10	15390.71206	1539.071206			
Total	11	15850.3199				
	Coefficients	Standard Error	t - Statistic	P - Value	Lower 95%	Upper 95%
Intercept	622.6827	272.8315094	2.282297509	0.043361	14.776083	1230.5893
x1	3.975591	7.275072415	0.546467521	0.595655	-12.23428	20.185465

3db Data Line

	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	Significance Level	
Regression	1	4166.594223	4166.594223	5.044271	0.048512351	
Residual	10	8260.052242	826.0052242			
Total	11	12426.64646				
	Coefficients	Standard Error	t - Statistic	P - Value	Lower 95%	Upper 95%
Intercept	1930.445	500.6487138	3.855886402	0.002672	814.92952	3045.9596
x1	-22.5162	10.02525168	-2.245945465	0.046217	-44.85383	-0.1785119

Table 4.15 Analysis of Variance (ANOVA) Results for Best-Fit Lines (cont.)

Best-Fit Line With Respect to Eq. 4-15

Pattern #4S1: N=3

All Data Line

	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	Significance Level	
Regression	1	1343362.354	1343362.354	20.41661	0.000170026	
Residual	22	1447545.541	65797.52459			
Total	23	2790907.895				
	Coefficients	Standard Error	t - Statistic	P - Value	Lower 95%	Upper 95%
Intercept	3327.996	730.8294159	4.553725399	1.42E-04	1812.3474	4843.6455
x1	1.692155	0.374497087	4.518474225	0.000155	0.9154952	2.4688157

2db Data Line

	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	Significance Level	
Regression	1	697160.9337	697160.9337	12.30812	0.005647728	
Residual	10	566423.4674	56642.34674			
Total	11	1263584.401				
	Coefficients	Standard Error	t - Statistic	P - Value	Lower 95%	Upper 95%
Intercept	1303.279	1474.833525	0.883678434	0.395773	-1982.856	4589.413
x1	2.824905	0.805207671	3.508293367	0.004898	1.0307899	4.6190195

3db Data Line

	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	Significance Level	
Regression	1	296339.398	296339.398	4.285724	0.065261995	
Residual	10	691457.0649	69145.70649			
Total	11	987796.463				
	Coefficients	Standard Error	t - Statistic	P - Value	Lower 95%	Upper 95%
Intercept	1942.257	2334.0643	0.832135255	0.42303	-3258.363	7142.8774
x1	2.340595	1.130613361	2.070198969	0.062751	-0.178569	4.8597586

Table 4.15 Analysis of Variance (ANOVA) Results for Best-Fit Lines (cont.)

Best-Fit Line With Respect to Eq. 4-15

Pattern #4S1: N=4

All Data Line

	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	Significance Level	
Regression	1	818131.1458	818131.1458	9.12363	0.006287859	
Residual	22	1972776.749	89671.67041			
Total	23	2790907.895				
	Coefficients	Standard Error	t - Statistic	P - Value	Lower 95%	Upper 95%
Intercept	3931.172	892.8552144	4.402921701	2.06E-04	2079.5012	5782.842
x1	1.365936	0.452216667	3.020534727	0.0060893	0.4280952	2.3037771

2db Data Line

	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	Significance Level	
Regression	1	328323.8949	328323.8949	3.510507	0.090465839	
Residual	10	935260.5061	93526.05061			
Total	11	1263584.401				
	Coefficients	Standard Error	t - Statistic	P - Value	Lower 95%	Upper 95%
Intercept	2391.701	2179.432374	1.097396385	0.29591	-2464.378	7247.78
x1	2.201995	1.175253244	1.873634816	0.087774	-0.416632	4.8206233

3db Data Line

	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	Significance Level	
Regression	1	20025.29576	20025.29576	0.206922	0.658906363	
Residual	10	967771.1672	96777.11672			
Total	11	987796.463				
	Coefficients	Standard Error	t - Statistic	P - Value	Lower 95%	Upper 95%
Intercept	5349.106	3128.601565	1.709743499	0.115335	-1621.854	12320.066
x1	0.681761	1.498749139	0.454886586	0.658037	-2.657661	4.0211826

Table 4.15 Analysis of Variance (ANOVA) Results for Best-Fit Lines (cont.)

Best-Fit Line With Respect to Eq. 4-14a

Straight Bar Data; Confinement Limit NOT Imposed

All Data Line

	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	Significance Level	
Regression	1	5282.376954	5282.376954	2.597206	0.353554404	
Residual	1	2033.868812	2033.868812			
Total	2	7316.245766				
	Coefficients	Standard Error	t - Statistic	P - Value	Lower 95%	Upper 95%
Intercept	252.7039	172.1743067	1.467721107	2.80E-01	-1934.969	2440.3765
x1	6.06456	3.763102531	1.611585037	0.248366	-41.74999	53.879106

Best-Fit Line With Respect to Eq. 4-15

Straight Bar Data with stirrups

All Data Line

	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	Significance Level	
Regression	1	352108.6178	352108.6178	2.476728	0.360363247	
Residual	1	142166.8624	142166.8624			
Total	2	494275.4802				
	Coefficients	Standard Error	t - Statistic	P - Value	Lower 95%	Upper 95%
Intercept	-762.008	3283.181741	-0.232094242	8.38E-01	-42478.61	40954.593
x1	2.680633	1.703327661	1.573762302	0.256196	-18.9621	24.32337

Table 4.16a Development Lengths predicted by Eq. 4-24 (before changes).

Atr	Fytr	s	AtrFytr/s		Concrete Clear Cover				
(in.^2)	(psi)	(in.)	(lbs./in.)	Ktr	3db	3.5db	4db	4.5db	5db
0.11	75000	1	8250	5.108359	6.43	6.072	5.751	5.4633	5.203
0.11	75000	2	4125	2.55418	9.201	8.485	7.872	7.3423	6.879
0.11	75000	3	2750	1.702786	10.74	9.781	8.976	8.2931	7.707
0.11	75000	4	2062.5	1.27709	11.73	10.59	9.652	8.8672	8.2
0.11	75000	5	1650	1.021672	12.41	11.14	10.11	9.2515	8.528
0.11	75000	6	1375	0.851393	12.91	11.54	10.44	9.5268	8.761
0.2	75000	1	15000	9.287926	4.307	4.143	3.992	3.8507	3.719
0.2	75000	2	7500	4.643963	6.802	6.403	6.048	5.7299	5.444
0.2	75000	3	5000	3.095975	8.43	7.825	7.301	6.8431	6.439
0.2	75000	4	3750	2.321981	9.576	8.803	8.145	7.5793	7.087
0.2	75000	5	3000	1.857585	10.43	9.516	8.753	8.1023	7.542
0.2	75000	6	2500	1.547988	11.08	10.06	9.21	8.4931	7.879
0.31	75000	1	23250	14.39628	3.069	2.985	2.905	2.8298	2.758
0.31	75000	2	11625	7.198142	5.158	4.925	4.713	4.5174	4.338
0.31	75000	3	7750	4.798762	6.673	6.288	5.946	5.6382	5.361
0.31	75000	4	5812.5	3.599071	7.822	7.298	6.84	6.4367	6.078
0.31	75000	5	4650	2.879257	8.722	8.076	7.519	7.0344	6.608
0.31	75000	6	3875	2.399381	9.448	8.694	8.052	7.4986	7.016
0.11	60000	1	6600	4.086687	7.31	6.851	6.446	6.0863	5.765
0.11	60000	2	3300	2.043344	10.07	9.218	8.499	7.8847	7.353
0.11	60000	3	2200	1.362229	11.52	10.42	9.509	8.7461	8.097
0.11	60000	4	1650	1.021672	12.41	11.14	10.11	9.2515	8.528
0.11	60000	5	1320	0.817337	13.02	11.63	10.51	9.5838	8.81
0.11	60000	6	1100	0.681115	13.45	11.98	10.79	9.8189	9.008
0.2	60000	1	12000	7.430341	5.048	4.824	4.62	4.4321	4.259
0.2	60000	2	6000	3.71517	7.694	7.187	6.742	6.3496	6
0.2	60000	3	4000	2.47678	9.323	8.588	7.961	7.4197	6.947
0.2	60000	4	3000	1.857585	10.43	9.516	8.753	8.1023	7.542
0.2	60000	5	2400	1.486068	11.22	10.18	9.308	8.5758	7.951
0.2	60000	6	2000	1.23839	11.83	10.67	9.719	8.9234	8.248
0.31	60000	1	18600	11.51703	3.662	3.543	3.432	3.3269	3.228
0.31	60000	2	9300	5.758514	5.972	5.662	5.382	5.1291	4.899
0.31	60000	3	6200	3.839009	7.561	7.071	6.641	6.2594	5.92
0.31	60000	4	4650	2.879257	8.722	8.076	7.519	7.0344	6.608
0.31	60000	5	3720	2.303406	9.607	8.829	8.168	7.5989	7.104
0.31	60000	6	3100	1.919505	10.3	9.415	8.667	8.0285	7.478
0.11	40000	1	4400	2.724458	8.944	8.266	7.683	7.1777	6.734
0.11	40000	2	2200	1.362229	11.52	10.42	9.509	8.7461	8.097
0.11	40000	3	1466.667	0.908153	12.74	11.41	10.33	9.4332	8.682
0.11	40000	4	1100	0.681115	13.45	11.98	10.79	9.8189	9.008
0.11	40000	5	880	0.544892	13.92	12.34	11.09	10.066	9.215
0.11	40000	6	733.3333	0.454076	14.25	12.6	11.3	10.237	9.359
0.2	40000	1	8000	4.95356	6.549	6.178	5.847	5.5493	5.281
0.2	40000	2	4000	2.47678	9.323	8.588	7.961	7.4197	6.947
0.2	40000	3	2666.667	1.651187	10.85	9.872	9.053	8.3587	7.764
0.2	40000	4	2000	1.23839	11.83	10.67	9.719	8.9234	8.248
0.2	40000	5	1600	0.990712	12.5	11.21	10.17	9.3004	8.57
0.2	40000	6	1333.333	0.825593	12.99	11.61	10.49	9.5699	8.798

Table 4.16b Development Lengths predicted by Eq. 4-25 (after changes).

Atr	Fytr	s	AtrFytr/s		Concrete Clear Cover				
(in.^2)	(psi)	(in.)	(lbs./in.)	Ktr	3db	3.5db	4db	4.5db	5db
0.11	75000	1	8250	5.108359	6.372	6.002	5.672	5.3772	5.111
0.11	75000	2	4125	2.55418	9.302	8.534	7.883	7.3242	6.839
0.11	75000	3	2750	1.702786	10.99	9.931	9.06	8.3295	7.708
0.11	75000	4	2062.5	1.27709	12.08	10.82	9.791	8.9433	8.231
0.11	75000	5	1650	1.021672	12.85	11.43	10.29	9.357	8.58
0.11	75000	6	1375	0.851393	13.41	11.87	10.65	9.6547	8.83
0.2	75000	1	15000	9.287926	4.205	4.04	3.888	3.7472	3.616
0.2	75000	2	7500	4.643963	6.759	6.344	5.977	5.6503	5.357
0.2	75000	3	5000	3.095975	8.475	7.833	7.281	6.8018	6.382
0.2	75000	4	3750	2.321981	9.708	8.874	8.172	7.5735	7.056
0.2	75000	5	3000	1.857585	10.64	9.644	8.82	8.1267	7.534
0.2	75000	6	2500	1.547988	11.36	10.24	9.313	8.5427	7.89
0.31	75000	1	23250	14.39628	2.97	2.887	2.809	2.7342	2.664
0.31	75000	2	11625	7.198142	5.066	4.829	4.614	4.4166	4.236
0.31	75000	3	7750	4.798762	6.625	6.226	5.872	5.5563	5.273
0.31	75000	4	5812.5	3.599071	7.829	7.278	6.799	6.3793	6.008
0.31	75000	5	4650	2.879257	8.788	8.099	7.51	7.0016	6.557
0.31	75000	6	3875	2.399381	9.569	8.758	8.074	7.4885	6.983
0.11	60000	1	6600	4.086687	7.291	6.81	6.389	6.017	5.686
0.11	60000	2	3300	2.043344	10.24	9.32	8.549	7.896	7.335
0.11	60000	3	2200	1.362229	11.84	10.63	9.635	8.8134	8.121
0.11	60000	4	1650	1.021672	12.85	11.43	10.29	9.357	8.58
0.11	60000	5	1320	0.817337	13.53	11.97	10.73	9.7166	8.881
0.11	60000	6	1100	0.681115	14.04	12.36	11.04	9.972	9.094
0.2	60000	1	12000	7.430341	4.953	4.727	4.52	4.3307	4.156
0.2	60000	2	6000	3.71517	7.694	7.161	6.697	6.2891	5.928
0.2	60000	3	4000	2.47678	9.434	8.645	7.977	7.4055	6.91
0.2	60000	4	3000	1.857585	10.64	9.644	8.82	8.1267	7.534
0.2	60000	5	2400	1.486068	11.52	10.36	9.418	8.6311	7.966
0.2	60000	6	2000	1.23839	12.19	10.9	9.863	9.0036	8.282
0.31	60000	1	18600	11.51703	3.559	3.441	3.33	3.2257	3.128
0.31	60000	2	9300	5.758514	5.899	5.58	5.294	5.0364	4.802
0.31	60000	3	6200	3.839009	7.555	7.04	6.591	6.1957	5.845
0.31	60000	4	4650	2.879257	8.788	8.099	7.51	7.0016	6.557
0.31	60000	5	3720	2.303406	9.742	8.903	8.197	7.5942	7.074
0.31	60000	6	3100	1.919505	10.5	9.533	8.728	8.0483	7.467
0.11	40000	1	4400	2.724458	9.026	8.301	7.683	7.1516	6.689
0.11	40000	2	2200	1.362229	11.84	10.63	9.635	8.8134	8.121
0.11	40000	3	1466.667	0.908153	13.22	11.72	10.53	9.5534	8.745
0.11	40000	4	1100	0.681115	14.04	12.36	11.04	9.972	9.094
0.11	40000	5	880	0.544892	14.57	12.77	11.37	10.241	9.318
0.11	40000	6	733.3333	0.454076	14.96	13.07	11.6	10.429	9.473
0.2	40000	1	8000	4.95356	6.496	6.112	5.77	5.4653	5.191
0.2	40000	2	4000	2.47678	9.434	8.645	7.977	7.4055	6.91
0.2	40000	3	2666.667	1.651187	11.11	10.03	9.143	8.3994	7.768
0.2	40000	4	2000	1.23839	12.19	10.9	9.863	9.0036	8.282
0.2	40000	5	1600	0.990712	12.95	11.51	10.35	9.4098	8.624
0.2	40000	6	1333.333	0.825593	13.51	11.94	10.71	9.7015	8.869

Table 4.17 Development Lengths predicted by Eq. 4-28.

Atr	Fytr	s	AtrFytr/s		Concrete Clear Cover				
(in.^2)	(psi)	(in.)	(lbs./in.)	Ktr	3db	3.5db	4db	4.5db	5db
0.11	75000	1	8250	5.108359	4.434	4.179	3.952	3.7477	3.564
0.11	75000	2	4125	2.55418	6.491	5.958	5.507	5.1186	4.782
0.11	75000	3	2750	1.702786	7.678	6.944	6.338	5.8295	5.396
0.11	75000	4	2062.5	1.27709	8.451	7.57	6.856	6.2645	5.767
0.11	75000	5	1650	1.021672	8.994	8.003	7.209	6.5581	6.015
0.11	75000	6	1375	0.851393	9.397	8.32	7.465	6.7696	6.192
0.2	75000	1	15000	9.287926	2.92	2.807	2.703	2.6057	2.515
0.2	75000	2	7500	4.643963	4.705	4.419	4.165	3.9395	3.737
0.2	75000	3	5000	3.095975	5.909	5.465	5.082	4.7501	4.459
0.2	75000	4	3750	2.321981	6.777	6.198	5.711	5.2947	4.935
0.2	75000	5	3000	1.857585	7.431	6.741	6.169	5.6859	5.273
0.2	75000	6	2500	1.547988	7.942	7.159	6.517	5.9805	5.526
0.31	75000	1	23250	14.39628	2.06	2.003	1.95	1.8986	1.85
0.31	75000	2	11625	7.198142	3.521	3.358	3.21	3.074	2.949
0.31	75000	3	7750	4.798762	4.611	4.336	4.092	3.8734	3.677
0.31	75000	4	5812.5	3.599071	5.455	5.074	4.743	4.4523	4.195
0.31	75000	5	4650	2.879257	6.129	5.652	5.244	4.8909	4.582
0.31	75000	6	3875	2.399381	6.679	6.116	5.641	5.2347	4.883
0.11	60000	1	6600	4.086687	5.078	4.746	4.455	4.1974	3.968
0.11	60000	2	3300	2.043344	7.155	6.513	5.977	5.5227	5.132
0.11	60000	3	2200	1.362229	8.284	7.436	6.746	6.1723	5.689
0.11	60000	4	1650	1.021672	8.994	8.003	7.209	6.5581	6.015
0.11	60000	5	1320	0.817337	9.482	8.387	7.519	6.8135	6.229
0.11	60000	6	1100	0.681115	9.837	8.664	7.741	6.9952	6.381
0.2	60000	1	12000	7.430341	3.442	3.287	3.144	3.0139	2.894
0.2	60000	2	6000	3.71517	5.36	4.992	4.671	4.3889	4.139
0.2	60000	3	4000	2.47678	6.583	6.036	5.573	5.176	4.832
0.2	60000	4	3000	1.857585	7.431	6.741	6.169	5.6859	5.273
0.2	60000	5	2400	1.486068	8.053	7.249	6.591	6.0431	5.579
0.2	60000	6	2000	1.23839	8.529	7.633	6.907	6.3072	5.803
0.31	60000	1	18600	11.51703	2.47	2.389	2.313	2.2414	2.174
0.31	60000	2	9300	5.758514	4.103	3.884	3.687	3.5085	3.347
0.31	60000	3	6200	3.839009	5.263	4.907	4.597	4.3231	4.08
0.31	60000	4	4650	2.879257	6.129	5.652	5.244	4.8909	4.582
0.31	60000	5	3720	2.303406	6.8	6.218	5.728	5.3093	4.948
0.31	60000	6	3100	1.919505	7.336	6.663	6.104	5.6304	5.225
0.11	40000	1	4400	2.724458	6.296	5.794	5.366	4.9968	4.675
0.11	40000	2	2200	1.362229	8.284	7.436	6.746	6.1723	5.689
0.11	40000	3	1466.667	0.908153	9.259	8.212	7.378	6.6976	6.132
0.11	40000	4	1100	0.681115	9.837	8.664	7.741	6.9952	6.381
0.11	40000	5	880	0.544892	10.22	8.96	7.976	7.1868	6.54
0.11	40000	6	733.3333	0.454076	10.49	9.168	8.141	7.3205	6.65
0.2	40000	1	8000	4.95356	4.521	4.256	4.02	3.8095	3.62
0.2	40000	2	4000	2.47678	6.583	6.036	5.573	5.176	4.832
0.2	40000	3	2666.667	1.651187	7.764	7.014	6.397	5.879	5.439
0.2	40000	4	2000	1.23839	8.529	7.633	6.907	6.3072	5.803
0.2	40000	5	1600	0.990712	9.065	8.059	7.254	6.5955	6.047
0.2	40000	6	1333.333	0.825593	9.461	8.371	7.506	6.8028	6.22

Table 4.18

PROPOSED CODE ADDITION TO ACI 318-95 - HEADED REINFORCING BAR

12.x Development of Deformed Headed Reinforcement in Tension

12.x.1 Development length ℓ_{dt}, in inches, for deformed bars in tension teminating in a standard anchorage plate or "head" (see ASTM draft specification A xx-95) shall be calculated in accordance with section 12.x.2 and multiplied by the applicable modification factor(s) set forth by section 12.x.3, but ℓ_{dt} shall not be less than $6d_b$ nor less than 6 in., and the following conditions must be satisfied.

1) Concrete clear cover (in all directions) must not be less than $3d_b$.
2) Transverse Reinforcement must be provided such that $A_{tr}f_{ytr}/s$ is not less than 2000 or no less than $5d_b$ of clear cover is provided.
3) A minimum of 3 transverse stirrups shall be positioned within the development length ℓ_{dt}.

12.x.2 *Basic Development Length*

12.x.2.1 The development length ℓ_{dt} , for a headed bar having a yield strength not greater than 60,000 psi shall be calculated as follows:

$$\ell_{dt} = [0.0116 d_b f_y / (f'c^{1/2})] \, [\alpha\beta\lambda\psi\delta]$$

12.x.2.2 The development length ℓ_{dt} , for a headed bar having a yield strength greater than 60,000 psi shall be the larger of the values calculated by the following equations:

1) $$\ell_{dt} = [(A_b f_y / 2.6(f'c^{1/2})) - 340A_b] \,/\, [\alpha\beta\lambda\gamma / (C + K_{tr})]$$
2) $$\ell_{dt} = [0.0116 d_b f_y / (f'c^{1/2})] \, [\alpha\beta\lambda\psi\delta]$$

12.x.3 The factors for use in the expression for development of headed bars, ℓ_{dt}, in section 12.x.2 are defined as follows:

δ = *Confinement*
The development length calculated by Eq. 2 of section 12.x.2.2 shall be multiplied by a factor equal to: $[3d_b / (C + K_{tr})]$

α = *Casting Position* (To be determined by future research)

λ = *Lightweight Aggregate Concrete* (To be determined by future research)

β = *Epoxy-Coated Reinforcement* (To be determined by future research)

ψ = *Excess Reinforcement* (To be determined by future research)

Notation:

f_y = yield strength of the bar being developed.

A_b = area of the bar being developed

$f'c$ = compressive strength of the concrete, psi.

C = spacing or cover dimension, in.

K_{tr} = Transverse Reinforcement Index = $A_{tr}f_{ytr}/1615s$

A_{tr} = total cross-sectional area of all transverse reinforcement which is within the spacing s and which crosses the potential plane of splitting through the reinforcement being developed, in.^{2}

f_{ytr} = specified yield strength of transverse reinforcement, psi.

s = max. spacing of transverse reinforcement within ℓ_{dt},center-to-center, in.

note: It shall be permitted to use $K_{tr} = 0$, as a design simplification, however requirements set forth by section 12.x.1 must still be satisfied.

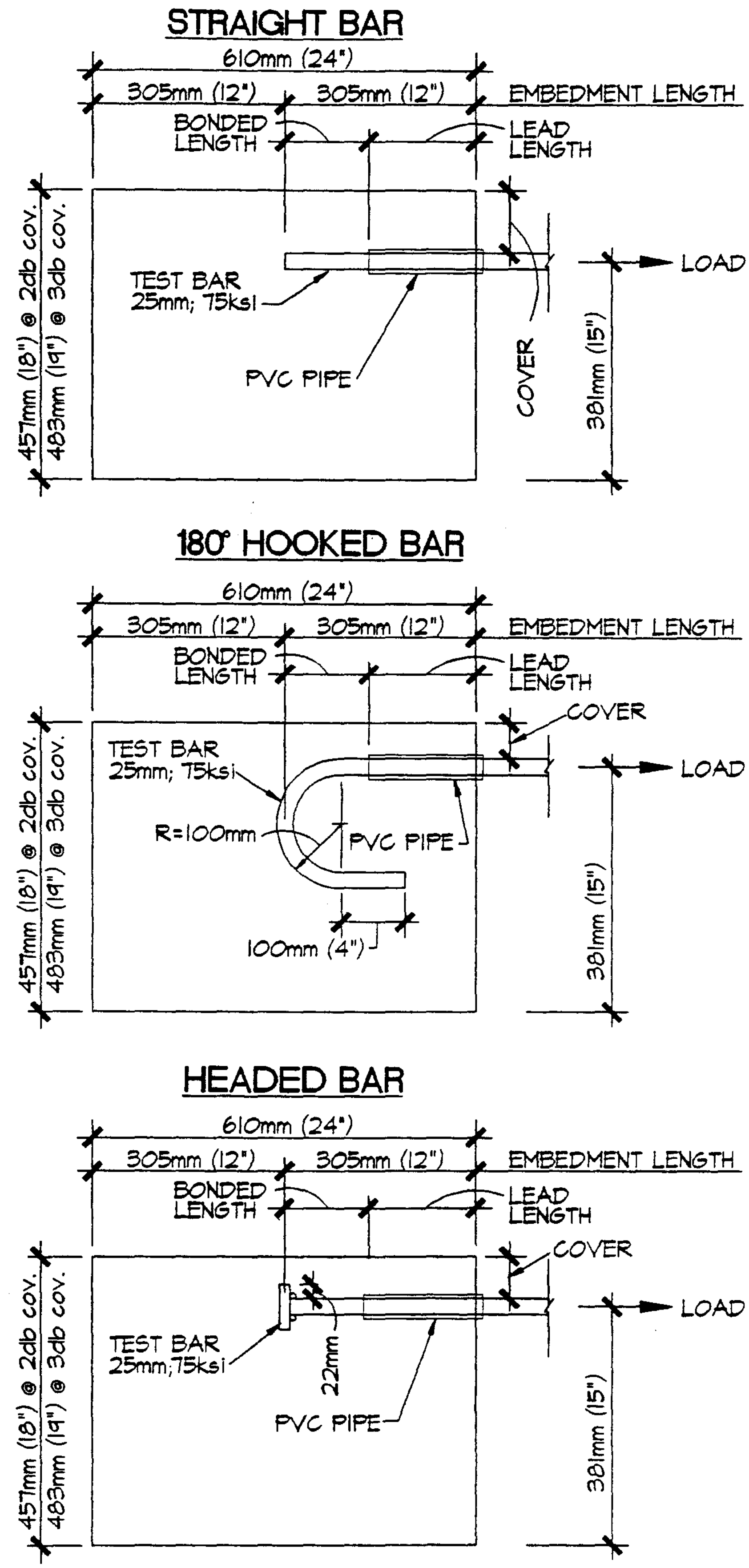


FIG. 2.1 Schematic Diagram – 3 Specimen Types.

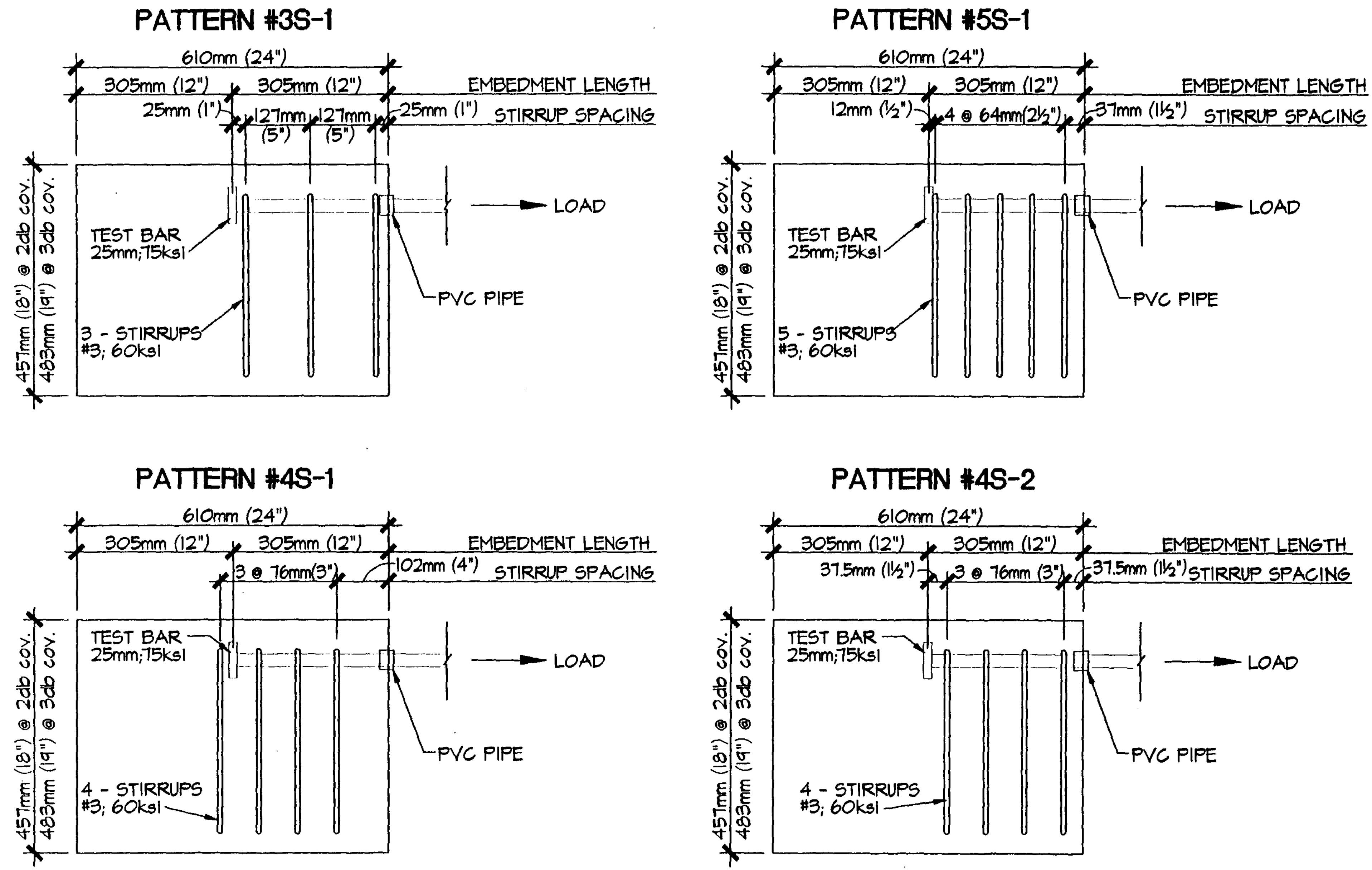


FIG. 2.2 Stirrup Spacing Patterns.

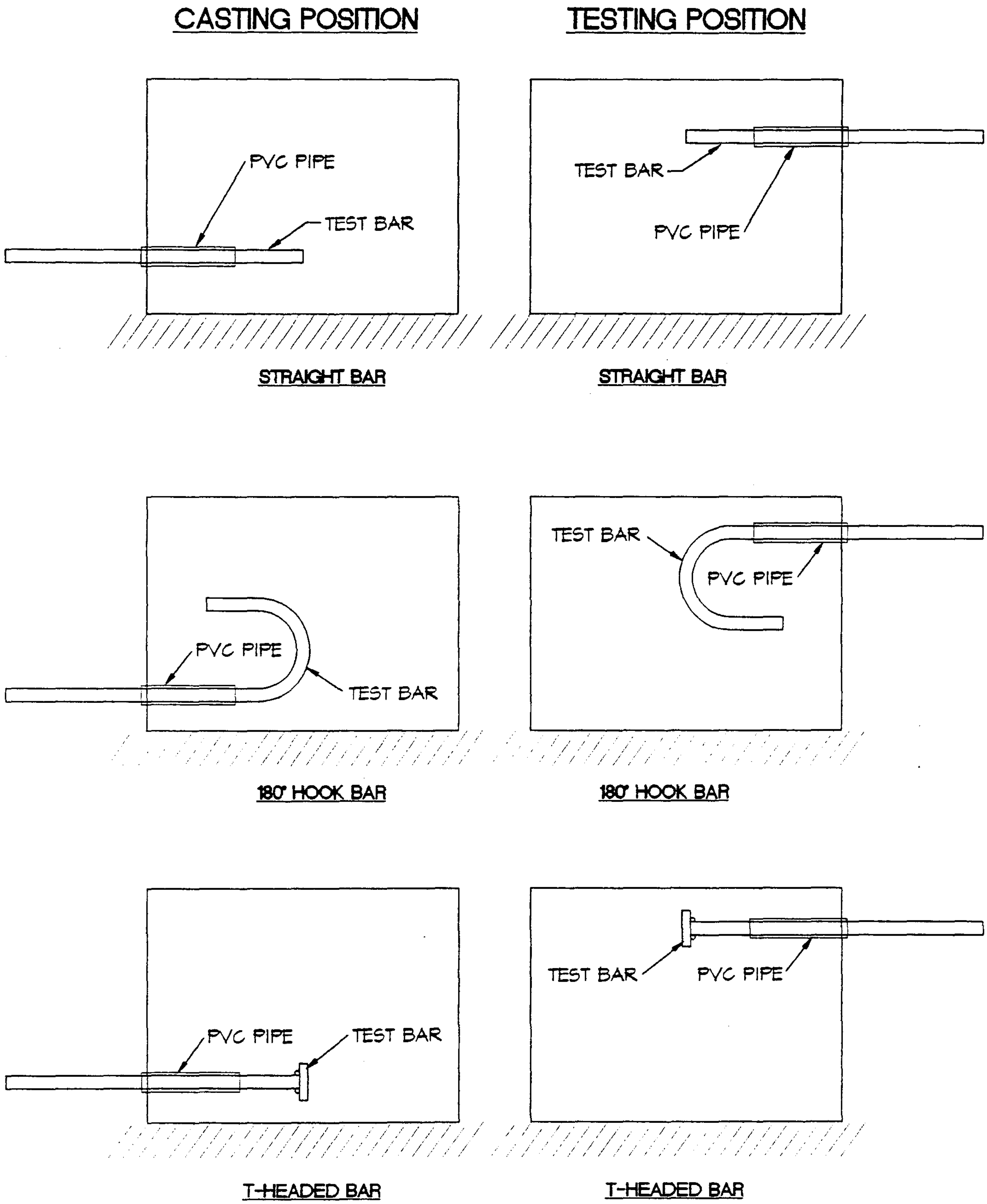


FIG. 2.3 Casting Position vs. Testing Position.

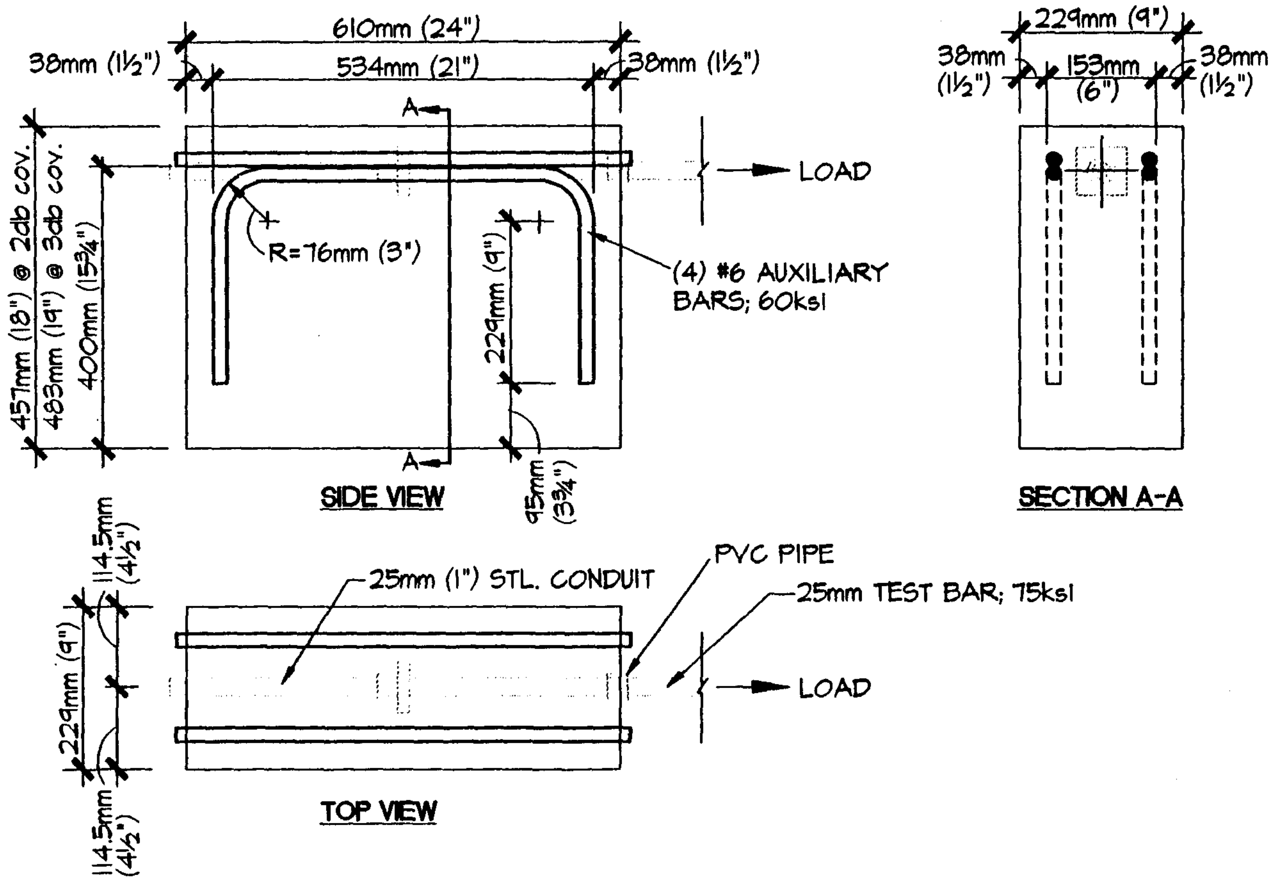


FIG. 2.4a Flexure Reinforcement.

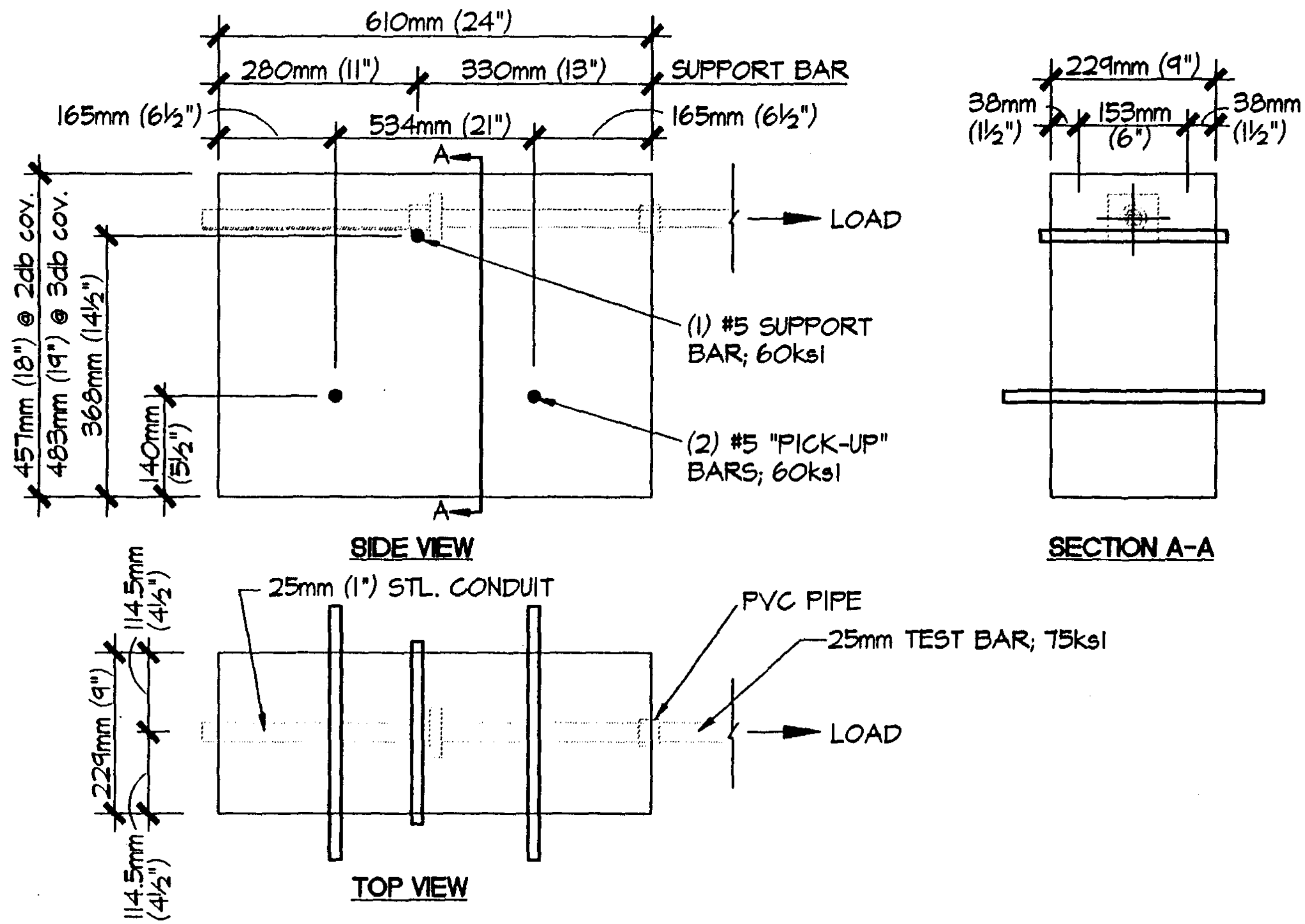


FIG. 2.4b Transverse Support Bar.

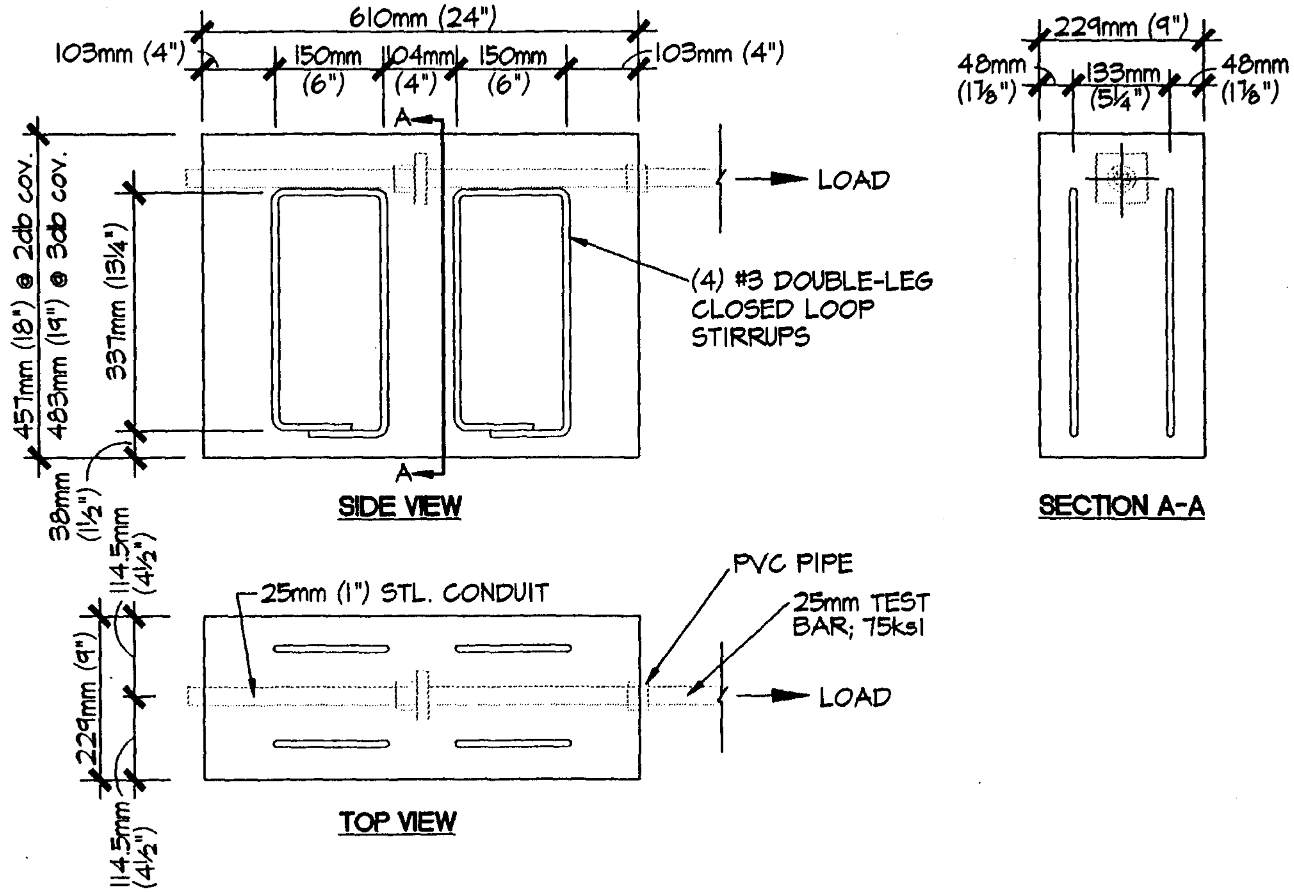


FIG. 2.4c Shear Reinforcement.

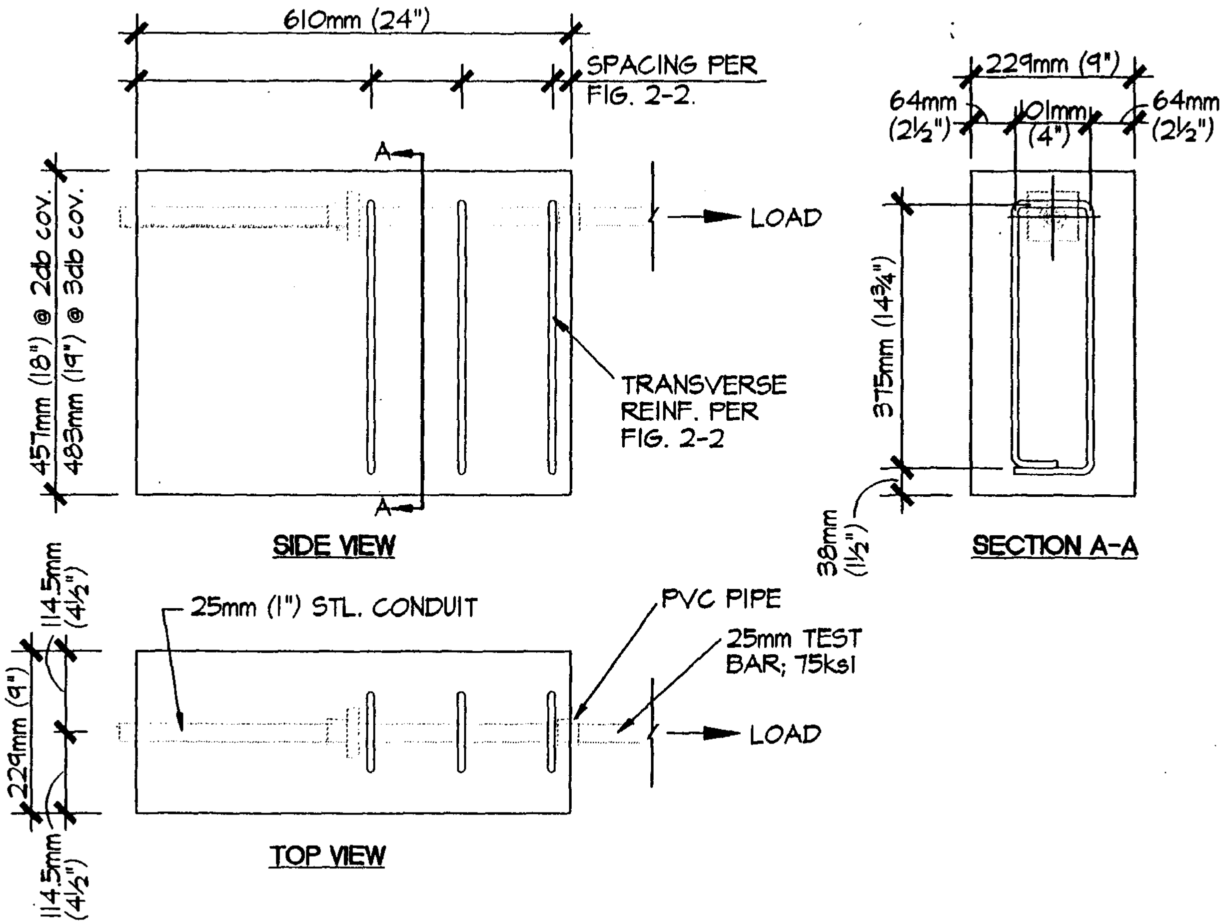


FIG. 2.4d Transverse Reinforcement.

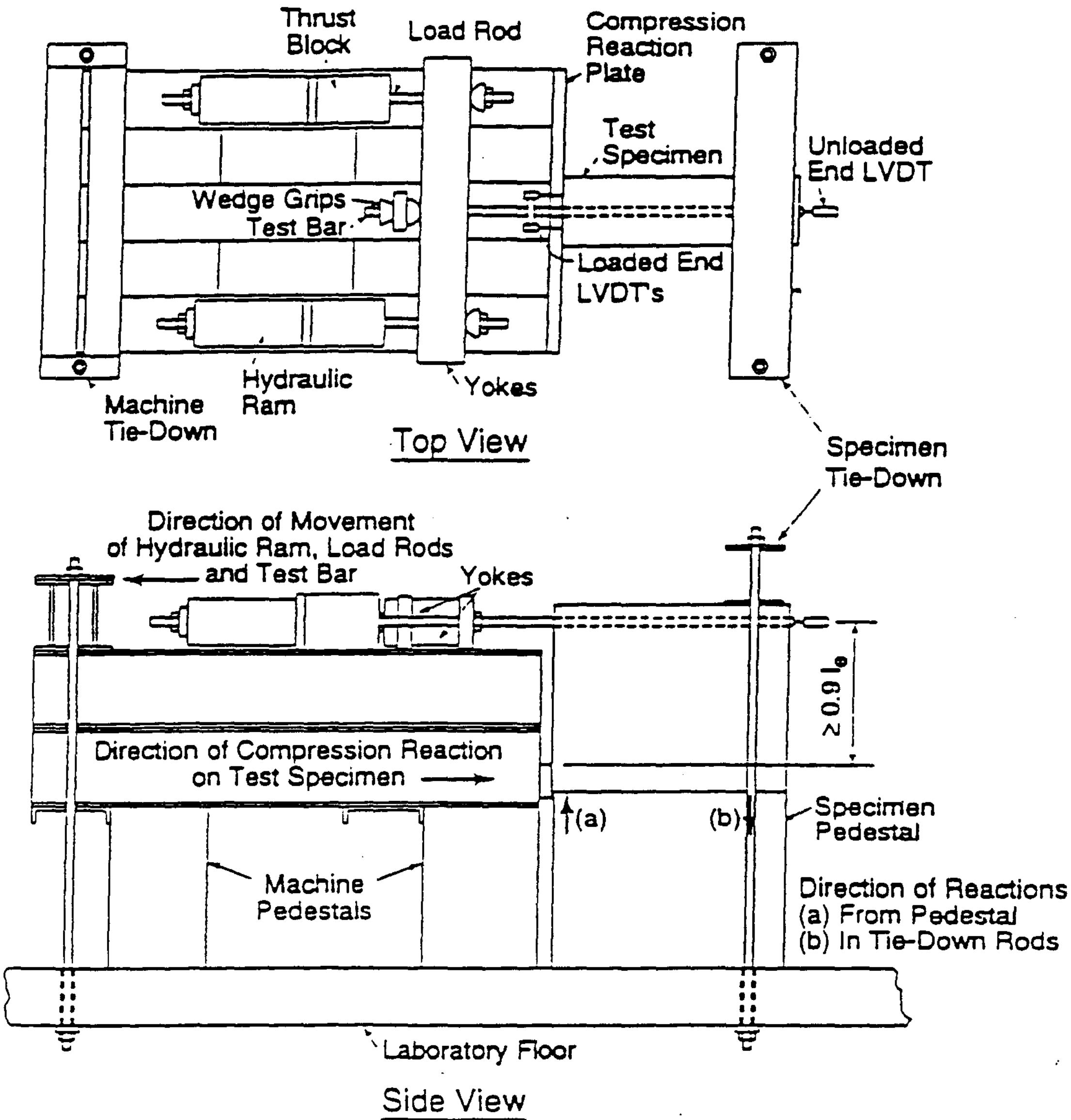


FIG. 2.5 Schematic of Test Apparatus (ASTM A944-95, 1996)

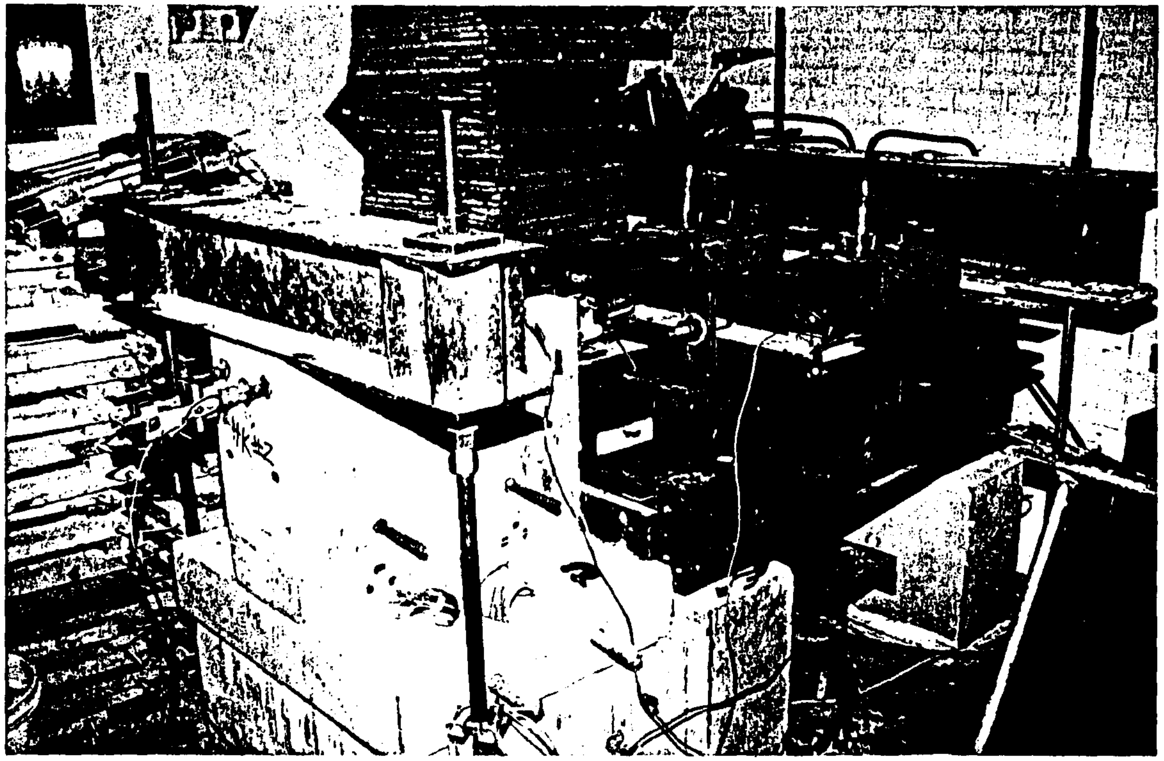


FIG. 2.6 Photo – Test Apparatus.

FIG. 3.1 Headed Tests – No PVC; No Stirrups.

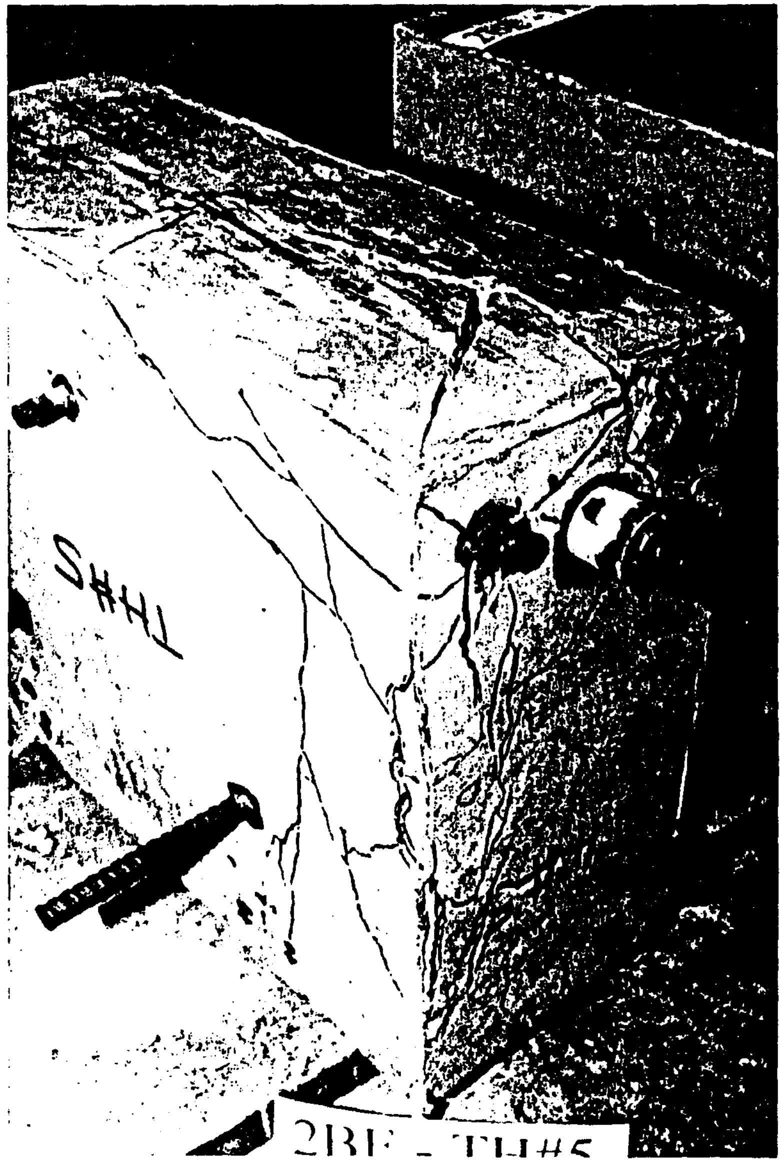


FIG. 3.2 Headed Tests – No PVC; With Stirrups.

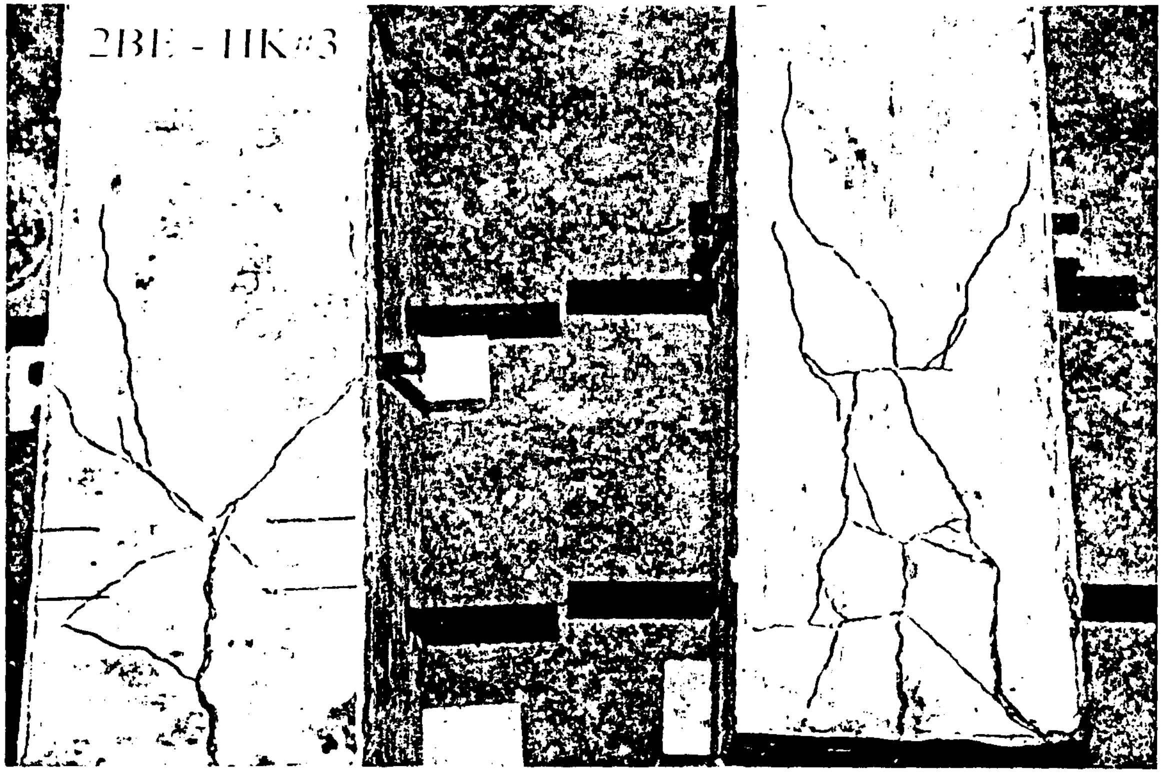


FIG. 3.3
Hooked Tests – No PVC; No Stirrups (HK#3 – Left).
Hooked Tests – No PVC; With Stirrups (HK#1 – Right).

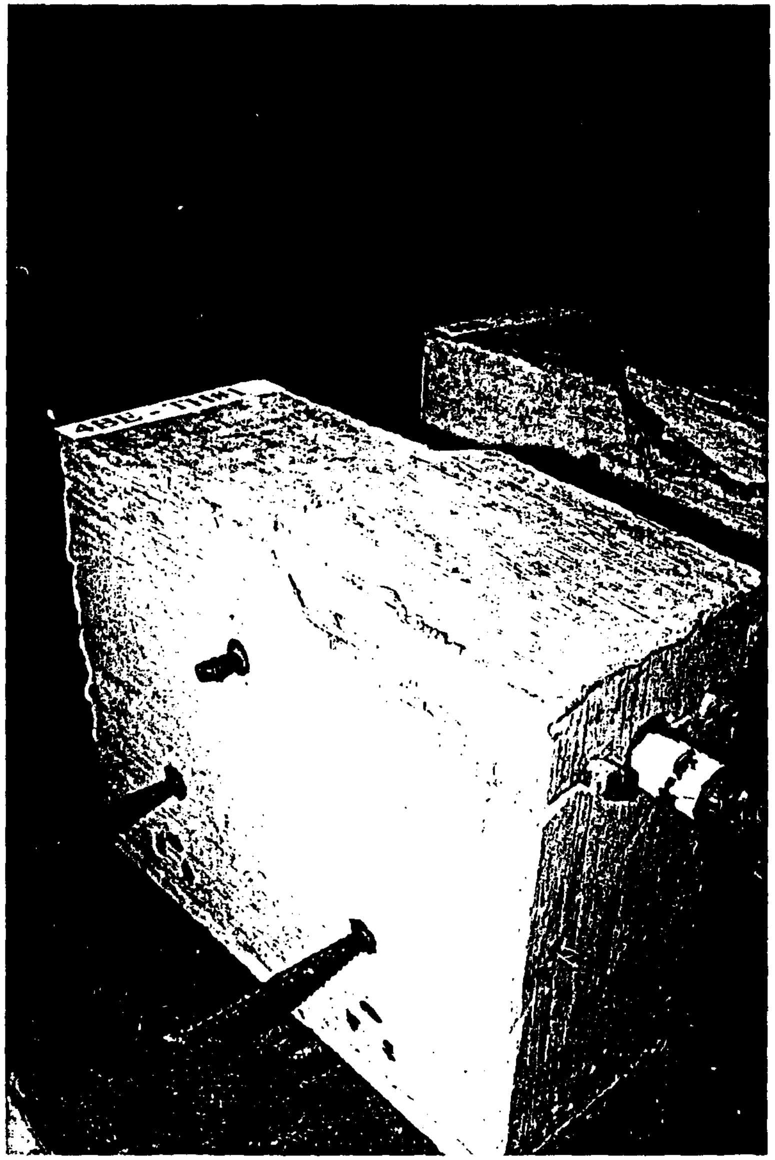


FIG. 3.4 Headed Tests – With PVC; No Stirrups.

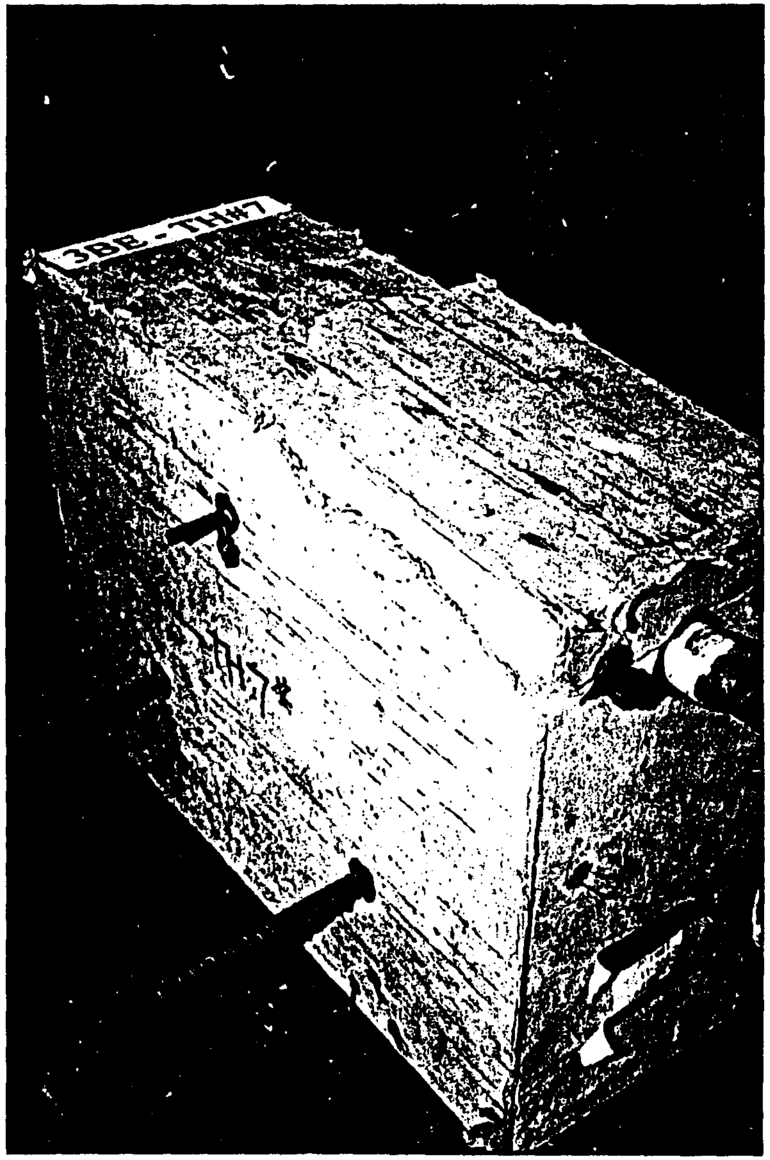
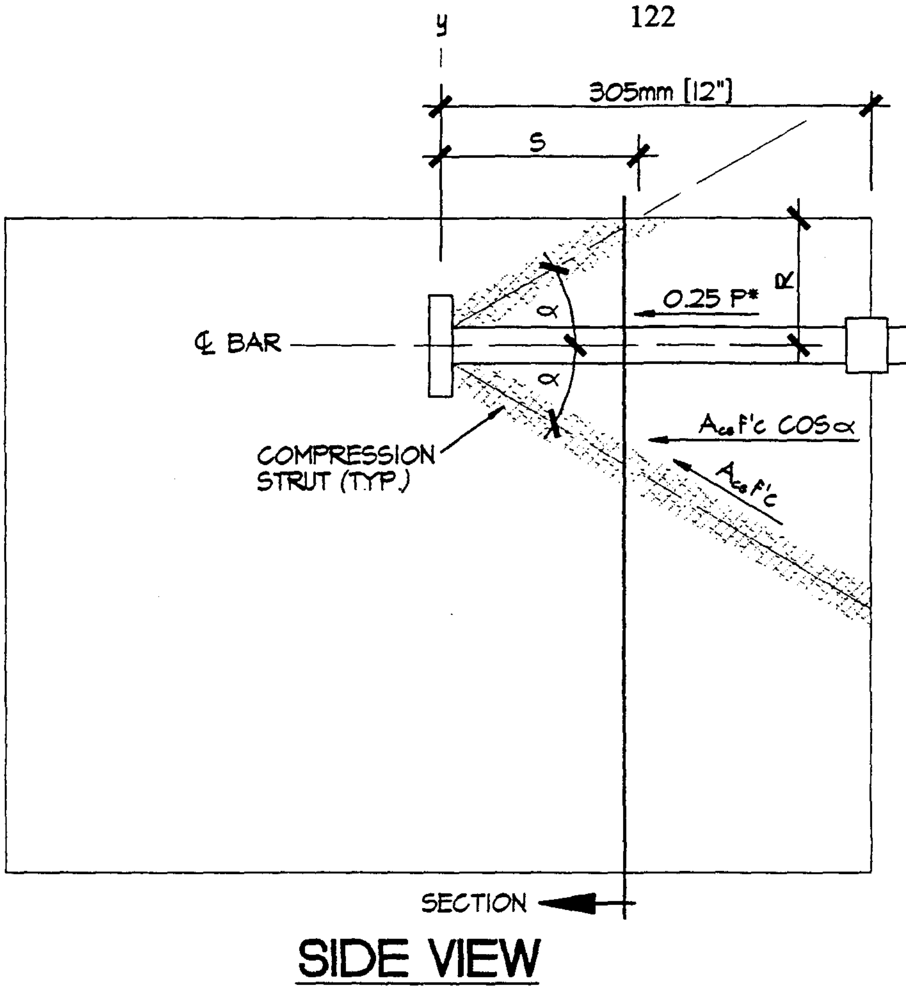


FIG. 3.5 Headed Tests – With PVC; With Stirrups.



* ASSUME BOND FORCE @ FAILURE ≈ 0.25 P. (DAHL, 1995).

R = SMALLEST DISTANCE FROM ℄ OF BAR TO EXTREME CONCRETE FIBER (CLR. COV. + ½db)

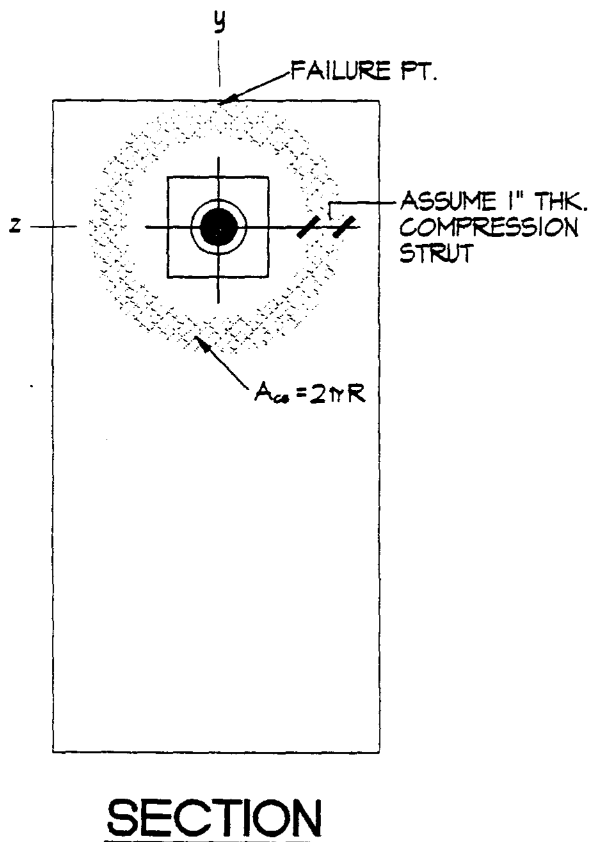
A_{cs} = AREA OF COMPRESSION STRUT @ CRITICAL SECTION.

P = APPLIED AXIAL LOAD

S = HORIZONTAL PROJECTION OF FAILURE POINT

f'c = CONCRETE STRENGTH (psi)

α = ANGLE OF COMPRESSION STRUT.



SUM FORCES IN "x" DIRECTION. ($\Sigma F_x = 0$)

(APPLIED LOAD) - (BOND FORCE) - (STRUT CAPACITY) = 0

$$P - (0.25P) - (A_{cs} f'c \cos\alpha) = 0$$

$$0.75P = (A_{cs} f'c \cos\alpha)$$

$$\cos\alpha = \frac{0.75P}{(A_{cs} f'c)}$$

SUBSTITUTE $A_{cs} = 2\pi R$.

$$\cos\alpha = \frac{0.75P}{(2\pi R\, f'c)}$$

FOR 2db OF COVER (R=65mm OR R=2.5")

$$\cos\alpha = \frac{0.04775 \times P}{f'c} \quad \text{(ENGLISH)}$$

$$\cos\alpha = \frac{0.073 \times P}{f'c} \quad \text{(S.I.)}$$

FOR 3db OF COVER (R=90mm OR R=3.5")

$$\cos\alpha = \frac{0.0341 \times P}{f'c} \quad \text{(ENGLISH)}$$

$$\cos\alpha = \frac{0.0522 \times P}{f'c} \quad \text{(S.I.)}$$

FIG. 3.6 Compression Strut Analysis.

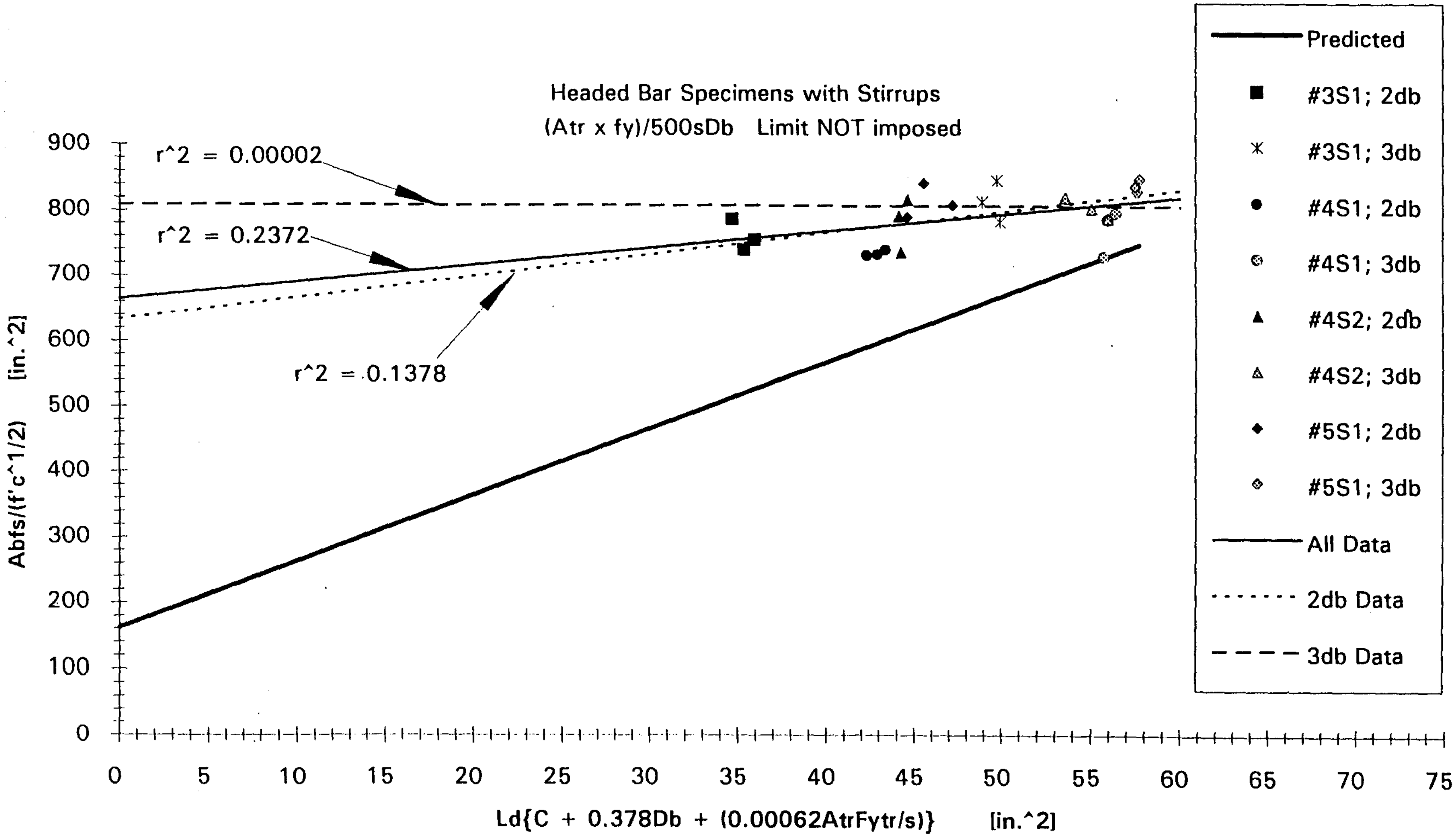


Figure 4.1a Best-Fit Lines with Respect to Eq. 4-14a.

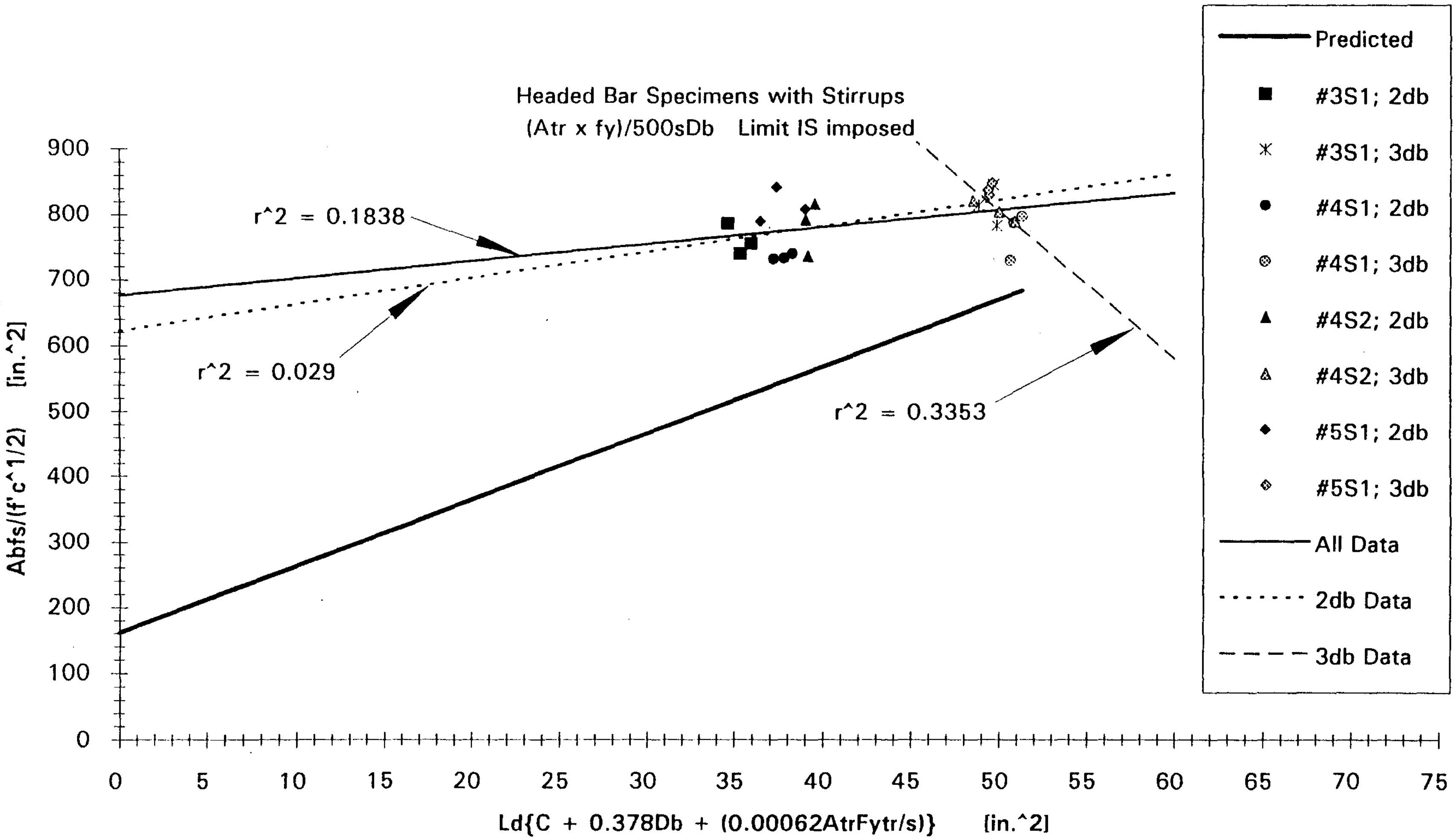


Figure 4.1b Best-Fit Lines with Respect to Eq. 4-14a.

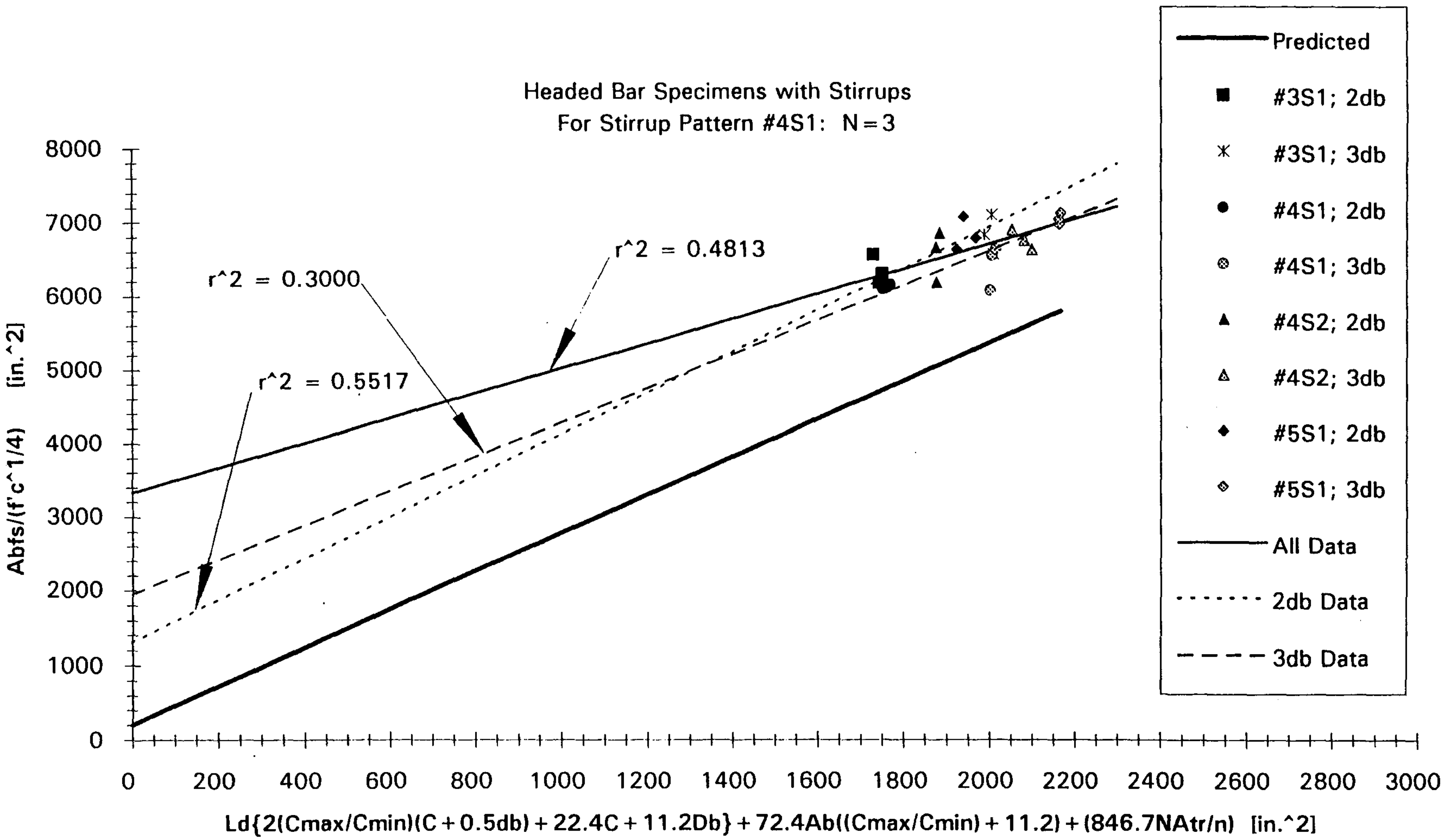


Figure 4.2a Best-Fit Lines with Respect to Eq. 4-15.

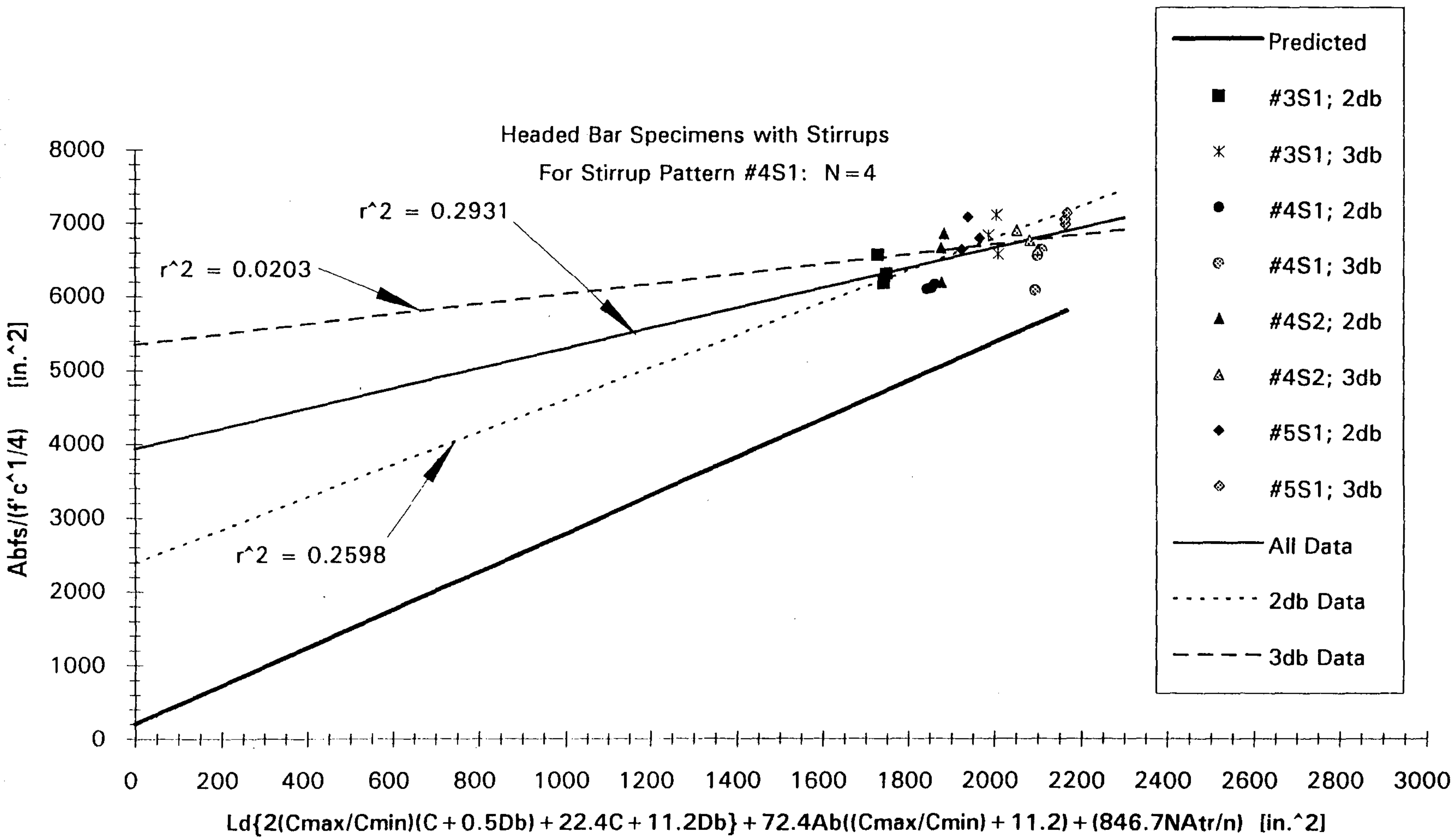


Figure 4.2b Best-Fit Lines with Respect to Eq. 4-15.

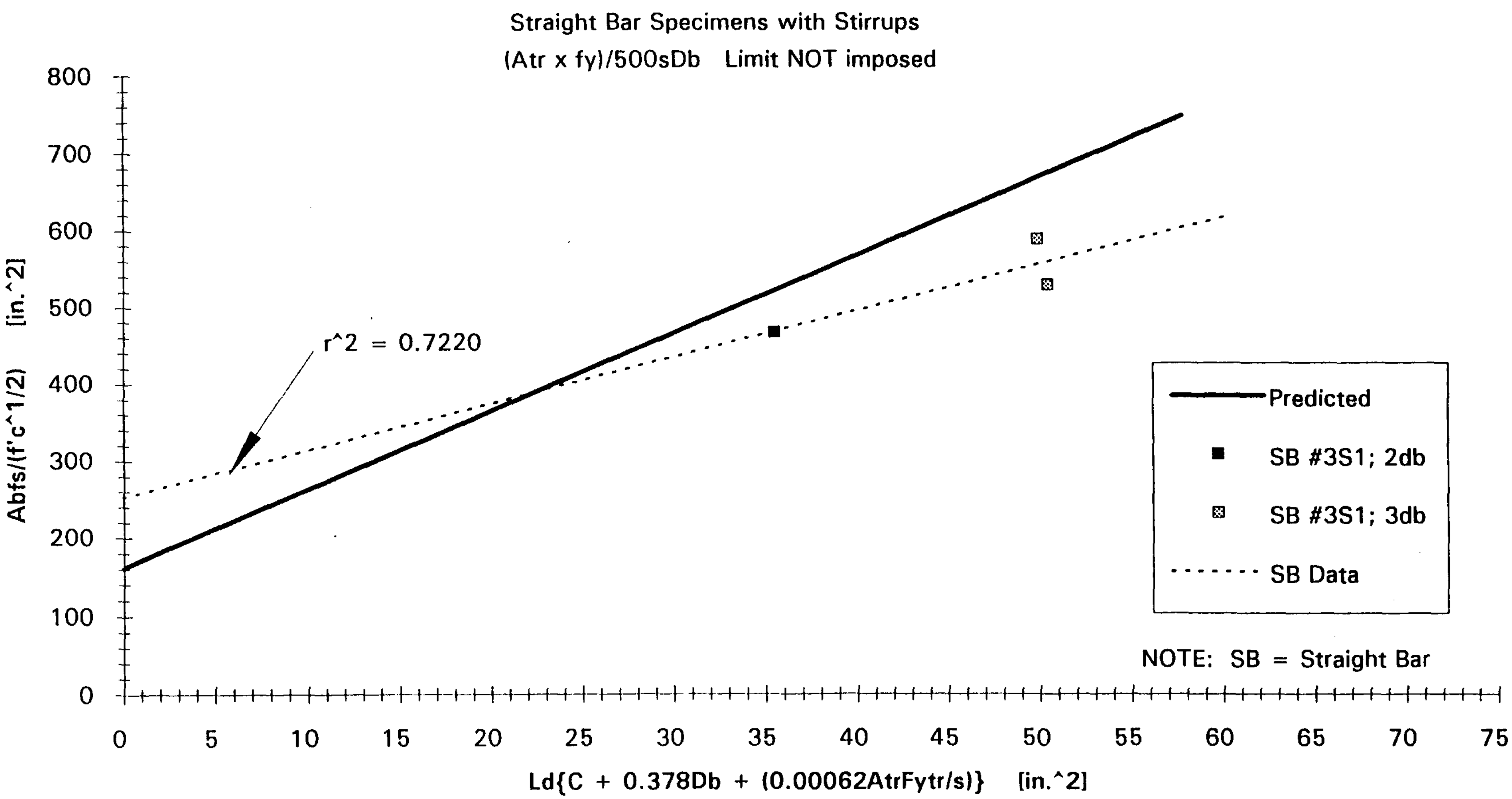


Figure 4.3 Best-Fit Lines with Respect to Eq. 4-14a (straight bar specimens only)

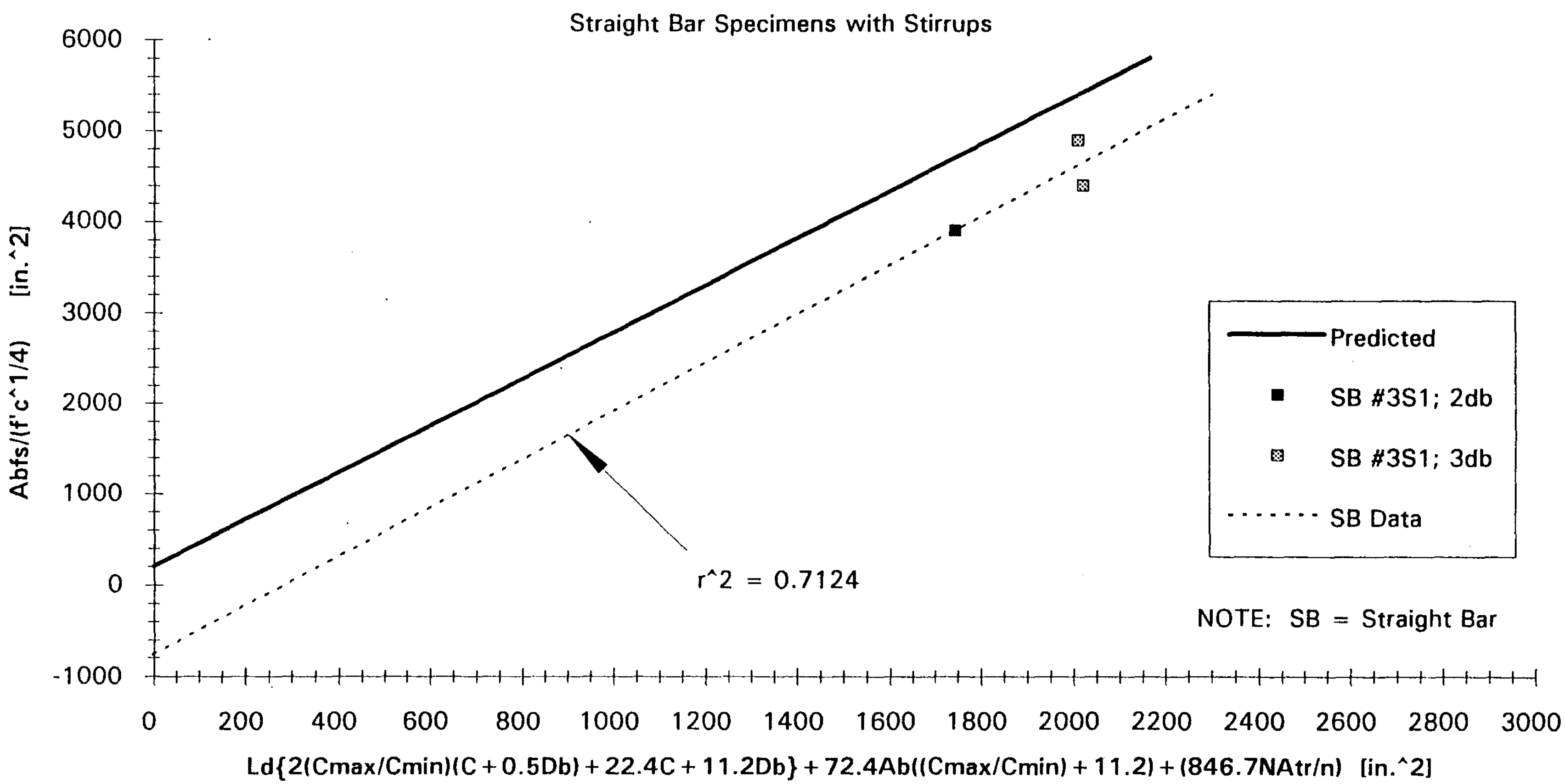


Figure 4.4 Best-Fit Lines with Respect to Eq. 4-15 (straight bar specimens only).

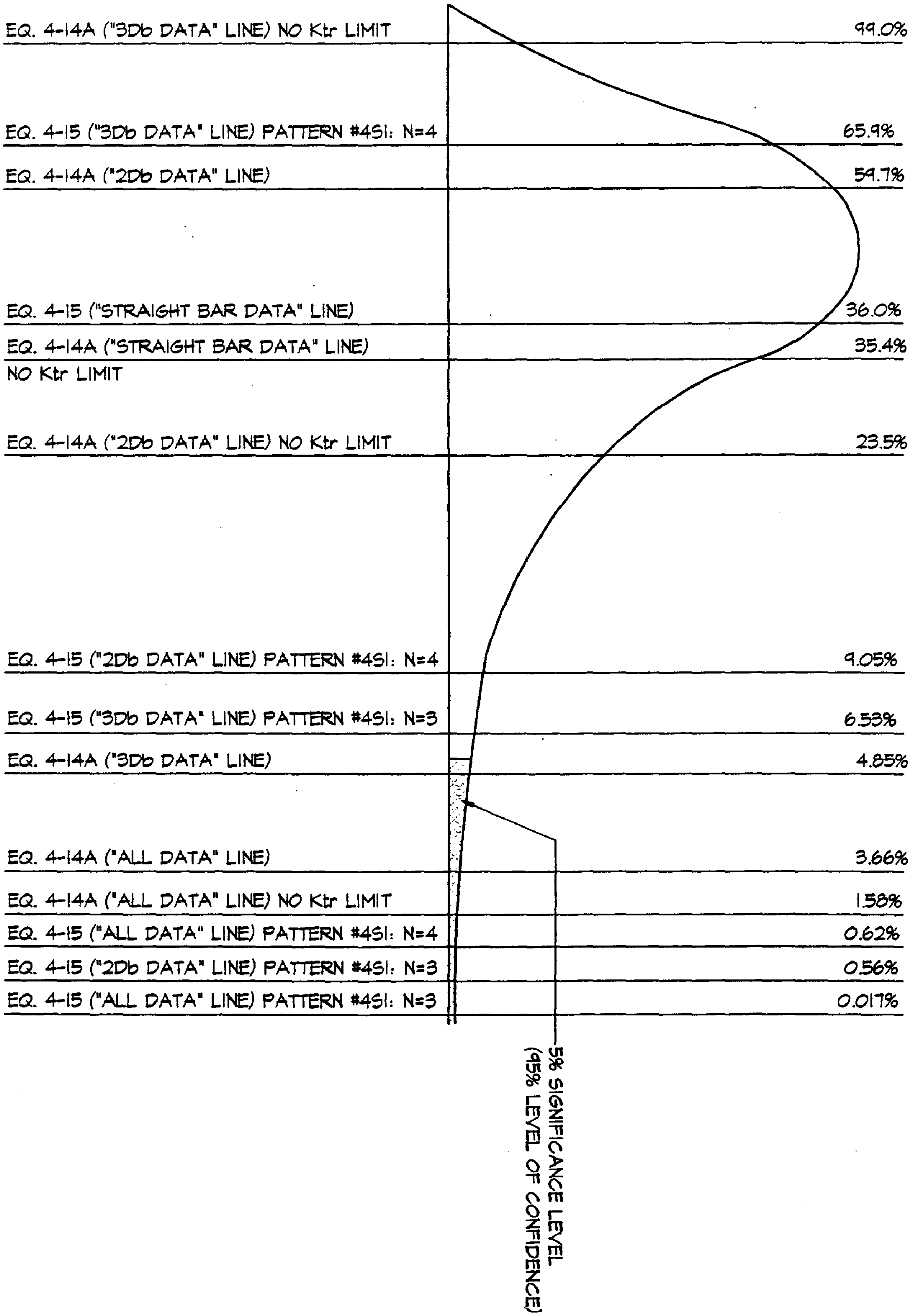
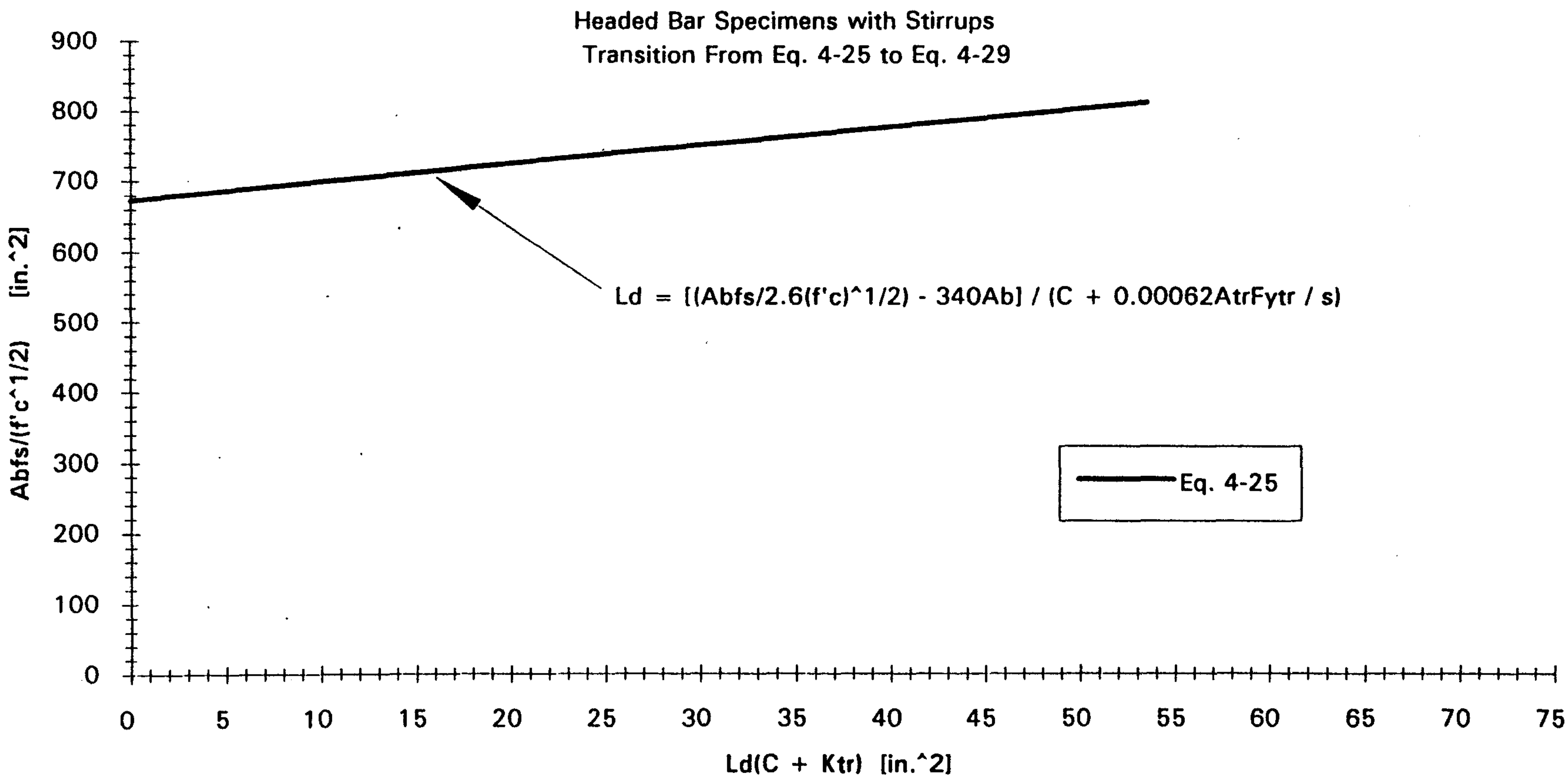


FIG. 4.5 Comparison of Headed Test Results to F-Distribution Curve.


Headed Bar Specimens with Stirrups
Transition From Eq. 4-25 to Eq. 4-29
Ld = [(Abfs/2.6(f'c)^1/2) - 340Ab] / (C + 0.00062AtrFytr / s)
Eq. 4-25
Abfs/(f'c^1/2) [in.^2]
Ld(C + Ktr) [in.^2]
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75

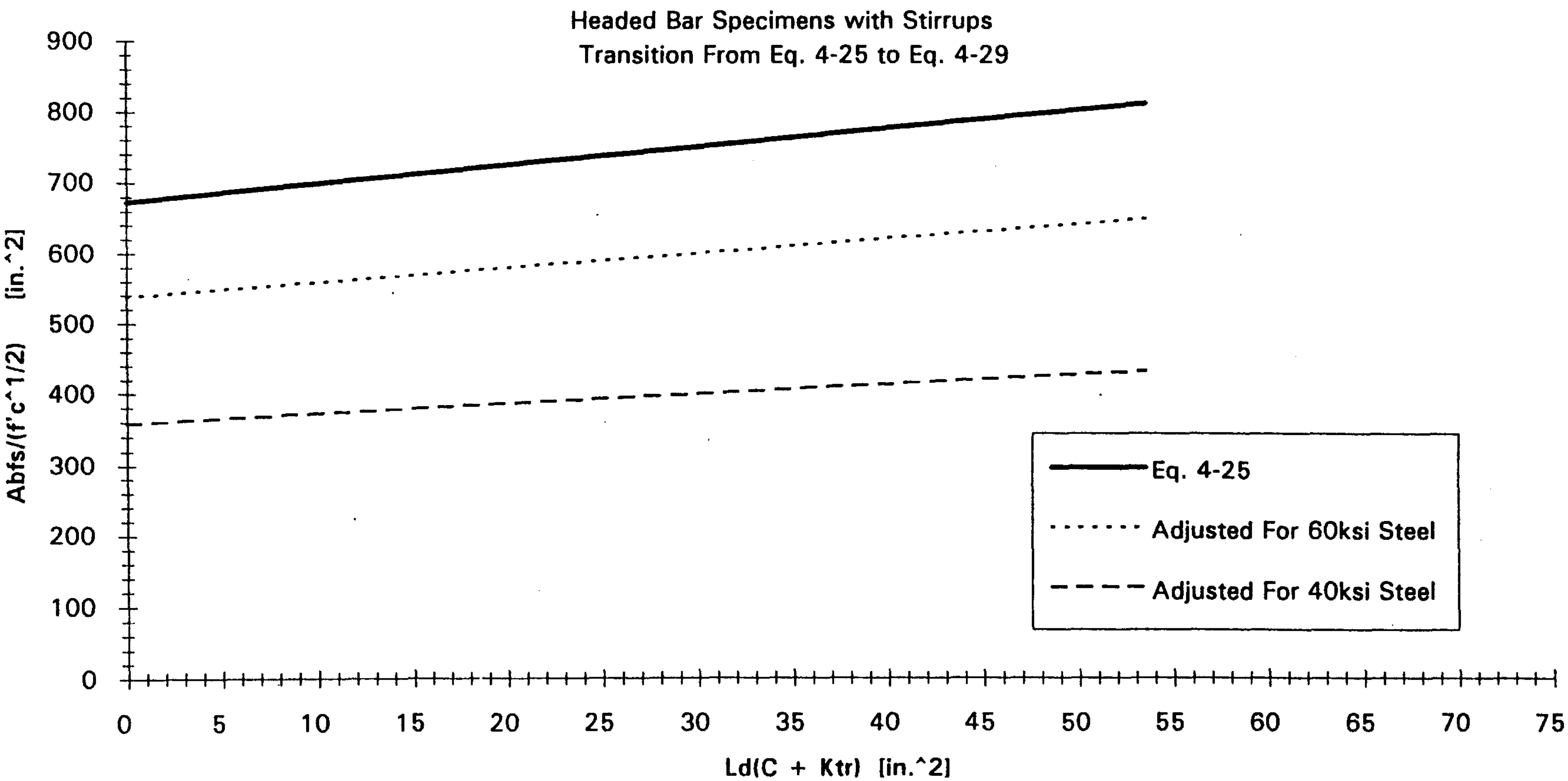


Figure 4.7 Best-Fit Design Equation for Headed Bar Development Length - Adjustments Made for Various Yield Strengths

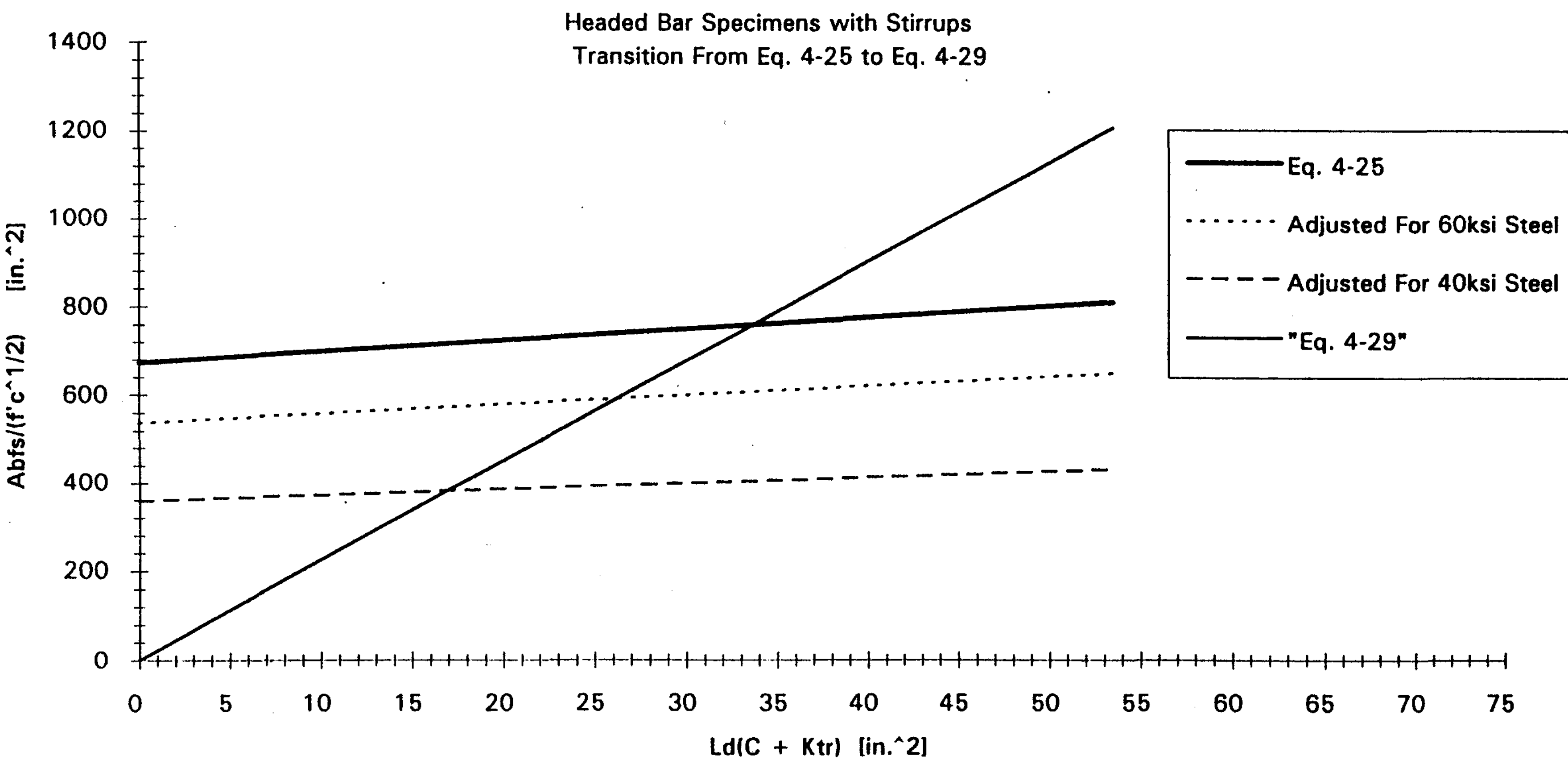


Figure 4.8 Alternate Design Equation (Eq. 4-29) for Headed Bar Devlopment Length

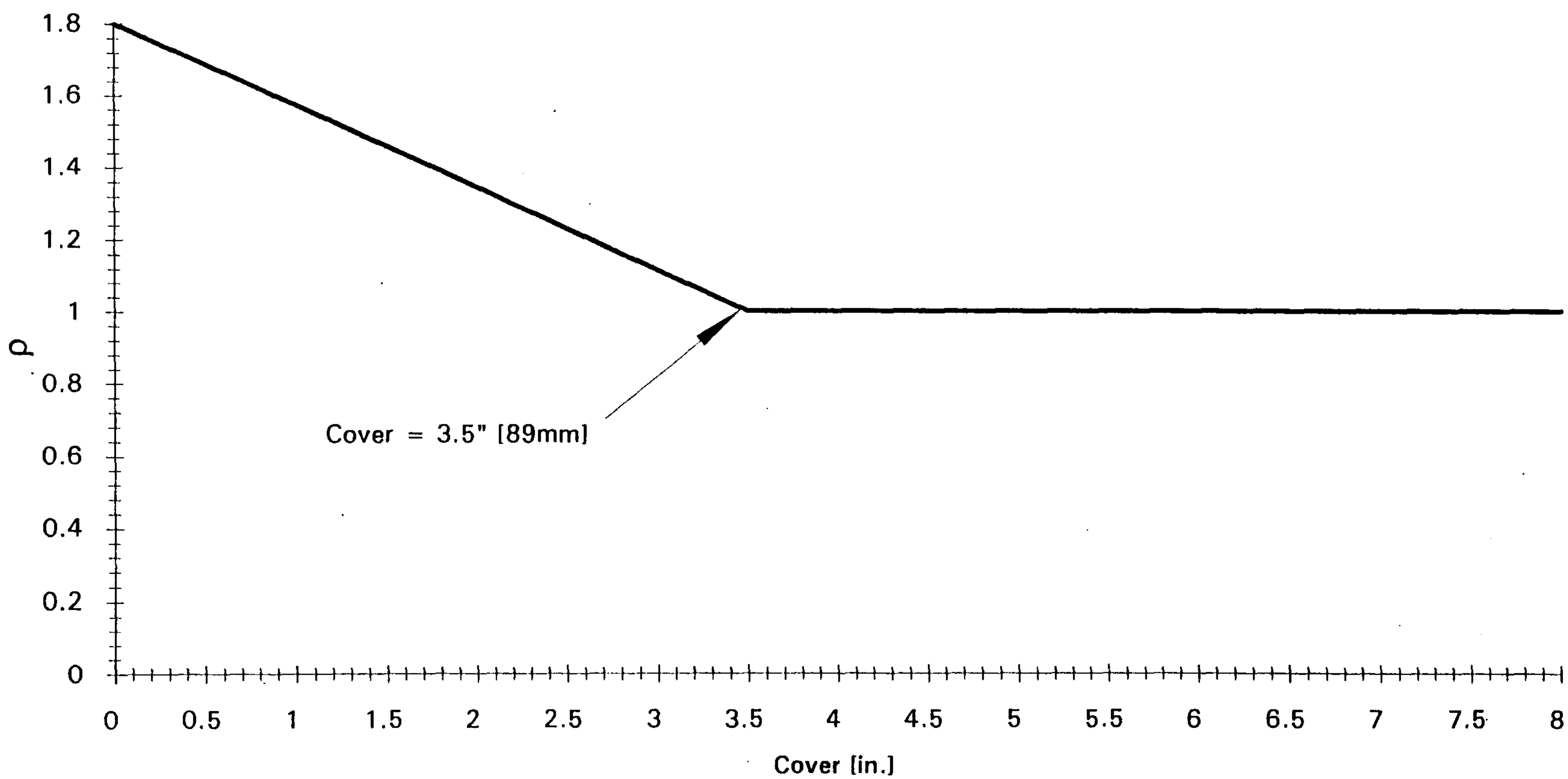


Figure 4.9 Smooth-Bar Correction Factor, "ρ"

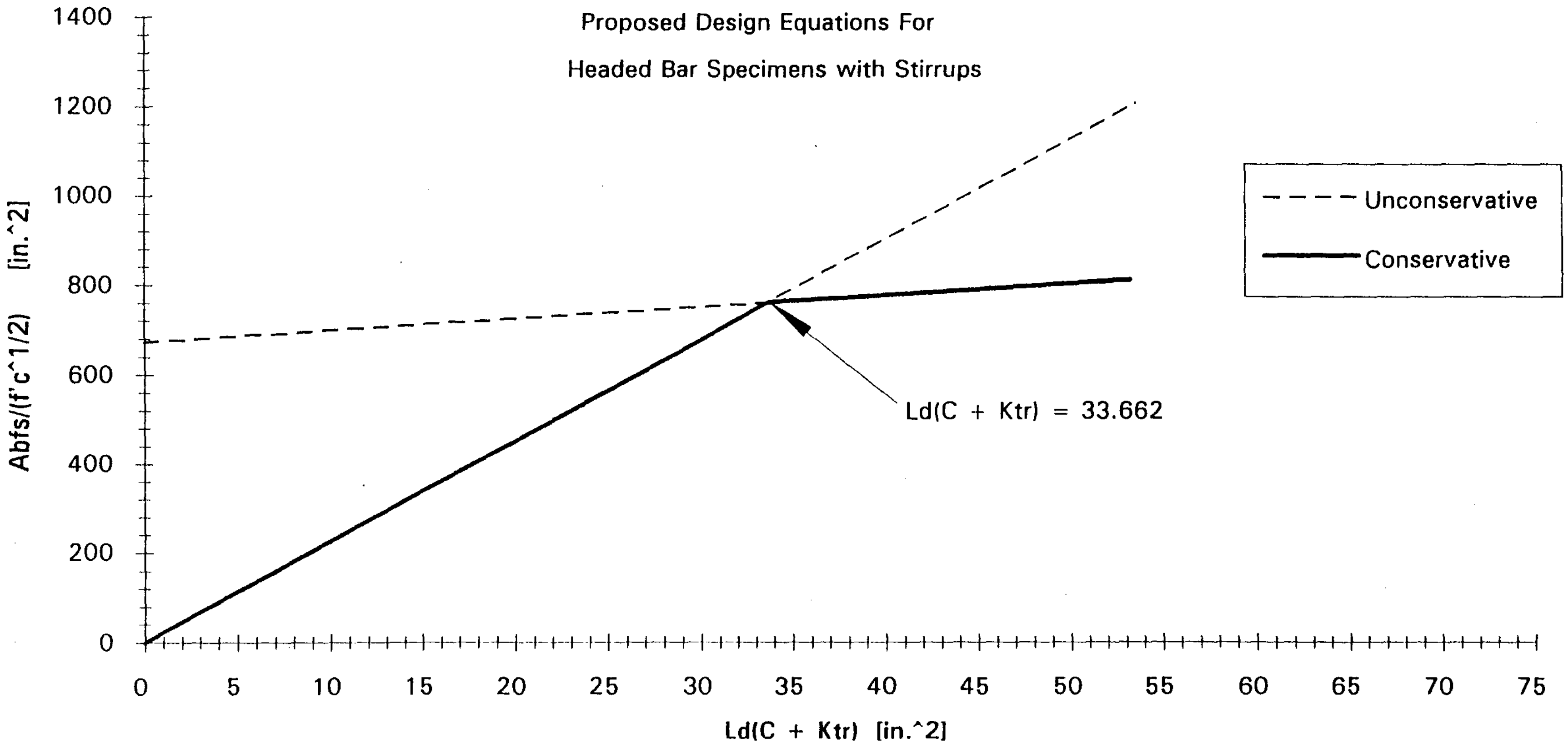


Figure 4.10 Comparison of Conservative and Unconservative Portions of Eqs. 4-25 and 4-29.

APPENDIX

Strut-Tie Models

Even though development lengths resulting from the best-fit lines are similar (Table A.1) to each other, observations from strut-tie models offer further reason to use Eq. 4-14a as a basis for the proposed expressions instead of Eq. 15. Figure A.1 presents a typical strut-tie analysis of a headed test specimen. Strut-tie models are provided for each of the transverse reinforcement configurations in the testing program. Each analysis is performed under the assumption that no clear cover is provided atop the headed bar and hence no additional capacity of the specimen can be attributed to that parameter. These models are divided into three basic groups. The first group includes models in which the applied loading is taken out only through the stirrups precisely as shown in Fig. A.1. The second group of models includes additional capacity contributions from the concrete as determined by an equation for fasteners recently under consideration by ACI (Fuchs et al. 1995). This equation describes the load capacity of the concrete and can be presented as:

$$\mathbf{N_b = K\lambda(f'c)^{1/2}(h_{ef})^{3/2}[0.7 + (0.3C / 1.5h_{ef})]} \qquad \text{(A-1)}$$

where N_b is the concrete breakout capacity (lbs.), C equals the cover (in.), h_{ef} is the embedment length (in.), K equals 21 for headed fasteners (Fuchs et al., 1995), f'c is the compressive strength of concrete (psi), and λ is equal to the quantity, $[(3h_{ef} + C) / 3h_{ef}]^{1/2}$. The third and final group of models is identical to those in the second group, however, the angle at which the compression strut distributes the load from the head is a constant, and is equal to 35°.

A summary of all strut-tie models, prepared in Table A.2, demonstrates the effectiveness of transverse reinforcement to provide a clamping force on the test bar and dissipate the applied load. In cases where concrete capacity is considered, models indicate that only one or two stirrups are necessary to provide the required capacity needed to yield the test bar. This result is evidence that development lengths displayed in Table A.1 may actually be smaller than those determined from the best-fit lines. Consequently, expressions developed from these lines are perhaps more conservative than would appear at first glance. For models where the compression strut is directed at a 35° angle, it is important to note that stirrup pattern #5S1 is the only transverse steel configuration that provides two stirrups that intersect the strut (Fig. A.2). Interestingly, it is that particular group of specimens that had the highest, and most consistent failure loads. Perhaps the most important point to be made concerning these models is the degree to which the capacity of a stirrup can affect the models outcome. Models presented in this report are considered using only Grade 60 steel. Use of Grade 75 steel for the stirrups would provide an additional 1.65 kips of capacity to each No. 3 stirrup. With the importance is placed on the ability to confine the concrete around the headed test bar, it is imperative that expressions used as a basis for headed bar development length need to account for both the area of the transverse steel, as well as the steel's yield strength. For this reason, best-fit lines plotted according to Eq. 4-14a again appear as a better foundation for preparing headed bar development expressions, due to the presence of the term f_{ytr}.

Table A.1a Development Lengths at Yield for Headed Reinforcement
Based Upon "All Data" Best-Fit line with respect to Eq. 4-14a.
Confinement Limit NOT Imposed.

Regression Line	X* (in.^2)	Fytr (psi)	Atr (in.^2)	s (in.)	Concrete Clear Cover 2db	2.5db	3db	3.5db	4db	4.5db	5db
All Data	55.043	75000	0.11	1	7.35	6.89	6.49	6.12	5.80	5.51	5.25
	55.043	75000	0.11	2	11.17	10.14	9.28	8.56	7.94	7.41	6.94
	55.043	75000	0.11	3	13.50	12.03	10.84	9.87	9.06	8.37	7.78
	55.043	75000	0.11	4	15.08	13.26	11.84	10.69	9.74	8.95	8.28
	55.043	75000	0.11	5	16.21	14.13	12.52	11.24	10.20	9.34	8.61
	55.043	75000	0.11	6	17.07	14.78	13.03	11.65	10.54	9.62	8.84
	55.043	75000	0.20	1	4.72	4.52	4.34	4.18	4.03	3.88	3.75
	55.043	75000	0.20	2	7.84	7.32	6.86	6.46	6.10	5.78	5.49
	55.043	75000	0.20	3	10.06	9.22	8.50	7.89	7.37	6.90	6.50
	55.043	75000	0.20	4	11.72	10.59	9.66	8.88	8.22	7.65	7.15
	55.043	75000	0.20	5	13.01	11.63	10.52	9.60	8.83	8.18	7.61
	55.043	75000	0.20	6	14.03	12.45	11.18	10.15	9.29	8.57	7.95
	55.043	75000	0.31	1	3.28	3.18	3.09	3.01	2.93	2.85	2.78
	55.043	75000	0.31	2	5.75	5.46	5.20	4.97	4.75	4.56	4.38
	55.043	75000	0.31	3	7.67	7.17	6.73	6.34	6.00	5.69	5.41
	55.043	75000	0.31	4	9.21	8.50	7.89	7.36	6.90	6.49	6.13
	55.043	75000	0.31	5	10.47	9.56	8.80	8.15	7.59	7.10	6.67
	55.043	75000	0.31	6	11.53	10.44	9.53	8.77	8.13	7.57	7.08
	55.043	60000	0.11	1	8.52	7.90	7.37	6.91	6.50	6.14	5.82
	55.043	60000	0.11	2	12.46	11.19	10.16	9.30	8.58	7.96	7.42
	55.043	60000	0.11	3	14.73	12.99	11.62	10.51	9.60	8.83	8.17
	55.043	60000	0.11	4	16.21	14.13	12.52	11.24	10.20	9.34	8.61
	55.043	60000	0.11	5	17.25	14.92	13.14	11.74	10.60	9.67	8.89
	55.043	60000	0.11	6	18.02	15.49	13.58	12.09	10.89	9.91	9.09
	55.043	60000	0.20	1	5.61	5.34	5.09	4.87	4.66	4.47	4.30
	55.043	60000	0.20	2	9.04	8.35	7.76	7.25	6.80	6.41	6.05
	55.043	60000	0.20	3	11.34	10.28	9.41	8.67	8.03	7.49	7.01
	55.043	60000	0.20	4	13.01	11.63	10.52	9.60	8.83	8.18	7.61
	55.043	60000	0.20	5	14.26	12.62	11.33	10.27	9.39	8.65	8.02
	55.043	60000	0.20	6	15.24	13.39	11.93	10.77	9.81	9.01	8.32
	55.043	60000	0.31	1	3.96	3.82	3.69	3.57	3.46	3.36	3.26
	55.043	60000	0.31	2	6.76	6.37	6.02	5.71	5.43	5.17	4.94
	55.043	60000	0.31	3	8.86	8.20	7.63	7.13	6.70	6.32	5.97
	55.043	60000	0.31	4	10.47	9.56	8.80	8.15	7.59	7.10	6.67

Table A.1a Development Lengths at Yield for Headed Reinforcement
Based Upon "All Data" Best-Fit line with respect to Eq. 4-14a. (cont.)
Confinement Limit NOT Imposed.

Regression Line	X* (in.^2)	Fytr (psi)	Atr (in.^2)	s (in.)	Concrete Clear Cover 2db	2.5db	3db	3.5db	4db	4.5db	5db
	55.043	60000	0.31	5	11.77	10.63	9.69	8.91	8.24	7.67	7.17
	55.043	60000	0.31	6	12.82	11.48	10.40	9.50	8.75	8.10	7.55
	55.043	40000	0.11	1	10.79	9.83	9.02	8.34	7.75	7.24	6.80
	55.043	40000	0.11	2	14.73	12.99	11.62	10.51	9.60	8.83	8.17
	55.043	40000	0.11	3	16.77	14.56	12.86	11.51	10.42	9.52	8.76
	55.043	40000	0.11	4	18.02	15.49	13.58	12.09	10.89	9.91	9.09
	55.043	40000	0.11	5	18.87	16.11	14.05	12.46	11.19	10.16	9.30
	55.043	40000	0.11	6	19.47	16.55	14.38	12.72	11.40	10.33	9.45
	55.043	40000	0.20	1	7.51	7.03	6.61	6.23	5.90	5.60	5.33
	55.043	40000	0.20	2	11.34	10.28	9.41	8.67	8.03	7.49	7.01
	55.043	40000	0.20	3	13.67	12.16	10.95	9.96	9.14	8.44	7.83
	55.043	40000	0.20	4	15.24	13.39	11.93	10.77	9.81	9.01	8.32
	55.043	40000	0.20	5	16.36	14.25	12.61	11.32	10.26	9.39	8.65
	55.043	40000	0.20	6	17.21	14.88	13.11	11.71	10.59	9.66	8.88
	55.043	40000	0.31	1	5.47	5.21	4.98	4.76	4.56	4.38	4.21
	55.043	40000	0.31	2	8.86	8.20	7.63	7.13	6.70	6.32	5.97
	55.043	40000	0.31	3	11.15	10.13	9.27	8.55	7.94	7.40	6.94
	55.043	40000	0.31	4	12.82	11.48	10.40	9.50	8.75	8.10	7.55
	55.043	40000	0.31	5	14.08	12.48	11.21	10.18	9.31	8.59	7.97
	55.043	40000	0.31	6	15.07	13.25	11.83	10.68	9.74	8.95	8.27

* X = Ld [C + (0.378Db) + (0.00062AtrFytr/s)]

Table A.1b Development Length at Yield for Headed Reinforcement
Based Upon "All Data" Best-Fit Line with respect to Eq.4-14a.
Confinement LImit IS Imposed.

Regression Line	X (in.^2)	Fytr (psi)	Atr (in.^2)	s (in.)	Concrete Clear Cover 2db	2.5db	3db	3.5db	4db	4.5db	5db
All Data	50.498	75000	0.11	1	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	75000	0.11	2	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	75000	0.11	3	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	75000	0.11	4	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	75000	0.11	5	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	75000	0.11	6	15.66	13.56	11.95	10.69	9.67	8.82	8.11
	50.498	75000	0.20	1	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	75000	0.20	2	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	75000	0.20	3	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	75000	0.20	4	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	75000	0.20	5	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	75000	0.20	6	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	75000	0.31	1	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	75000	0.31	2	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	75000	0.31	3	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	75000	0.31	4	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	75000	0.31	5	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	75000	0.31	6	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	60000	0.11	1	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	60000	0.11	2	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	60000	0.11	3	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	60000	0.11	4	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	60000	0.11	5	15.83	13.68	12.05	10.77	9.73	8.87	8.16
	50.498	60000	0.11	6	16.54	14.21	12.46	11.09	9.99	9.09	8.34
	50.498	60000	0.20	1	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	60000	0.20	2	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	60000	0.20	3	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	60000	0.20	4	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	60000	0.20	5	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	60000	0.20	6	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	60000	0.31	1	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	60000	0.31	2	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	60000	0.31	3	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	60000	0.31	4	15.36	13.33	11.78	10.55	9.55	8.73	8.03

Table A.1b Development Length at Yield for Headed Reinforcement
Based Upon "All Data" Best-Fit Line with respect to Eq.4-14a. (cont.)
Confinement LImit IS Imposed.

Regression Line	X (in.^2)	Fytr (psi)	Atr (in.^2)	s (in.)	Concrete Clear Cover 2db	2.5db	3db	3.5db	4db	4.5db	5db
	50.498	60000	0.31	5	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	60000	0.31	6	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	40000	0.11	1	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	40000	0.11	2	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	40000	0.11	3	15.39	13.35	11.80	10.56	9.56	8.73	8.04
	50.498	40000	0.11	4	16.54	14.21	12.46	11.09	9.99	9.09	8.34
	50.498	40000	0.11	5	17.31	14.78	12.89	11.43	10.27	9.32	8.53
	50.498	40000	0.11	6	17.87	15.18	13.20	11.67	10.46	9.48	8.67
	50.498	40000	0.20	1	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	40000	0.20	2	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	40000	0.20	3	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	40000	0.20	4	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	40000	0.20	5	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	40000	0.20	6	15.79	13.65	12.03	10.75	9.71	8.86	8.15
	50.498	40000	0.31	1	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	40000	0.31	2	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	40000	0.31	3	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	40000	0.31	4	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	40000	0.31	5	15.36	13.33	11.78	10.55	9.55	8.73	8.03
	50.498	40000	0.31	6	15.36	13.33	11.78	10.55	9.55	8.73	8.03

* X = Ld [C + (0.378Db) + (0.00062AtrFytr/s)]

Table A.1c Development Length at Yield for Headed Reinforcement
Based Upon "All Data" Best-Fit Line with respect to Eq. 4-15.
For Pattern #4S1 N=3

				Cmax/Cmin ratio						
				2.00	1.60	1.33	1.14	1.00	1.13	1.25
	X*	Atr	N**	Concrete Clear Cover						
Regression Line	(in.^2)	(in.^2		2db	2.5db	3db	3.5db	4db	4.5db	5db
All Data	2041.22	0.11	1	18.58	16.25	14.39	12.88	11.65	10.32	9.24
	2041.22	0.11	2	17.16	15.03	13.32	11.94	10.80	9.57	8.56
	2041.22	0.11	3	15.75	13.81	12.26	10.99	9.95	8.81	7.88
	2041.22	0.11	4	14.33	12.60	11.20	10.05	9.10	8.05	7.20
	2041.22	0.11	5	12.91	11.38	10.13	9.10	8.25	7.30	6.52
	2041.22	0.20	1	17.42	15.25	13.52	12.11	10.96	9.71	8.68
	2041.22	0.20	2	14.85	13.04	11.58	10.39	9.41	8.33	7.44
	2041.22	0.20	3	12.27	10.83	9.65	8.67	7.87	6.95	6.21
	2041.22	0.20	4	9.70	8.62	7.71	6.95	6.32	5.58	4.97
	2041.22	0.20	5	7.12	6.40	5.78	5.23	4.78	4.20	3.73
	2041.22	0.31	1	16.00	14.03	12.45	11.16	10.11	8.95	8.00
	2041.22	0.31	2	12.01	10.61	9.45	8.50	7.71	6.81	6.08
	2041.22	0.31	3	8.02	7.18	6.45	5.83	5.32	4.68	4.16
	2041.22	0.31	4	4.03	3.75	3.45	3.17	2.92	2.55	2.24
	2041.22	0.31	5	0.04	0.32	0.45	0.51	0.53	0.41	0.32

* X = Ld {[2 (Cmax / Cmin)(C + 0.5Db)] + 22.4C + 11.2Db} + { 72.4Ab [(Cmax / Cmin) +11.2]} + {846.7NAtr/n}
** N is the number of stirrups intersecting the potential splitting failure plane.

Table A.1d Development Length at Yield for Headed Reinforcement
Based Upon "All Data" Best-Fit Line with respect to Eq. 4-15.
For Pattern #4S1 N=4

				Cmax/Cmin ratio						
				2.00	1.60	1.33	1.14	1.00	1.13	1.25
	X*	Atr	N**	Concrete Clear Cover						
Regression Line	(in.^2)	(in.^2		2db	2.5db	3db	3.5db	4db	4.5db	5db
All Data	2087.12	0.11	1	19.28	16.85	14.91	13.35	12.07	10.70	9.58
	2087.12	0.11	2	17.86	15.63	13.85	12.40	11.22	9.94	8.89
	2087.12	0.11	3	16.44	14.41	12.78	11.46	10.37	9.18	8.21
	2087.12	0.11	4	15.03	13.20	11.72	10.51	9.52	8.43	7.53
	2087.12	0.11	5	13.61	11.98	10.66	9.57	8.67	7.67	6.85
	2087.12	0.20	1	18.12	15.85	14.04	12.57	11.38	10.08	9.02
	2087.12	0.20	2	15.54	13.64	12.11	10.86	9.83	8.70	7.78
	2087.12	0.20	3	12.97	11.43	10.17	9.14	8.29	7.33	6.54
	2087.12	0.20	4	10.39	9.22	8.24	7.42	6.74	5.95	5.30
	2087.12	0.20	5	7.82	7.00	6.30	5.70	5.20	4.57	4.06
	2087.12	0.31	1	16.70	14.63	12.98	11.63	10.53	9.32	8.34
	2087.12	0.31	2	12.71	11.21	9.98	8.96	8.13	7.19	6.42
	2087.12	0.31	3	8.72	7.78	6.98	6.30	5.74	5.05	4.50
	2087.12	0.31	4	4.73	4.35	3.98	3.64	3.34	2.92	2.58
	2087.12	0.31	5	0.74	0.92	0.98	0.97	0.95	0.79	0.66

* X = Ld {[2 (Cmax / Cmin)(C + 0.5Db)] + 22.4C + 11.2Db} + { 72.4Ab [(Cmax / Cmin) +11.2]} + {846.7NAtr/n}

** N is the number of stirrups intersecting the potential splitting failure plane.

Table A.2 Summary of Strut-Tie Model Results

Type 1: **No Consideration given to Concrete Breakout Capacity**

Stirrup Pattern	1st Stirrup	2nd Stirrup	3rd Stirrup
#3S1	Yielded (1")	Yielded (6")	14.8% of Yield (11")
#4S1	Yielded (2")	Yielded (5")	20.4% of Yield (8")
#4S2	Yielded (1.5")	Yielded (4.5")	35.2% of Yield (7.5")
#5S1	Yielded (0.5")	Yielded (3")	93.4% of Yield (5.5")

Type 2: **Consideration given to Concrete Breakout Capacity**

f'c=4000psi; C=0; Lamda=1.0; => Nb=38.65kips

Stirrup Pattern	1st Stirrup	2nd Stirrup	3rd Stirrup
#3S1	Yielded (1")	29.9% of Yield (6")	n/a
#4S1	Yielded (2")	15.9% of Yield (5")	n/a
#4S2	Yielded (1.5")	28.8% of Yield (4.5")	n/a
#5S1	Yielded (0.5")	76.5% of Yield (3")	n/a

f'c=5000psi; C=0; Lamda=1.0; => Nb=43.20kips

Stirrup Pattern	1st Stirrup	2nd Stirrup	3rd Stirrup
#3S1	Yielded (1")	18.3% of Yield (6")	n/a
#4S1	Yielded (2")	1.9% of Yield (5")	n/a
#4S2	Yielded (1.5")	13.3% of Yield (4.5")	n/a
#5S1	Yielded (0.5")	53.2% of Yield (3")	n/a

f'c=4000psi; C=0; Lamda=1.17; => Nb=45.22kips

Stirrup Pattern	1st Stirrup	2nd Stirrup	3rd Stirrup
#3S1	Yielded	13.2% of Yield (6")	n/a
#4S1	89.7% of fytr	n/a	n/a
#4S2	Yielded	6.5% of Yield (4.5")	n/a
#5S1	Yielded	43.1% of Yield (3")	n/a

f'c=5000psi; C=0; Lamda=1.17; => Nb=50.54kips

Stirrup Pattern	1st Stirrup	2nd Stirrup	3rd Stirrup
#3S1	98.4% of Yield (1")	n/a	n/a
#4S1	49.2% of Yield (2")	n/a	n/a
#4S2	65.6% of Yield (1.5")	n/a	n/a
#5S1	Yielded (0.5")	16.1% of Yield (3")	n/a

Table A.2 Summary of Strut-Tie Model Results (cont.)

Type 3: Compression Strut Angle Acting only at 35 degrees (Fig. A.2)*

Consideration NOT given to Breakout Capacity of Concrete

	Load to Head (kips)	Load to Stirrups	1st Stirrup Status	2nd Stirrup Status
Nb=0	28.52	19.97	Yielded (0.5")	Yielded (3")

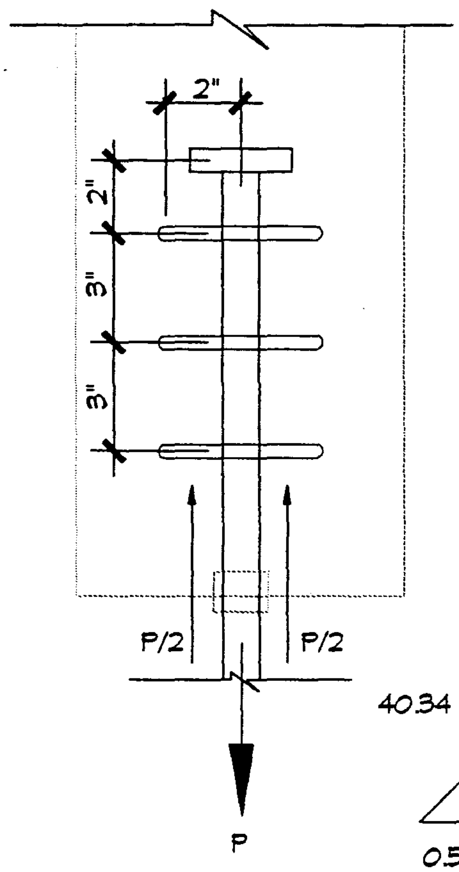
Consideration given to Breakout Capacity of Concrete

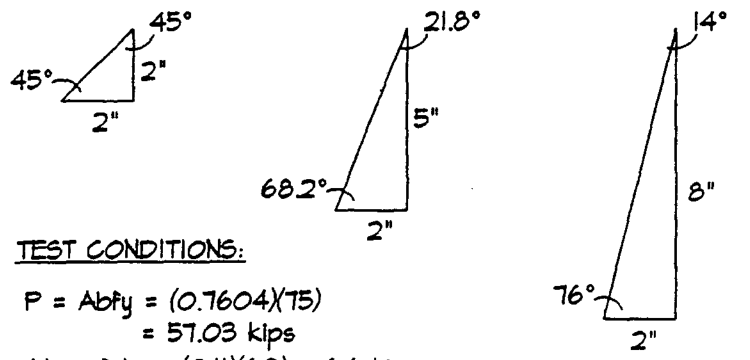
	Load to Head (kips)	Load to Stirrups(kips)	1st Stirrup Status	2nd Stirrup Status
Nb=38.65kips	18.38	6.43	97.4% of Yield (0.5")	n/a
Nb=43.20kips	13.83	4.84	73.4% of Yield (0.5")	n/a
Nb=45.22kips	11.81	4.13	62.6% of Yield (0.5")	n/a
Nb=50.54kips	6.49	2.27	34.4% of Yield (0.5")	n/a

TABLE NOTES:

* Indicates use of stirrup pattern #5S1 results only.
( ) Indicate the distance of the stirrup from the head.

GEOMETRY FOR PATTERN #4S1



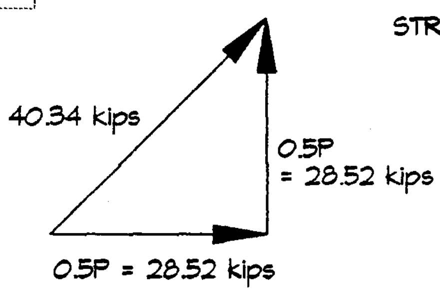


TEST CONDITIONS:

P = Abfy = (0.7604)(75)
= 57.03 kips

Atr x fytr = (0.11)(60) = 6.6 kips

FORCE TO 1ST STIRRUP



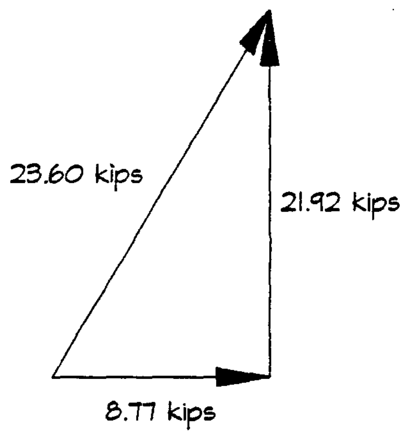
STRUT = (28.52 / COS 45°) = 40.34 kips

CAPACITY OF STIRRUP = 6.6 kips

REMAINDER = (28.52 - 6.6) = 21.92 kips

TRANSFERED BACK ONTO BAR = 21.92 kips

FORCE TO 2ND STIRRUP



STRUT = (21.92 / COS 21.8°) = 23.60 kips

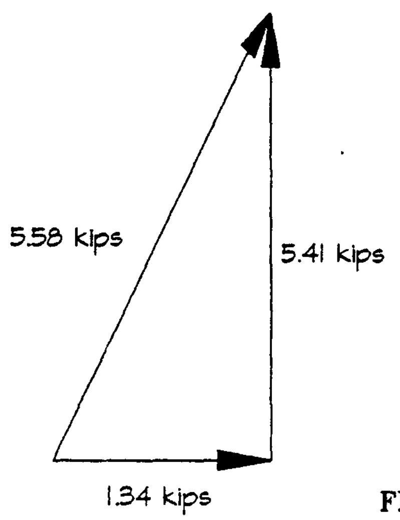
(23.60)(COS 68.2°) = 8.77 kips = (STIRRUP LOAD)

CAPACITY OF STIRRUP = 6.6 kips

REMAINDER = (8.77 - 6.6) = 2.16 kips

TRANSFERED BACK ONTO BAR = (2.16 / TAN 21.8°)
= 5.41 kips

FORCE TO 3RD STIRRUP



STRUT = (5.41 / COS 14°) = 5.58 kips

(5.58)(COS 76°) = 1.34 kips = (STIRRUP LOAD)

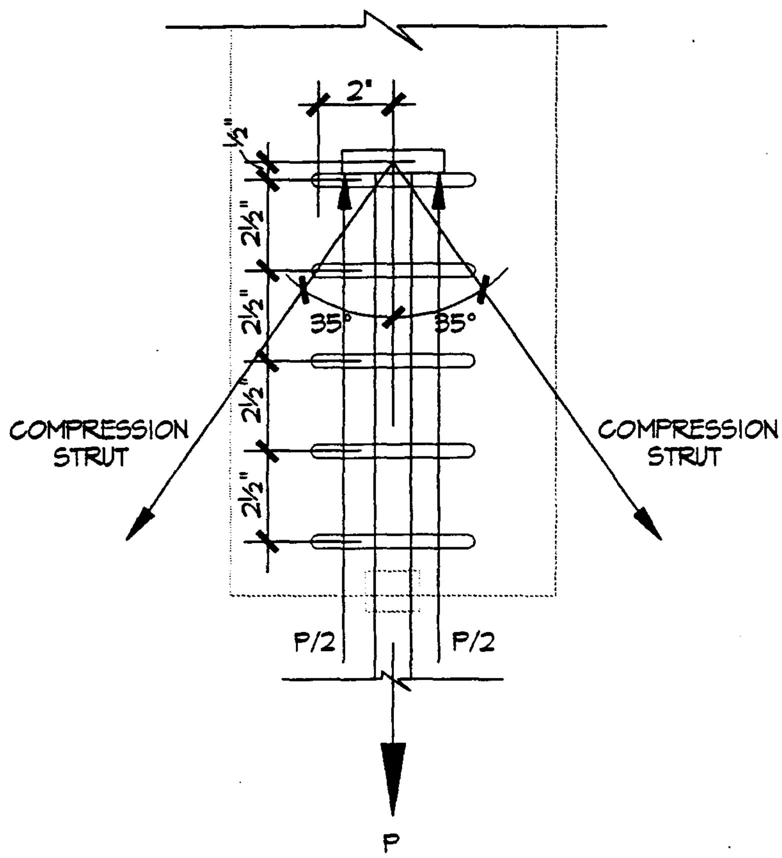
CAPACITY OF STIRRUP = 6.6 kips

% OF STIRRUP CAPACITY USED = (1.34 / 6.6)
= 20.4%

NOTE: FOR A SUMMARY OF ALL STRUT-TIE MODEL RESULTS SEE TABLE 4.17.

FIG. A.1 Typical Strut-Tie Analysis.

STRUT-TIE MODEL - PATTERN #5S1



-- IF THE STRUT ANGLE IS LIMITED TO 35°, THIS PATTERN IS THE ONLY PATTERN OF THE 4 TESTED IN WHICH THE STRUT INTERSECTS 2 STIRRUPS. INTERESTINGLY, THIS PATTERN FAILED AT CONSISTENTLY HIGHER LOADS THAN THE OTHER 4 PATTERNS TESTED.

FIG. A.2 Typical Strut-Tie Analysis - Stirrup Pattern #5S1.