Bond and Development of Bundled Reinforcing Steel

by

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Thesis

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APPROVED BY

SUPERVISING COMMITTEE:

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to my mother and father

ABSTRACT

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In the construction of reinforced concrete structures, it is sometimes advantageous or even necessary to place reinforcement in bundles. Bundling may be required because of restrictions on member dimensions. Grouping of steel may result in narrower, more graceful members, or allow for easier placement and vibration of concrete.

Current codes and design recommendations allow as many as four bars to be placed in a group or bundle. There are provisions for increasing development length based on the size of the bundle, but in general there is scant guidance to aid the designer using bar bundles. There is a need for greater understanding of the bond mechanics of bundles, and test data to support embedment and detailing specifications.

Tests were conducted on two, three, and four bar bundles in an effort to understand behavior and evaluate existing codes and specifications. Analysis of a spectrum of bundle sizes provides a broad foundation for the investigation of behavior. It also aids in identifying which parameters have the greatest influence on ultimate bond strength. Included in the program were tests on individual bars having an area equivalent to the two and four bar bundles. These are intended to test the concept of an "equivalent bar", which is introduced in codes as a means of satisfying spacing requirements based on bar diameter.

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Chapter I:
Introduction

1.1 General Background

In the construction of reinforced concrete structures, it is sometimes advantageous or even necessary to place reinforcement in bundles. Bundling may be required because of restrictions on member dimensions. Grouping of steel may result in a narrower, more graceful member. Top steel might be bundled to allow for easier placement and vibration of concrete. For any of these or other reasons, a designer may choose to place longitudinal reinforcement in bundles.

A pier bent cap from a TxDOT project in Austin, TX is shown in Figure 1.1. These members commonly contain bundled reinforcement. Figure 1.2 shows a reinforcement cage constructed for another pier bent cap, using bundled #11 bars in multiple layers. Even after the reinforcement has been bundled and placed in several layers, the cage remains quite congested. Note also from Figure 1.3 that the loading configuration of these inverted tees does not provide any additional restraint to splitting in the plane of the bars, as it would in a typical frame member or simply supported span.

Current codes allow as many as four bars to be placed in a group or bundle. There are provisions for increasing the length of anchorage based on the size of the bundle, but in general there is scant guidance in the code to aid the designer using bar bundles. Very little information is available in published literature on tests of bundled bar anchorages, either. There is a need for greater understanding of the bond mechanics of bundles, and test data to support code development length and detailing specifications.

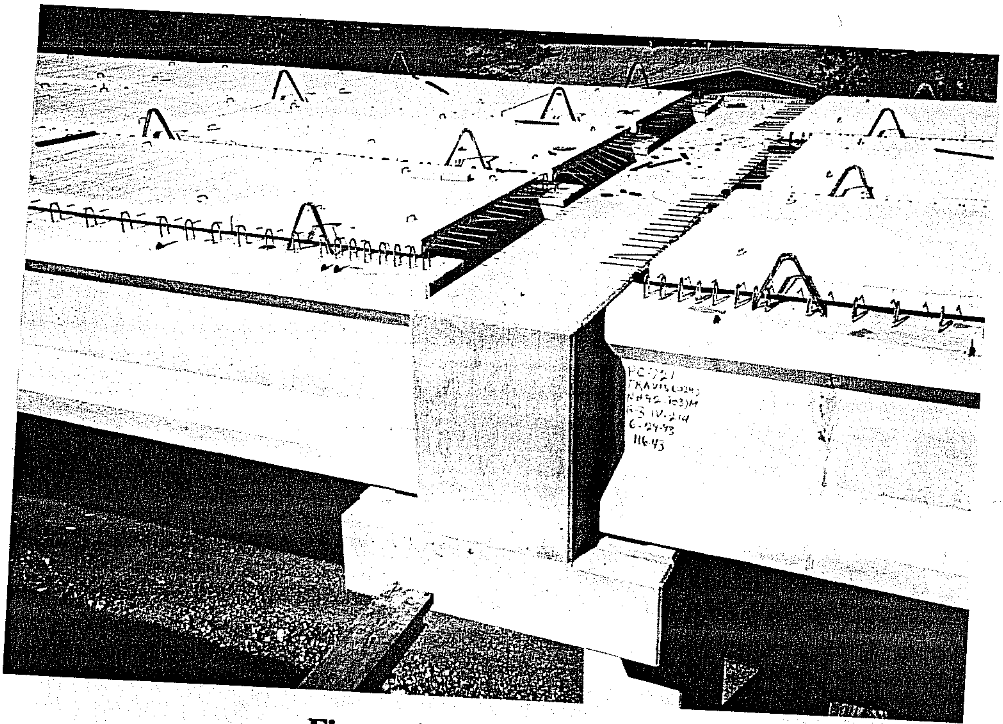


Figure 1.1 Pier Bent Cap

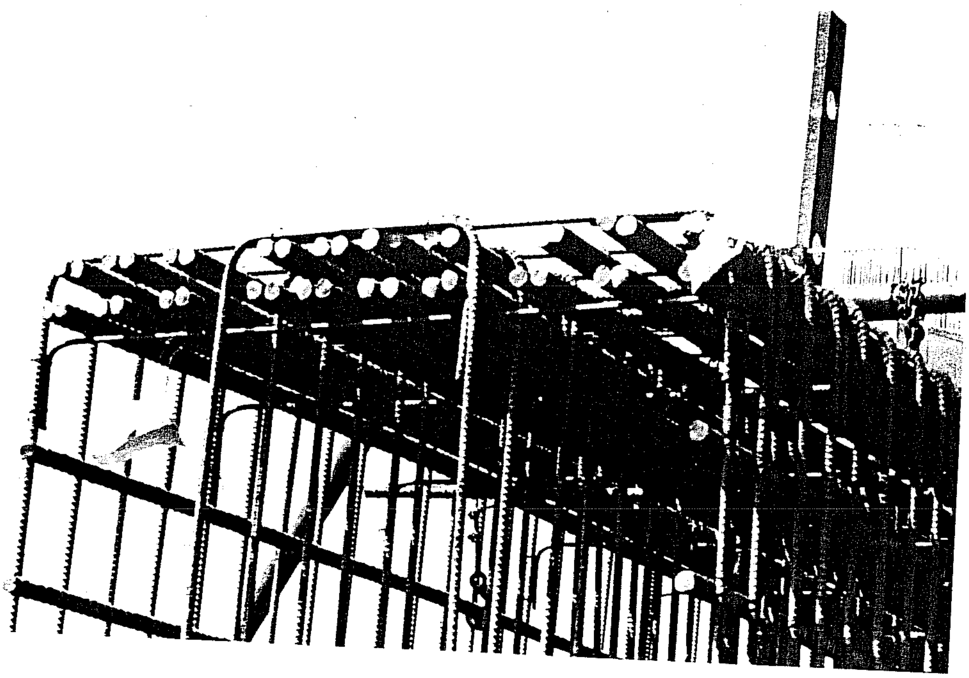


Figure 1.2 Reinforcement Cage

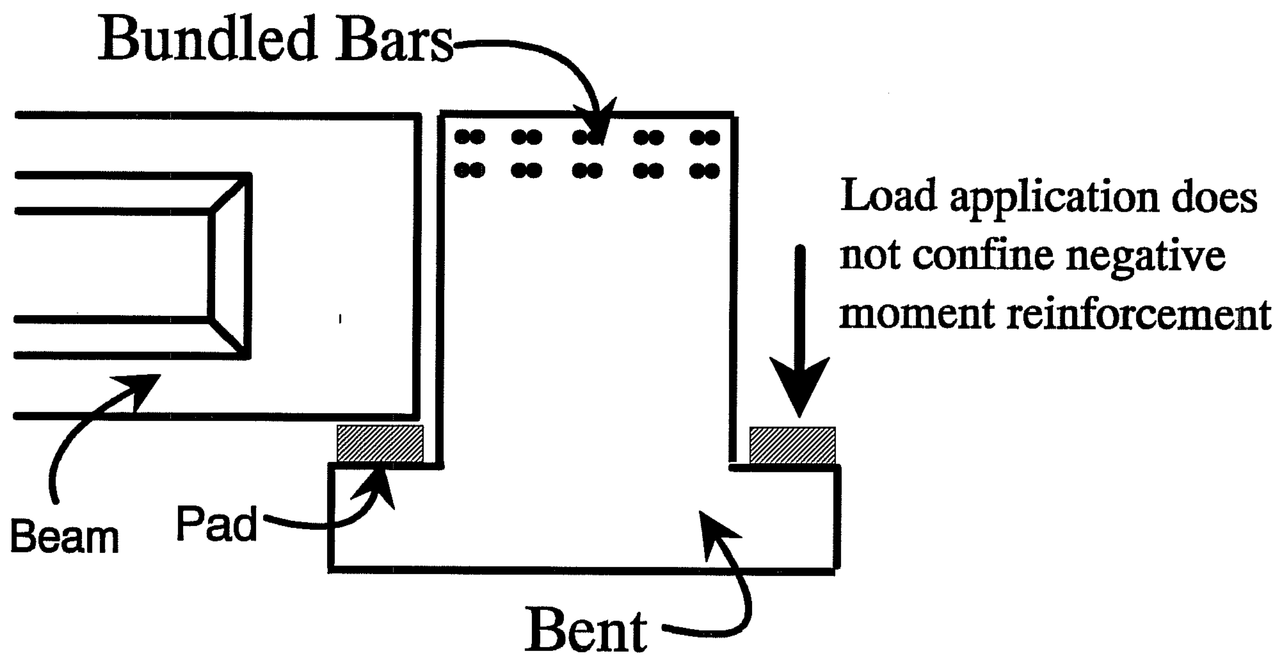


Figure 1.3 Loading Configuration of Bent Caps

1.2 Objective

The aim of the testing program reported herein is to shed light on the behavior and mechanics of bundled bars, and to provide recommendations useful in the detailing of anchorages for them. Tests resulting in bond failures produce values of both ultimate bond stress and, by extrapolation, development length required to reach yield stress. Correlations can then be made between the test values and current code and design procedures, as well as with other tests available in the literature. Such comparisons provide insight into the effect of bundling on bond mechanics, and provide a measure of the accuracy of current code and design specifications.

1.3 Scope

Tests were conducted on two, three, and four bar bundles in an effort to understand behavior and evaluate existing codes and specifications. Analysis of a spectrum of bundle sizes provides a broad foundation for the investigation of behavior. It also aids in identifying which parameters have the greatest influence on ultimate bond strength. Included in the program were tests on individual bars having an area equivalent to the two and four bar bundles. These are intended to test the concept of an "equivalent bar", which is introduced in codes and specifications as a means of satisfying spacing requirements based on bar diameter.

Chapter II:
Background

There is not an extensive body of information on bundled bars. In fact, a literature search located only one paper on bundled bar development, and a few others on crack control for bundled bars. This lack of information is reflected to a degree in current codes and specifications, where very little specific instruction is given on the detailing of bundled bar embedments. The available information from the literature and current codes and specifications is summarized below.

2.1 Bond and Anchorage of Bundled Reinforcement

In 1958, Hanson and Reiffenstuhl reported the results of an investigation of the feasibility of using bundled bar details in beams and columns (Hanson, 1958). The first half of the program consisted of tests of pairs of beams. The first beam of the pair had conventionally spaced reinforcement; the second, bundled reinforcement. The same number of bars were used in each set of tests. Four bar bundles of number 6 and number 8 bars were tested, as well as three bar bundles of number 9 bar. The bundles were top cast in short, deep beams. Two types of steel were used: "intermediate" grade steel, with a yield strength of approximately 47 ksi, and a high strength steel, with a yield strength of approximately 82 ksi.

All the beams with intermediate grade steel failed in yielding of the reinforcement. Three of the four tests with high strength reinforcement failed in bond, the fourth failing in flexure after bond slip was recorded. The authors state that, "...when only external bar perimeter was used to calculate bond stress, there was no systematic difference in ultimate bond stress developed by spaced and bundled bars." The authors' conclusion was that bundling reinforcement is a safe detailing practice, as long as each bar is "individually well anchored." They also recommend that bond stress for the bars be computed on the basis of the surface area of the bundle in direct contact with the concrete. No specific recommendations for the design of embedments for bar bundles were made.

2.2 Crack Control for Bundled Reinforcement

The literature search located two other papers, dealing with applying code provisions for crack control when detailing bundled bars. While perhaps not directly applicable to questions of development length, the discussions are still interesting in that they involve questions about bundled bar behavior.

In 1972, Nawy proposed a method for applying the crack control provisions of ACI 318-71 to bundled bars (Nawy, 1972). The concern was that there was no specific instruction in the code for interpreting the equations for bundled geometries. Nawy proposed that designers modify the equation with parameters which account for the change in exposed bar area when the bars are grouped together.

Lutz presented a similar modification in 1974 (Lutz, 1974). He felt that Nawy's modification was confusing. Instead, he presented a different method of modifying the code equations, based on slightly different assumptions about how grouping the bars changed their effective perimeter. The argument over which perimeter reflects behavior most accurately is particularly interesting in that it points to a good deal of confusion over the issue: Lutz states, "There is very little experimental information that could be used to aid in evaluating the expressions presented."

2.3 Current Codes and Design Specifications

2.3.1 Detailing

The general detailing requirements for bundled bars in both AASHTO (AASHTO, 1992) and ACI (ACI 318, 1989) are identical. AASHTO Section 8.21.5 specifies that the number of bars in a bundle is limited to four, and bars larger than number 11 are limited to bundles of two. It further states that when individual bars within a bundle are terminated within a span, the cutoff points must be separated by 40 bar diameters. Finally, it requires that spacing limitations based on bar diameter must be satisfied, in the case of bundles, on the basis of a single bar having area equivalent to that of the bars in the bundle. These same requirements are found in ACI Section 7.6.6, with the exception that ACI does not allow bundling of bars larger than number 11 due to concerns of excessive crack widths.

2.3.2 Development Length

The basic development length for number 11 and smaller bars is:

$$l_d = \frac{0.04 \cdot A_b f_y}{\sqrt{f_c}}$$

In the AASHTO specification, this equation is lengthened by factors for casting position, lightweight aggregate, and epoxy coating. The value may be reduced if sufficient clear cover and spacing is provided, the bars are enclosed in spiral reinforcement, or if reinforcement is provided in excess of that required for flexural capacity.

The ACI code specifies factors to be used as multipliers of the basic equation, accounting for clear spacing, cover, and transverse reinforcement, which may increase the development length. The AASHTO factors for these parameters will only reduce length, if they apply. ACI also allows reductions for excess reinforcement, wide bar spacing and cover, and both spiral reinforcement and closely spaced stirrups. The factors in the ACI code are not all the same as those in AASHTO.

Presently, very little is said in addition to this in the codes regarding the development of bundled bars. AASHTO Section 8.28 states:

> The development length of individual bars within a bundle, in tension or compression, shall be that for the individual bar, increased by 20 percent for a three-bar bundle, and 33 percent for a four-bar bundle.

The ACI code contains the same provisions in Section 12.4. These provisions are based on the amount of surface area on the inside of the bundle, which does not have direct contact with the surrounding concrete and therefore cannot transfer stress through bond.

Chapter III:
Test Description

3.1 Design of Tests

The intent of this research was to explore the effect on development length of placing bars in groups or bundles. In order to determine the required development length for bundled bars, tests must be performed which fail in bond before the longitudinal reinforcement yields. If a given embedment length proves long enough to yield reinforcement, the only conclusion that can be reached is that that particular length is greater than or equal to the required development length. It could be much longer than needed, or very near the minimum requirement.

If, however, a test fails in bond, and if the bar stress at failure is known, it is possible (assuming a linear relationship between bond and development length) to extrapolate from the test embedment length the minimum length required to reach nominal yield. The designer may then choose the margin of safety to be applied to that length. All the specimens in this program were designed to fail in bond.

3.1.1 Basis for Design

The specimens were intended to model realistic field use of bundled bars. For this reason, the dimensions were based on a sample detail from the TxDOT Bridge Design Examples (TxDOT, 1990), shown in Figure 3.1. The design selected includes bundles of #11 bars. The specimens were built at roughly half scale, using #6 bars. This was the largest scale which could be tested conveniently with the facilities at Ferguson Laboratory.

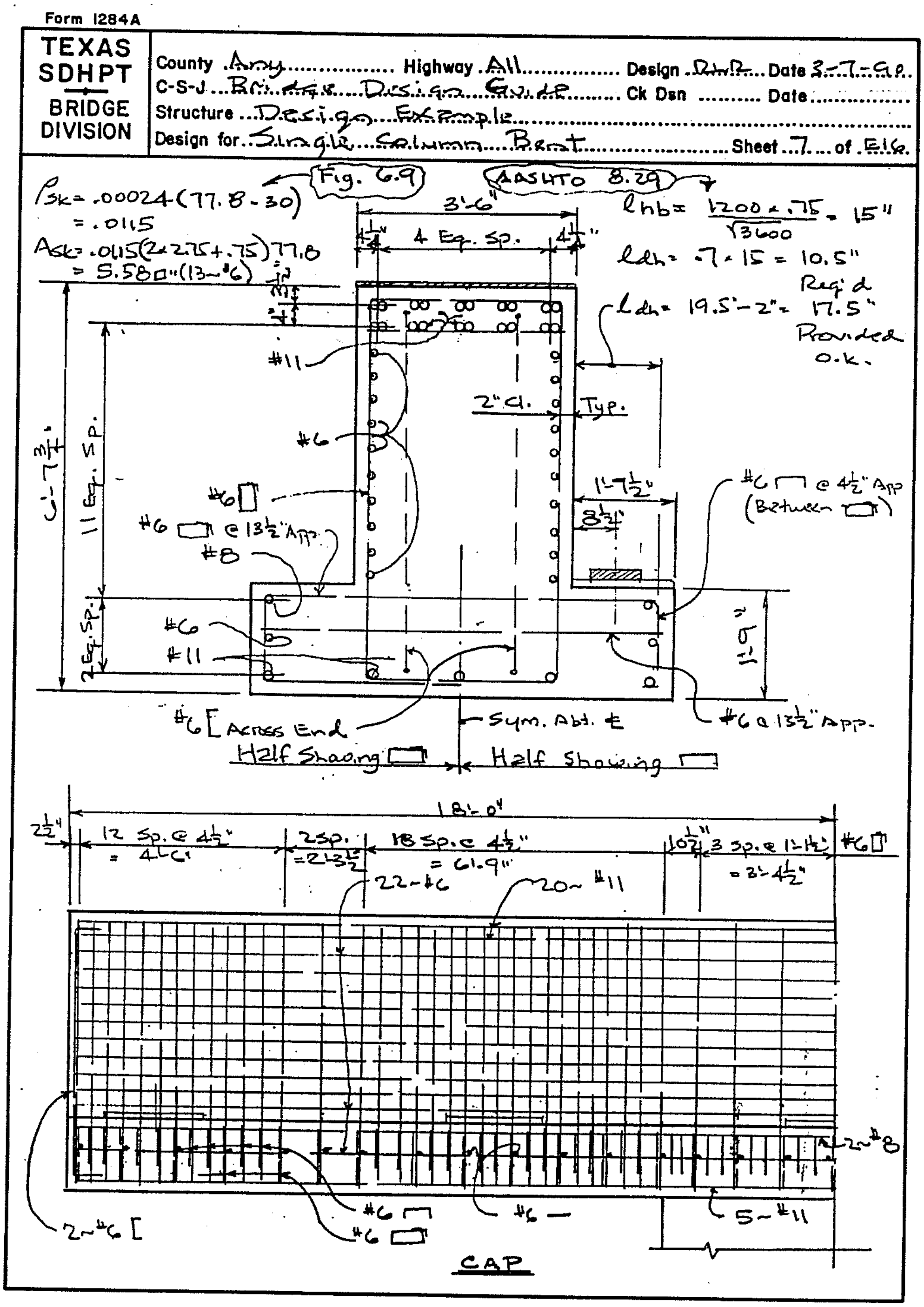


Figure 3.1 Design Guide Example

3.1.2 Variables

The following items were considered in examining bundled bar behavior and anchorage:

- Bundle Size
- Equivalent Bars
- Transverse Reinforcement
- Casting Position

3.1.2.1 Bundle Size

In order to investigate the bond mechanics of bundled bars, the full range of permissible bundle sizes was tested. Figure 3.2 shows the bar patterns and spacings. The two bar bundle tests were performed by Chen (Chen, 1994) as the first part of this project, and the author tested the three and four bar patterns. This progression of tests allows comparison between the range of two to four bars in a bundle. The inclusion of the two bar bundles in two layers is interesting, because the same number of bars are embedded as in the four bar bundle case. These two tests may reveal differences in bond mechanics and strength in the layering of the bars--the four bar bundles having no vertical spacing, the two layers of two bar bundles having a vertical clear spacing of 1.33 d_b.

3.1.2.2 Equivalent Bars

The second area of investigation deals with the concept of equivalent bars. In the AASHTO and ACI documents' provisions for development length, certain specifications must be satisfied on the basis of bar diameter. For a bundle of bars, the bar diameter is taken as the diameter of a "round" bar having the same cross sectional area as the bundle. Therefore tests were done on bars of area roughly equivalent to that of the two bar bundle and the four bar bundle. The results should give an indication of the accuracy of the equivalent bar concept.

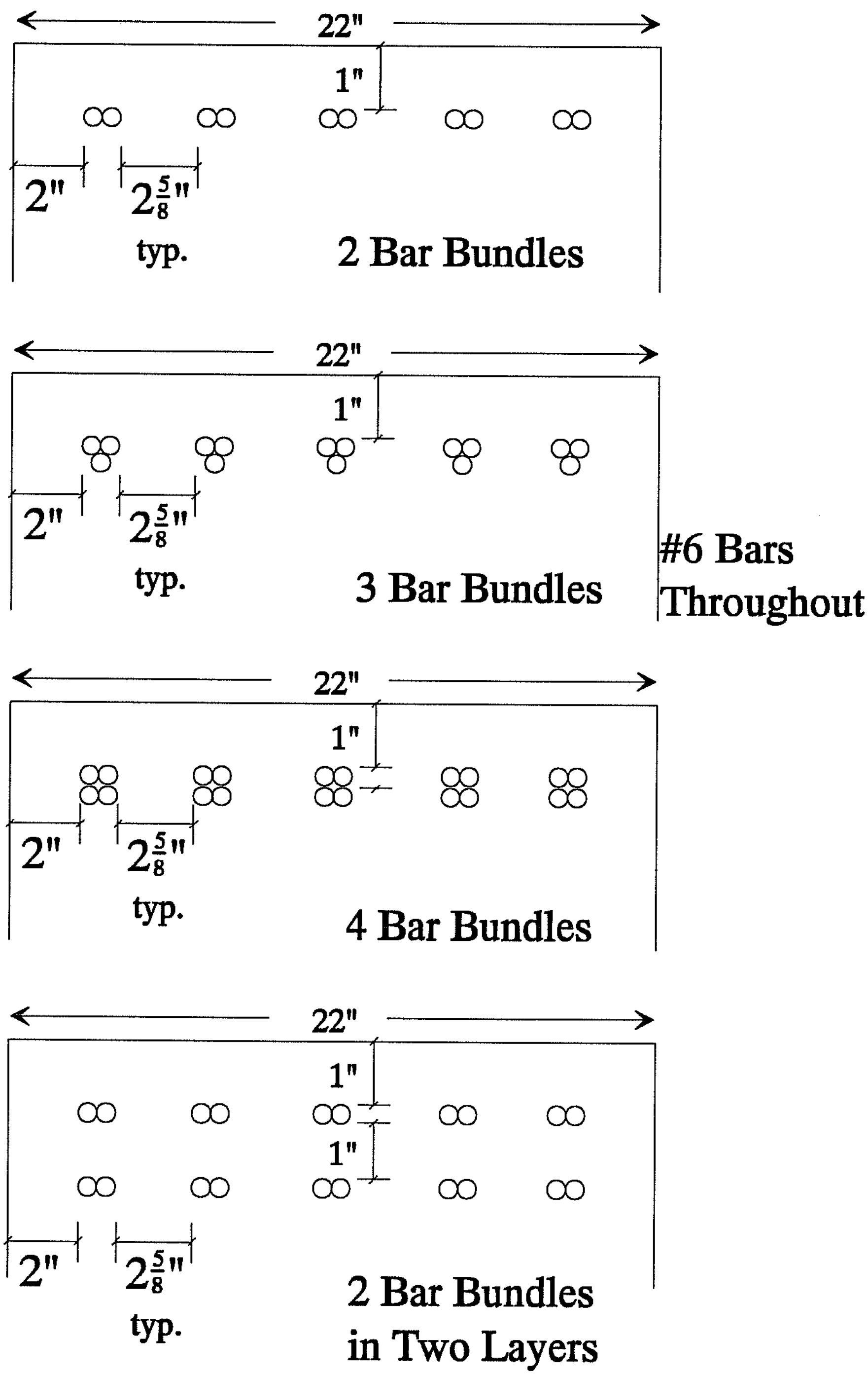


Figure 3.2 Bar Pattern and Spacing

It was not possible to test bars of exactly equivalent area, because there was no exact match in standard bar sizes. However, because ultimate bond stress varies little with small changes in bar size, it was assumed that tests on standard bars of nearly the same dimensions as the equivalent bar would provide an accurate basis for comparison.

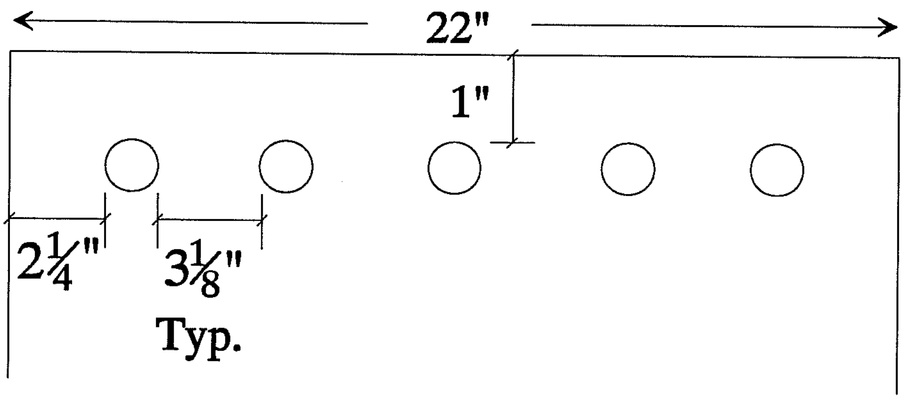
Two number 6 bars have an equivalent bar area of 0.88 square inches, which equates to an equivalent diameter of 1.06 inches. A number 8 bar was substituted for the equivalent bar, since the diameter of a number 8 is 1.0 inches. This is a difference in diameter of 5.7%. Similarly, the equivalent bar for four number 6 bars has an area of 1.77 square inches and a diameter of 1.50 inches. A number 11 bar was used to approximate this equivalent bar; it has a diameter of 1.41 inches, a difference of 6.0%. Figure 3.3 shows the pattern and spacing of the "equivalent" bars.

3.1.2.3 Transverse Reinforcement

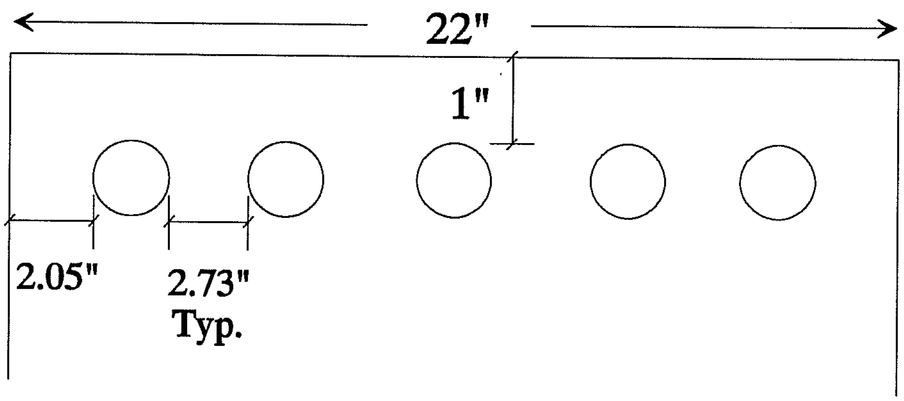
Tests with and without transverse reinforcement were done for each geometry. The test without transverse reinforcement was included as a necessary step in examining bond mechanics of bundled bars, even though such a situation generally is not acceptable in practice. Correspondingly, tests with transverse reinforcement were included to provide insight into the influence of transverse reinforcement on behavior, as well as to incorporate practical geometries into the test progression. The amount of transverse reinforcement was constant in every test with transverse reinforcement: two pairs of number 4 ties, arranged as in Figure 3.4, were spaced at 5⅓ inches.

3.1.2.4 Casting Position

Casting position was considered for two reasons. First, casting position is very much a factor in the pier bent caps which represent the prototype for the test. So, to determine if the detrimental effects of top casting are in any way compounded by large bundle sizes, the four bar bundles were top cast. Secondly, top casting was an unavoidable result of economizing the construction of the test



Single #8 Bars



Single #11 Bars

Figure 3.3 Single Bar Pattern and Spacing

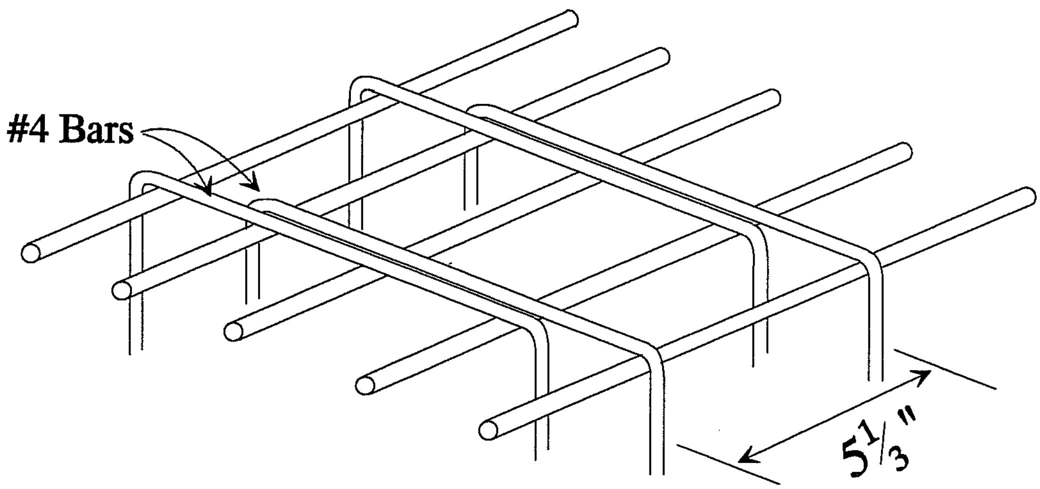


Figure 3.4 Stirrup Layout

specimens by including multiple tests in each beam. Tests which were to be directly compared were all cast in the same position to minimize this effect in the relationships between these tests. For instance, both the single #11 bars and the bundle of four #6 bars, which were to be compared, were top cast.

3.1.3 Bond Failure

The design for bond failure began with an estimation of the derived development length for an individual bar. The goal was to select a length which would fail in bond, but not before the bars reached a substantial fraction of their yield stress. A moderate to high bar stress at failure is desirable because the bond mechanics are likely to be similar to those at yield stress. The mechanism of bond failure for extremely low values of stress might be different than that for high stress. Both the current ACI code equations and the Orangun equation, developed by Orangun, et al (Orangun, 1977), were used to estimate development length required to develop yield in the bars. Based on these predictions, a test length of 24 inches was selected for those sections without transverse reinforcement, and 16 inches for those with transverse reinforcement. These lengths were used throughout the testing program, allowing for direct comparison between tests with the same development length.

3.1.4 Confining Forces

A particular difficulty in the design of the tests was determining a way to apply load to the specimens without introducing confining forces to the embedment region. Figure 3.5 demonstrates that confining force from load application will counteract the splitting force in the plane of the bars, thereby artificially increasing the apparent bond stress at failure. The decision was made to isolate the test section, employing a "bond breaker" to prevent the transmission of confining stress to the embedment zone. The system is illustrated in Figure 3.6. The bundles were placed in metal ducts from the point of maximum moment to the " bond breaker". The ducts served to prevent

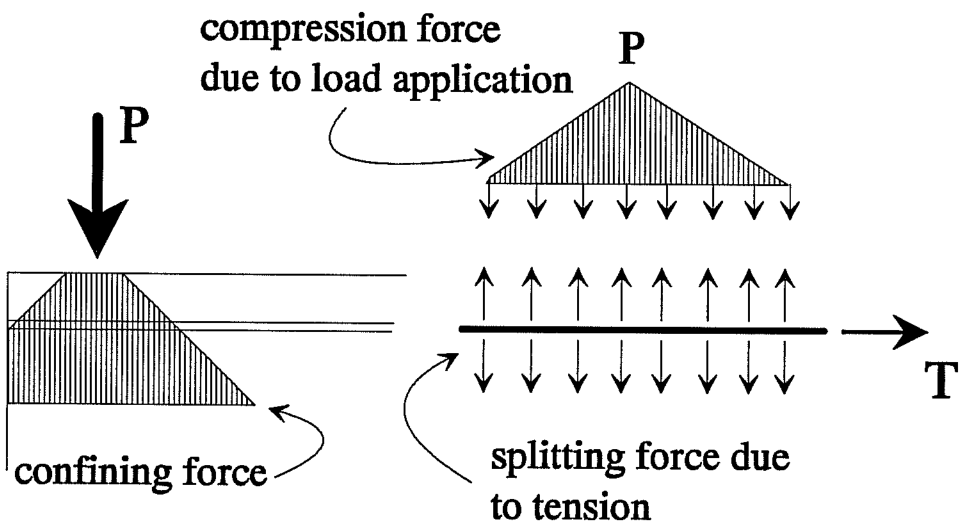
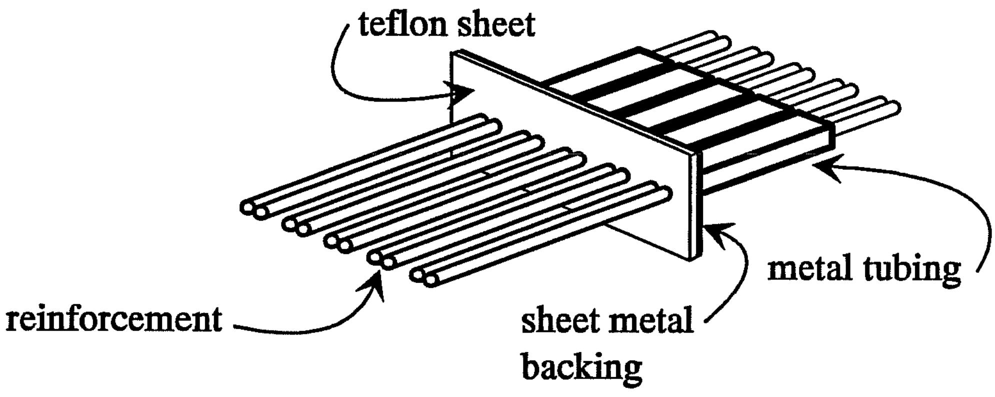


Figure 3.5 Confining Effect of Load Application



Bond Breaker

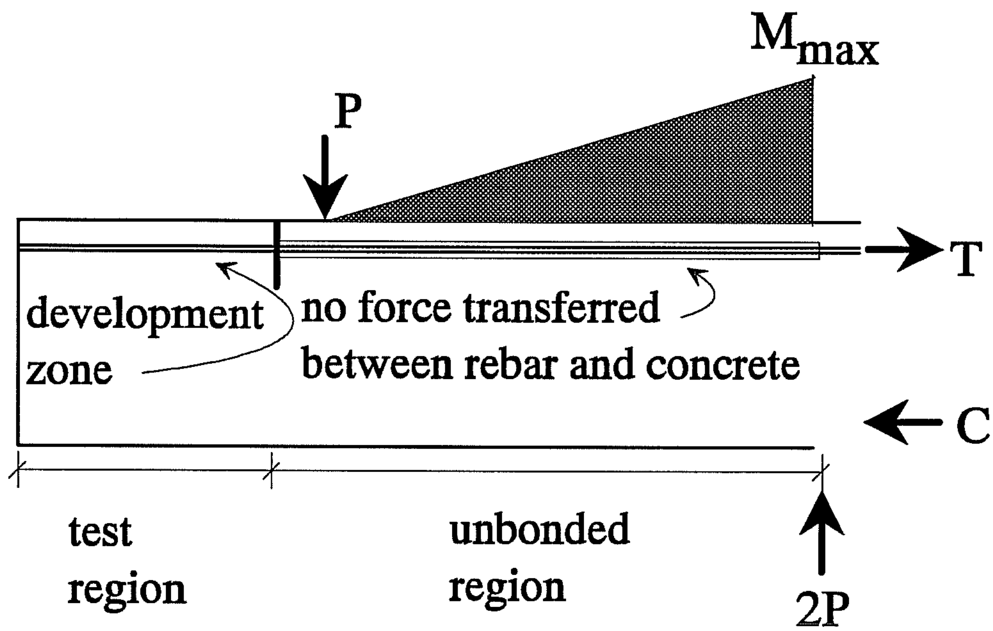


Figure 3.6 Bond Breaker System

transfer of stress between the bars and concrete, with the result that all of the embedment for the bars is limited to a well-defined development length.

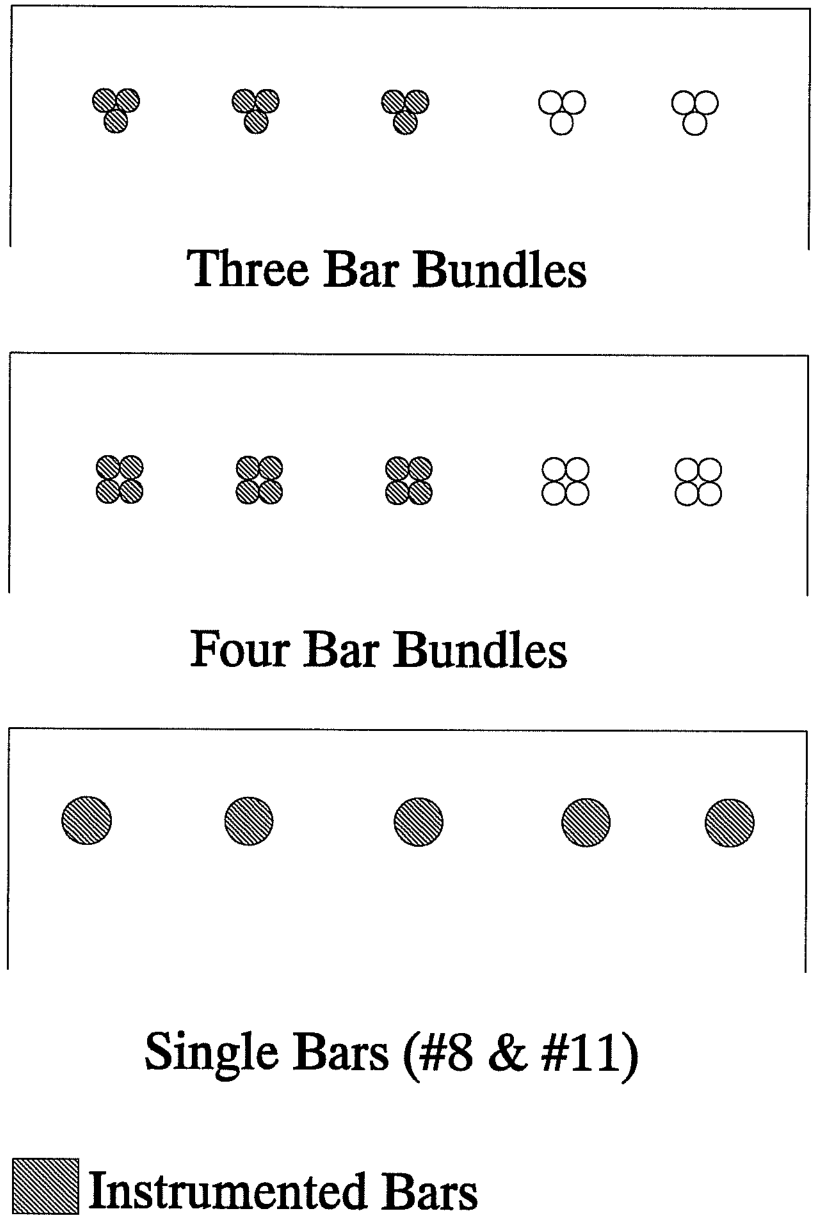
A "bond breaker", constructed by epoxying thin (1/16") sheets of teflon to sheet metal, was placed between the test region and the unbonded region. The bond breaker had two functions. It effectively isolated the test section from the rest of the beam, providing a well defined embedment length, without introducing a gap or discontinuity between the embedment block and the adjacent concrete. Secondly, the smooth teflon surface did not bond to the concrete, so confining forces from the nearby applied load were not transferred through the bond breaker to the embedment zone. As a result, splitting of the concrete in the test region was unrestricted by the applied loads.

3.1.5 Instrumentation

Strain gages were placed on the longitudinal steel and transverse ties. The transverse ties were instrumented such that the gage coincided with the plane of the bars, where a splitting crack was anticipated. On the longitudinal bars, the gages were placed in the unbonded region, about 3 inches from the bond breaker. Placing the gages outside the embedment zone eliminated any concerns about local variations in stress (due to cracking) affecting measurements. The tubing around the bars also protected the gages during placement of concrete. Figure 3.7 shows the gaged bars in each specimen. In some of the tests on two bar bundles, the entire section was gaged. The results were nearly symmetric about the cross-section, indicating that it is sufficient to gage only half the section without losing accuracy in results. For the three and four bar bundles, only half the bundles were instrumented, though in both cases all the bars in the bundle were gaged, as indicated in the figure. In the single bar tests, each bar was instrumented.

3.1.6 Beam Details

Each specimen contained four test regions. Figure 3.8 gives the details of beam one, which contained the three and four bar bundle tests: those of beam



3.7 Location of Strain Gages

two, the tests of single #8 and #11 bars, are in Figure 3.9. The inclusion of four separate tests in each beam (one located at the top and bottom of either end) had several beneficial effects. The beams were more economical, both in terms of the amount of material required and in time savings in the construction of fewer cages. More importantly, the same concrete strength applied to a number of tests, minimizing the effects of variation in concrete strength between tests.

Because the loading on the beams resulted in a low span-to-depth ratio (3.2), and high applied shears, both vertical and horizontal shear reinforcement was required. It was also necessary to place a second layer of steel to control cracking and rotation of the end block. The latter are referred to as "crack control bars" in the figures.

The very first tests on two bar bundles (from the previous section of the program) demonstrated a tendency of the end block to rotate as the bars were stressed. This rotation did not occur as long as the bars on the side opposite that being tested were still embedded in the concrete. But if, for instance, the three bar tests had been completed, leaving the three bar bundles no longer embedded in the concrete, then there was no steel to restrain the end block from rotating when the four bar bundles were tested. The crack control bars were placed to provide this resistance during the tests of, in this example, the four bar bundles. This is illustrated in Figure 3.10. Note that these extra bars do not provide any additional embedment or effect the ultimate bond stress of the longitudinal steel because they are not continuous across the section where peak stresses are reached in the embedded bars.

3.1.7 Test Numbering

The tests are referred to by a three part code which identifies the pattern of bars in the test, the development length of the bars, and the casting position. The first number refers to either the number of bars in the bundle, or the standard bar size for the single bar tests. The tests of three bar bundles begin with a three, and the tests of single number 8 bars are denoted "#8". A special case is the two bar bundles in two layers--this test is referred to as "2x2". The development length is given in inches, and also denotes the presence or absence

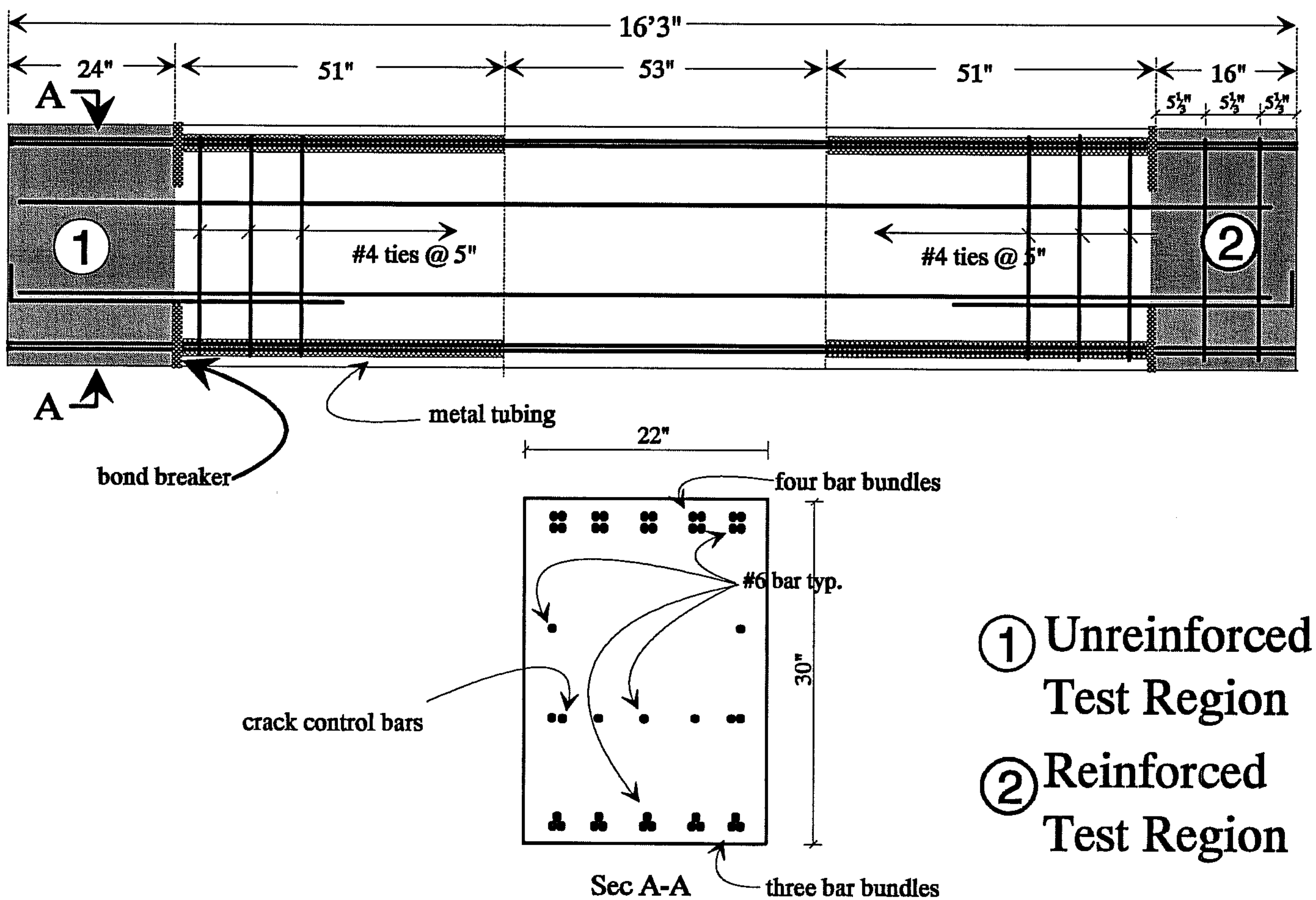


Figure 3.8 Layout of Beam 1

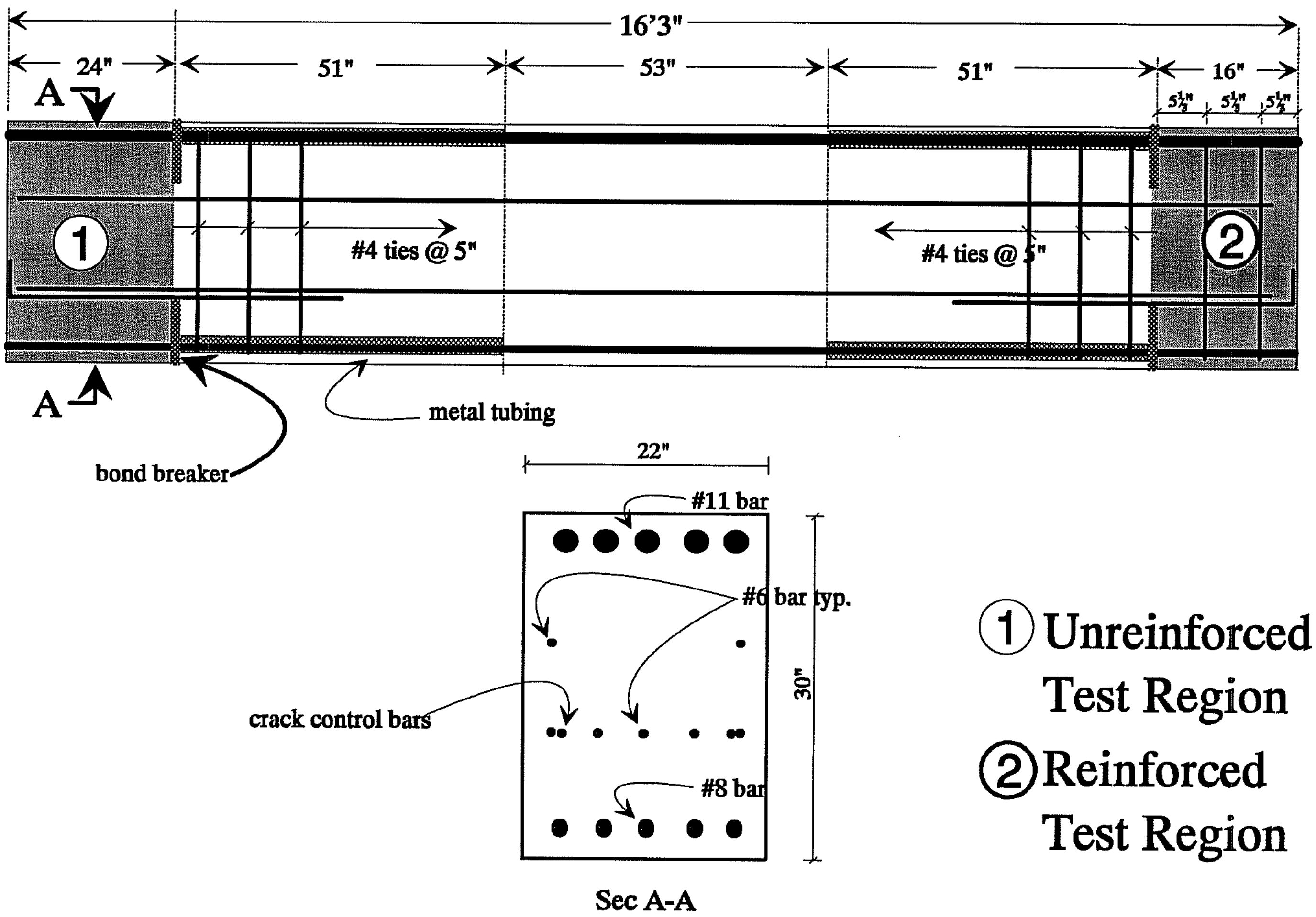
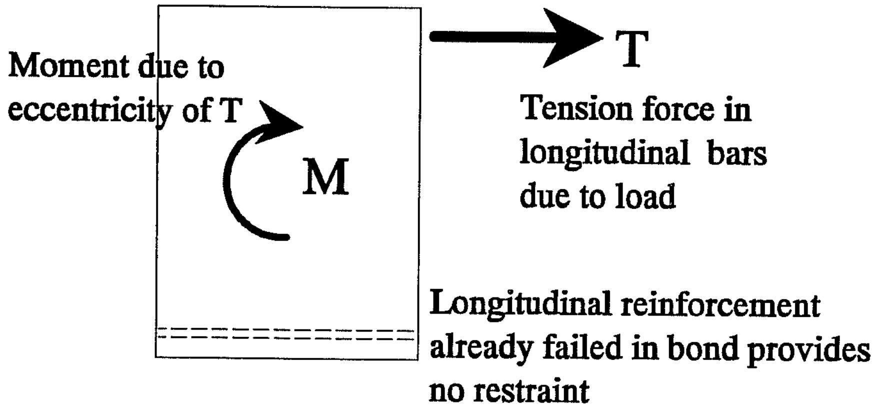
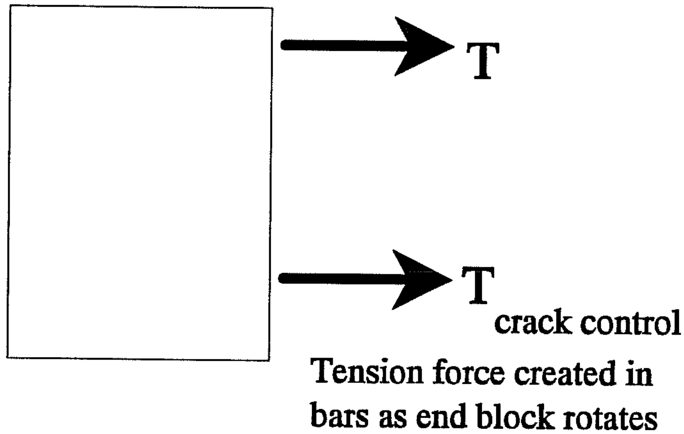


Figure 3.9 Layout of Beam 2



End block rotates due to moment created by unbalanced, eccentric load.



End block retstrained from rotation by crack control bars.

Figure 3.10 Function of Crack Control Bars of transverse reinforcement. All unreinforced sections were 24 inches long, and every test with transverse reinforcement was 16 inches long. Top or bottom casting is denoted by "T" or "B". The tests are listed by this index in Table 3.11.

3.2 Testing Procedure

3.2.1 Loading Detail

The load was applied to the beam in a simple three point loading scheme. The apparatus is shown in Figures 3.12 and 3.13. The load was applied with a pair of 200 kip rams, which were connected in series to the hydraulic pump, such that the load in the rams was equal. The load from the rams was carried to the reaction floor by high strength steel rods anchored in the floor. A loading beam applied the load, via a roller support, to the beam. A roller support was located at midspan on the reaction floor, and a second loading beam provided passive anchorage at the other end of the span.

Figure 3.14 shows the forces in the loaded beam. The bars being tested in the diagram are those in the upper left corner of the beam. This diagram illustrates again the function of the bond breaker system. The bonded region in the center of the beam develops the tension force in the test bars through embedment to the right of the point of maximum moment. Note from the bar force diagram that the force in the bars is constant over the unbonded region, since there is no contact between the bars and the concrete, and hence no transfer of stress. The force in the bars only drops over the test region, where the bars are embedded. The central bonded region provided the necessary resistance to the test regions at either end of the beam.

3.2.2 Data Acquisition

The data was collected by a computer based data acquisition unit. The strain gages, pressure transducer, and linear potentiometers (used to measure displacement during the test but not used for any computations) were connected to the data acquisition system. When instructed, the computer scanned all of the

test	description
2-16-T	2 bar bundles, with transv. reinf., top cast
2-16-B	2 bar bundles, with transv. reinf., bottom cast
2-24-T	2 bar bundles, without transv. reinf., top cast
2-24-B	2 bar bundles, without transv. reinf., bottom cast
3-16-B	3 bar bundles, with transv. reinf., bottom cast
3-24-B	3 bar bundles, without transv. reinf., bottom cast
4-16-T	4 bar bundles, with transv. reinf., top cast
4-24-T	4 bar bundles, without transv. reinf., top cast
2x2-16-T	2 bar bundles in two layers, with transv. reinf., top cast
2x2-24-T	2 bar bundles in two layers, without transv. reinf., top cast
#8-16-B	single # 8 bars, with transv. reinf., bottom cast
#8-24-B	single #8 bars, without transv. reinf., bottom cast
#11-16-T	single #11 bars, with transv. reinf., top cast
#11-24-T	single # 11 bars, without transv. reinf., top cast

Table 3.11 Test Notation

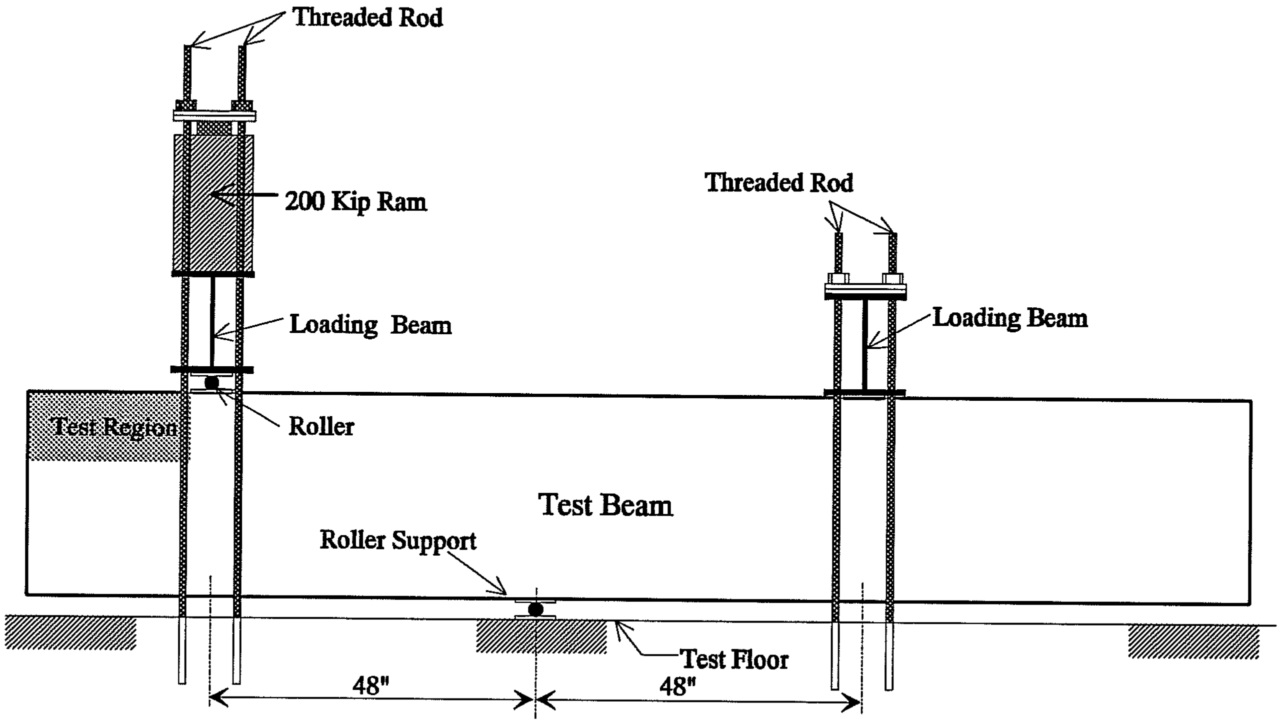


Figure 3.12 Side View of Test Apparatus

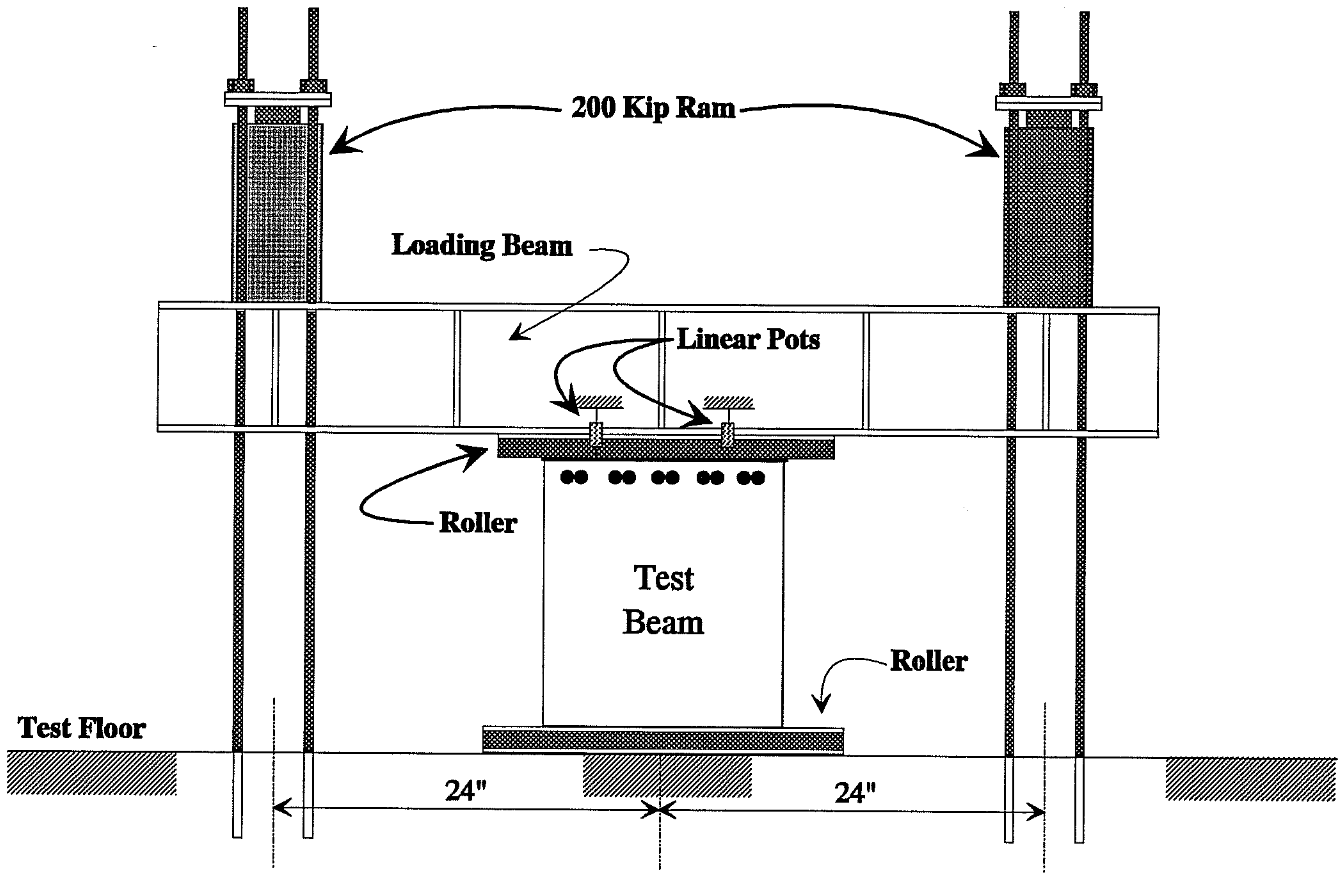


Figure 3.13 Front View of Test Apparatus

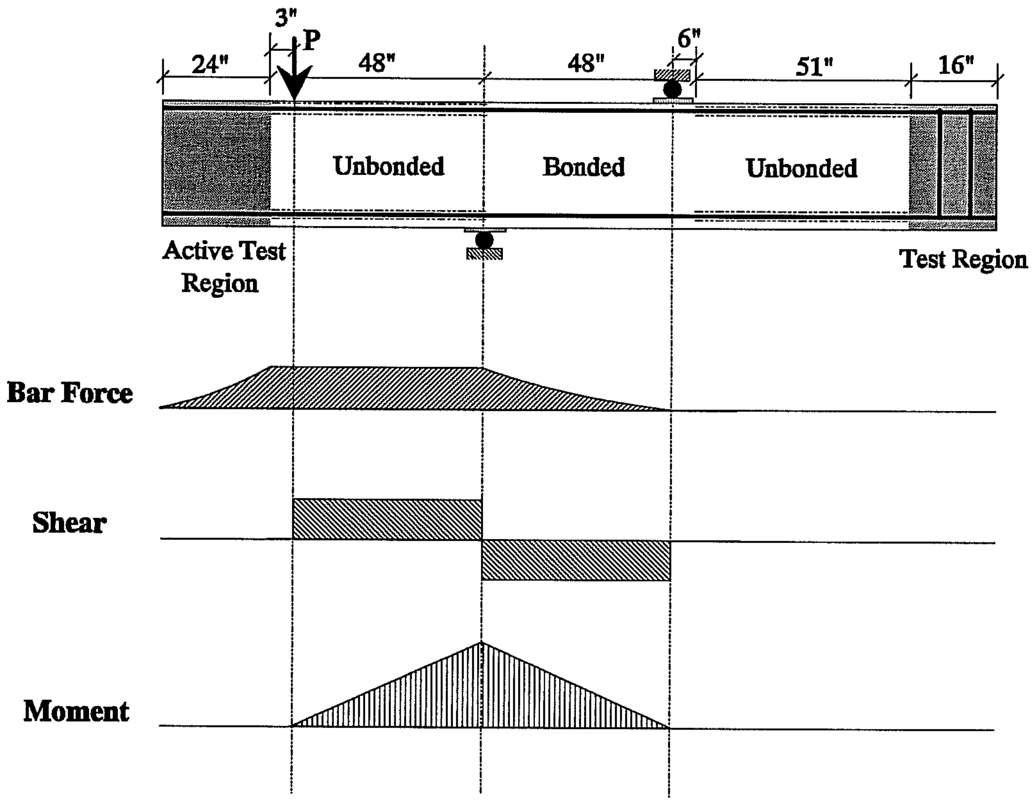


Figure 3.14 Beam Layout and Forces

measuring devices, and recorded the readings on disk. The program also printed a hardcopy of each scan, providing instantaneous conversions of the readings to stresses and load. These readouts were extremely useful in monitoring the test's progress.

3.2.3 Testing Procedure

The load was applied manually to the beam via a hydraulic pump. The load on the beam was a direct function of the pressure in the hydraulic lines: the pressure was monitored during the test by a dial gauge and a pressure transducer. The individual operating the pump gauged the load interval using the readout on a voltmeter attached to the pressure transducer.

Readings were taken after each incremental application of load. The initial load steps were on the order of 10 kips. The data acquisition system printed a copy of the stresses at each scan, and this information was used to determine the appropriate load increment for the next step. The size of the step was reduced as the bars neared the expected failure load. Regular inspection of the beam and the marking of cracks also provided a measure of the performance. The load steps were reduced near the end of the test to a level which resulted in a change in bar stress of approximately 1 ksi per increment.

The three bar bundle tests, located at the bottom of beam one, were tested first, since the four bar bundles had the potential to fail at high loads and produce significant damage to the beam. After one of the tests was performed, the beam was repositioned for another test. Similarly, the single #8 bar pattern was tested first in beam two.

3.2.4 Concrete Strengths

Specified strength for both of the beams was 3000 psi. Concrete was ordered from a local ready-mix plant, and the maximum aggregate size was ⅜". No admixtures were used. The concrete was placed in the forms in lifts of 10 to 15 inches, and each lift was vibrated. The specimens were cured for at least seven days under wet burlap, covered with plastic. Values of f'_c were obtained using standard concrete cylinder tests on 12" by 6" cylinders. The 28 day strengths were used as the basis of comparison between the tests.

Chapter IV: Performance of Bars

4.1 Collection and Verification of Data

The performance of the bars is evaluated using measured strains. Steel strains were recorded using gages placed directly on the reinforcement. In addition, a pressure transducer monitored applied loads, which were recorded as a way to verify the strain data.

Preliminary analysis required conversion of the strain data to stresses using Young's Modulus. Material tests on coupons cut from the specimens were conducted to provide yield values for cases where strains were in the inelastic range. The stresses were checked for accuracy by computing the resisting moment, based on the "measured" stress in the bars, and comparing it with the moment computed from the externally applied loads, which were based on the pressure transducer readings. The values of moment are tabulated in Table 4.1.

The moments compared well, indicating that the strain gauge data were sufficiently accurate to become the basis for evaluating the tests. In three of the tests, the longitudinal bars yielded. The yield stress of the bars was used to compute maximum bond stress in these cases. The bond stress obtained using the yield stress of the bars may not represent the maximum or ultimate strength in bond, but is still quite useful for making comparisons.

4.2 Test Results

A summary of all the results, including bar stresses, concrete strengths, yield strengths, and as-built dimensions, is given in Table 4.2.

Test	M(stresses) in-k	M(applied load) in-k	$\Delta = \frac{(M_{str} - M_{ld})}{M_{str}}$
3-16	11200	11900 in-k	- 6.1% *
3-24	10200	10800	- 5.5%
4-16	8380	7970	4.8%
4-24	8840	8160	7.7%
#8-16	-- *	-- *	N/A
#8-24	-- *	-- *	N/A
#11-16	8360	8090	3.2%
#11-24	9290	8350	10.0%

Table 4.1

Accuracy of Strain Gauge Data as Measured Against Applied Load

***Bars yielded. Bond stress not computed from strain gauge data.**

Test	Avg. steel stress at failure	f'c, psi	Actual clear cover	Actual embedded length	Yield strength
2 - 16 T	37 ksi	2918	1"	16"	--
2 - 16 B	54 ksi	2500	1.125"	16"	--
2 - 24 T	42 ksi	2918	1"	24"	--
2 - 24 B	51 ksi	4210	1.125"	23.5"	--
3 - 16 B	yielded	3732	--*	--**	61 ksi
3 - 24 B	55 ksi	3732	0.875	24"	61 ksi
4 - 16 T	32 ksi	3732	0.75"	16"	--
4 - 24 T	33 ksi	3732	1.25"	24"	--
2x2- 16 T	37 ksi	2550	1"	16"	--
2x2- 24 T	48 ksi	4200	1.5"	24"	--
#8 - 16 B	yielded	3932	--*	--**	65 ksi
#8 - 24 B	yielded	3932	--*	--**	65 ksi
#11- 16 T	36 ksi	3932	0.875	16	--
#11- 24 T	40 ksi	3932	0.875"	23.75"	--

Table 4.2 Test Results

*Measurement not possible. Assumed cover = 1.0"

**Measurement not possible. Assumed length = designed test length

4.2.1 Three Bar Bundles

In the three bar bundle tests, five bundles of three #6 bars were embedded in the test zone. One test had no transverse reinforcement, while the other had pairs of #4 ties, spaced at 5⅓ inches. The bundles confined by ties were tested first, and nearly all the bars yielded. The specimen appeared to be near flexural failure: to avoid damaging the beam and jeopardizing the remaining tests, the beam was unloaded. The section had some longitudinal cracks, one over each of the outermost or corner bundles, but experience obtained in previous tests indicated that the specimen was not near bond failure.

In order to obtain as much useful information as possible from this test, several bars were removed and tested to determine yield strength. Measured yield was then used in the computation of maximum bond stress. The value of bond stress in cases where the bars yielded is therefore lower than the value at ultimate bond strength.

The three bar bundles without any transverse reinforcement failed in bond. Cracks were first observed over the corner bundles, beginning at the lead end of the embedded length (at the bond breaker), and extending toward the end of the beam. When the cracks lengthened to roughly two-thirds of the development length, the specimen failed. The concrete split in the plane of the bars, as well as longitudinally along the corner bars, a pattern that was typical in tests of two bar bundles.

Three individual bars (of nine instrumented) had values of stress, based on measured strains, larger than yield. In computing the average stress for all the bars in this test, these three bars were considered to be at yield.

4.2.2 Four Bar Bundles

The largest bundles consisted of four #6 bars. There were two tests, each containing five bundles, one with and one without transverse reinforcement. The transverse reinforcement consisted of two pairs of #4 ties, spaced at 5⅓ inches. The four bar bundles were placed in a top cast position. The bars without transverse reinforcement were tested first.

The bundles failed in bond in a pattern typical of other tests in the program. The first cracking was longitudinally along the corner bars, beginning at the lead end of the embedment. The cracks extended to a point two thirds of the way along the bars, when the entire section failed.

There were some interesting aspects to the failure of the four bar bundles without transverse reinforcement. The failure plane passed through the bars as was expected, but close inspection indicated that there were two distinct planes of splitting: one roughly corresponding to a plane through the upper bars in the bundle, and the second to a plane through the inner or lower layer. In addition, the bundles themselves retained wedges of concrete between the bars which gave the bundle a square appearance. It is possible that the actual failure surface was not the entire exposed area of the bars, but rather that as the bars slipped, the concrete sheared off in such a fashion as to leave a square perimeter behind. This observation led to some speculation about the behavior of the bar group, and in particular questions about what should be considered the effective perimeter of the bars. This is discussed further in Section 4.3.1.

The four bar bundles with transverse ties also failed in bond. Cracks developed along the corner bars, and, towards the end of the test, a shorter longitudinal crack formed over the middle bundle. The bond failure in this test was not as dramatic as the unreinforced case, and the cover did not actually spall off as in the previous test. At failure, the cover split over the ties as well as in the plane of the bars, and while the concrete was clearly debonded, it did not come off cleanly or permit a clear determination of the failure surface. The additional confinement and congestion of the transverse reinforcement contributed to the difficulty in inspecting and defining the failure surface.

None of the bars in either of the four bar bundle tests reached yield.

4.2.3 Single #8 Bars

The tests of single #8 bars were designed to compare with bundles of equivalent area, 2 #6 bars in this case, as described earlier. The specimen contained five #8 bars; one test region with transverse ties, and one without. The bars in both tests reached yield, and the tests had to be stopped to avoid excessive damage to the beam before the remaining tests could be performed. The unreinforced case showed some slight cracking over the corner bars, but the section with transverse ties showed no signs of distress when the test was terminated. A bar was removed from the specimen and tested to determine yield strength for use in ultimate strength computations. Because of this, the tests in which the bars yielded provide a value for comparison which is less than the ultimate bond strength.

4.2.4 Single #11 Bars

A single layer of five #11 bars was tested for comparison with bundles having four #6 bars. As with the other tests, one test region was reinforced with transverse steel consisting of two pairs of #4 ties spaced at 5⅓ inches, while the other was unreinforced. The test region without any ties had a dramatic bond failure, with cracks once again initiating at the lead end of the embedment and progressing longitudinally along the outermost bars until the entire region suddenly split. The failure surfaces passed through the plane of the bars and the longitudinal cracks in the cover above the corner bars.

The section reinforced with transverse steel also experienced a bond failure, although the ties kept the cover from spalling suddenly. Cracks formed over the bars at the edge of the beam first, and over the middle bar and the ties at failure. None of the bars in either test approached the nominal yield stress of the steel.

4.3 Conversion of Data

4.3.1 Computed Bond Stress

To make comparisons among the various test results, bar stresses determined from strains were converted to uniform or average bond stresses. Bond stress is the shear stress at the interface of the rebar and concrete. It allows force in the steel to be transferred to the surrounding concrete. To minimize the influence of concrete strength, the bond strength was normalized by $\sqrt{f'_c}$. The equation for bond stress is:

$$u=\frac{A_s f_s}{l_d p_e}$$

where A_s = total area of steel in bundle
f_s = steel stress at failure
l_d = anchorage length
p_e = effective perimeter of bundle

Bond stress was computed for the "effective" bars on the basis of the dimensions of the single bar. In order to perform the computation for bundled bars, an effective perimeter had to be defined.

Bond stress is defined as the force in a bar or bundle, divided by the surface area of the bar being developed. Surface area for a round bar is simply its length times its circumference, but the surface of a bundle is a less well defined quantity. It would actually be more accurate to say that the surface of a bundle is a less well understood quantity, in the context of its contribution to bundled bar behavior. The failure plane of a bundle may comprise the entire contact surface of the bars within it, or the bundle may behave more like a single unit--a single, round-cornered square bar, for instance, in the case of a four bar bundle.

To help define surface area, the bond stress was calculated using two values for the perimeter of the bundles. The perimeter was maximized by considering the bundle as a number of adjacent circles, excluding the section in the interior of the bundle. The minimum perimeter is obtained if the shape is taken as a square, triangle, or rectangle, with rounded corners. Figure 4.3 shows the shapes used in the calculations, and the relative differences between the values of perimeter are listed in Table 4.4.

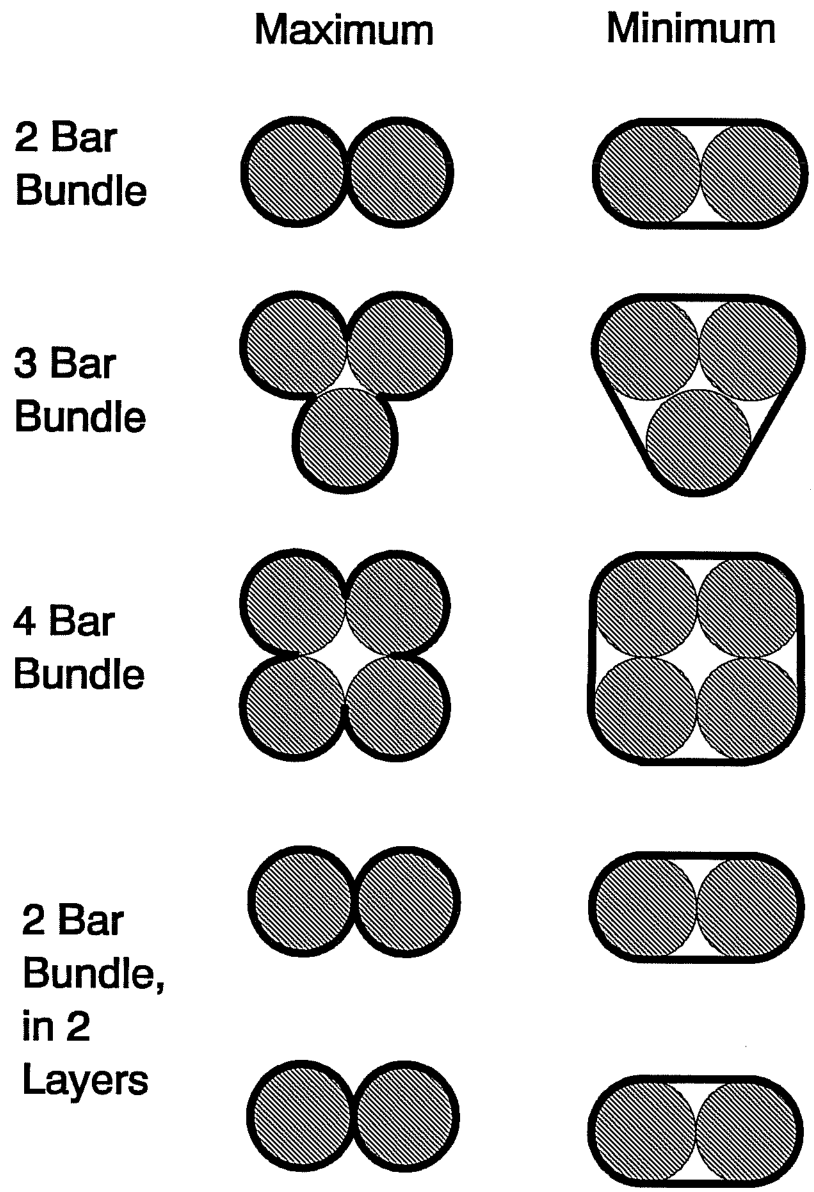


Figure 4.3 Perimeters

Bundle Size (#6 Bars)	Maximum Perimeter	Minimum Perimeter	Δ(Max-Min/Min)
2 Bar	4.72 in	3.86 in	22.3 %
3 Bar	5.9 in	4.61 in	28.0 %
4 Bar	7.08 in	5.36 in	32.1 %

Table 4.4

Difference, in %, of Perimeters for Various Bundle Geometries

4.3.2 Bond Stress Predicted by the Orangun Equation

An equation, developed by Orangun et al. (Orangun, 1977), was employed to provide a reference between these tests and other tests reported in the literature. Bond stress was computed using the properties and dimensions from Table 4.2. The term A_{tr}, the area of transverse steel divided by the number of bars confined, incorporates the effect of transverse reinforcement. This term was changed in the case of bundled bars. Tests on two bar bundles reported by Chen (Chen, 1994) showed that the equation correlated better with results if the term was defined as the area of transverse reinforcement divided by the number of bundles being confined, instead of the total number of bars.

4.3.3 Computation of Development Length

Up to this point, bond stress has been used to investigate bundled bar behavior and to attempt to develop a better idea of how a bundle behaves. But for proposes of design, discussions of lengths are much more straightforward and useful. To this end, Table 4.5 contains values of development length from the test data, Orangun equation, and current AASHTO and ACI documents.

4.3.3.1 From Test Data

The conversion of the test results to development lengths was very straightforward. Consider that the equation for development length is:

$$l_d = \frac{A_s f_y}{u \cdot p}$$

where l_d = development or anchorage length
A_s = area of bar or bundle
f_y = nominal yield value of steel
u = ultimate bond stress
p = perimeter of bar or bundle

test	development length			
	measured	AASHTO	ACI	Orangun
2-16 T	25.9	27.4	35.6	32.3
2-16 B	17.8	21.1	29.6	20
2-24 T	34.5	27.4	35.6	51.8
2-24 B	28.2	16.3	22.8	23.6
3-16 B	15.7	20.7	41.5	18
3-24 B	26.2	20.7	41.5	34.9
4-16 T	29.8	32.2	59.8	28.4
4-24 T	43.6	32.2	59.8	40.6
2x2-16 T	26	29.3	38.1	34.1
2x2-24 T	30	22.8	29.6	33.5

Table 4.5 Development Lengths

For the computation of u_t, bond stress from test results, the equation may be rewritten:

$$u_t = \frac{A_s f_s}{l_t p}$$

where f_s = stress in steel at failure
l_t = anchorage length of test

Substituting u_t for u above, l_d becomes:

$$l_d = \frac{f_y}{f_s} \cdot l_{test}$$

since A_s and p are constant.

4.3.3.2 From Orangun Equation

Development lengths were obtained from the Orangun equation by taking the bond stress resulting from the equation and converting it to development lengths using modified perimeters for #6 bars. The perimeters were modified on the basis of "maximum perimeter" as discussed later in 4.4.1.3. For instance, a #6 bar has a perimeter of 2.36 inches. If the bar is placed in a bundle of three bars, 20% of the perimeter of the bar is shrouded in the interior of the bundle; the effective perimeter becomes 2.36/1.20=1.97 inches. This effective perimeter was used in the first equation for l_d given above to obtain development lengths. The Orangun equation includes effects of bar diameter, cover, spacing, and transverse reinforcement.

4.3.3.3 From AASHTO Specifications

Current AASHTO specifications (AASHTO, 1992) were used to compute the development length of the bundles on the basis of a single #6 bar, adjusted by the applicable factors including Section 8.28, which mandates increased lengths for bundled geometries. AASHTO includes effects of bar area, casting position, and bundling.

4.3.3.4 From ACI Code

The current ACI code (ACI-318, 1989) was also employed to calculate development length. While the basic l_d formula is identical in AASHTO and ACI, the latter also contains factors which account for spacing, transverse reinforcement, and cover. For bundles, these spacing provisions are satisfied on the basis of the "equivalent bar" diameter. ACI requires the same increase in length for bundling specified in AASHTO Sec. 8.28.

4.4 Presentation of Results

4.4.1 Bundle Size

First, the behavior was evaluated on the basis of the number of bars in a bundle. As noted before, the stress in the bars at bond failure has been converted to an ultimate bond stress for each case, normalized by $\sqrt{f'_c}$ to minimize the influence of concrete strength. The ultimate bond stress is tabulated for the following progression of geometries: two bar bundles, three bar bundles, two bar bundles in two layers, and four bar bundles. The latter two cases have the same number of bars, arranged differently. Figure 4.6 shows the bar patterns being considered.

4.4.1.1 Bundles Without Transverse Reinforcement

The values of bond stress for bars without any transverse reinforcement are given for both a maximum and minimum bundle perimeter, as explained earlier. The stresses calculated using the maximum and minimum perimeter are given in Table 4.7. The casting position has significant effects on bond strength, so direct comparisons should only be made between tests cast in similar positions.

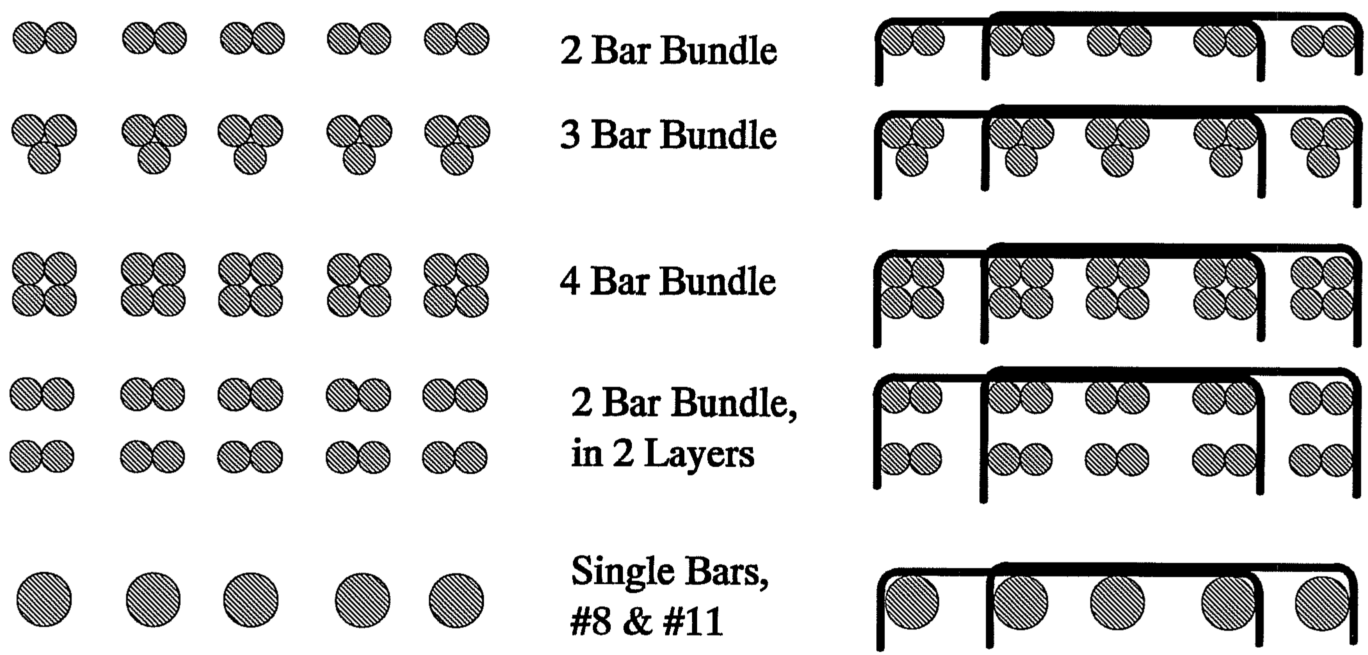


Figure 4.6 Bar Patterns

Effective Perimeter	Casting Position	$\frac{u}{\sqrt{f_c'}}$ average of all bars			
		2 bar bundles	3 bar bundles	2 bar bundles in 2 layers	4 bar bundles
Maximum Perimeter	Top	6.0	--	5.8	5.6
	Bottom	6.1	8.4	--	--
Minimum Perimeter	Top	7.4	--	7.1	7.4
	Bottom	7.5	10.7	--	--

Table 4.7: Effect of Bundle Size

Ultimate Bond Stress of Tests Without Transverse Reinforcement

There is no obvious difference in the ultimate bond stress for the top cast bundles, except for the effect of the definition of perimeter. The top cast progression of tests includes two bar bundles in one and two layers, and four bar bundles. The bond stresses are around the same value. The three bar test was bottom cast, and is compared to a two bar bundle which was also bottom cast. The three bar bundle has a consistently and significantly higher bond stress than that of the two bar bundle for each definition of perimeter. This difference is discussed in section 4.4.2, Distribution of Stress Within a Bundle.

4.4.1.2 Bundles With Transverse Reinforcement

The findings for the tests with transverse reinforcement are similar. The trend, as can be seen in Tables 4.8, is an essentially uniform ultimate bond strength for the top cast bundles with a particular perimeter definition, regardless of bundle size. The three bar bundle strength is again higher than that of the two bar bundles. The three bar bundle test in these tables is based on the yield strain of the bars, and therefore the bond stress in the table may be lower than the ultimate bond stress. Still, the values are consistently above those of the corresponding two bar bundle test.

The presence of transverse steel clearly leads to higher ultimate bond stress, as can be seen from Table 4.9. The increase ranges from 33 to just over 100 percent of the unconfined value. This effect has been well documented in past research and experience.

4.4.1.3 Effect of Perimeter on Computation

Two values of ultimate bond stress were calculated for each test. This reflects the different effective perimeters discussed in Section 4.3.1. The following comparisons were made in an effort to determine which perimeter most accurately reflects behavior.

Effective Perimeter	Casting Position	$\frac{u}{\sqrt{f'_c}}$ average of all bars			
		2 bar bundles	3 bar bundles	2 bar bundles in 2 layers	4 bar bundles
Maximum Perimeter	Top	8.0	--	8.6	8.2
	Bottom	12.6	14.0	--	--
Minimum Perimeter	Top	9.8	--	10.5	10.8
	Bottom	15.4	17.9	--	--

Table 4.8: Effect of Bundle Size
Ultimate Bond Stress of Tests With Transverse Reinforcement

test	cast	$\frac{u}{\sqrt{f'_c}}$		% change (referenced to case w/o reinf.)
		without trans. reinf.	with trans. reinf.	
2 bar bundle	top	6.0	8.0	33%
2 bar bundle	bottom	6.1	12.6	107%
3 bar bundle	bottom	8.4	14.0	66.7%
4 bar bundle	top	5.6	8.2	46.4%

Table 4.9: Effect of Transverse Reinforcement on Ultimate Bond Strength of Bundled Bars

The change in the effective perimeter resulting from the different geometries is recorded as a percent of the minimum value in Table 4.4. The difference in perimeter increases with the number of bars in the bundle. These values are geometric properties of the shapes in Figure 4.3. The changes in the magnitude of the bond stress for the individual tests will be the same as the changes in the magnitude of perimeter for the corresponding bundle geometry, since all other values are constant within those calculations. An inspection of the relationships between the bond stresses for the range of bundle sizes and perimeters is most useful.

The ultimate bond stress over a range of bundle sizes is graphed for the different effective perimeters in Figure 4.10. All the tests shown in this graph were top cast-- the three bar bundle is not included in the progression because it was bottom cast. There is no significant or consistent trend indicated by using different perimeters in the computation of bond stress, as long as the same approach is used consistently for all the bundle geometries.

For further insight into which effective perimeter represents behavior more closely, comparison is made between the test results and predictions computed using the Orangun equation. The bond stress obtained from the test results correlates very well to that predicted by the Orangun equation if the stress is computed using the maximum effective perimeter of the bundle. The ratios of the test values to the calculated values is shown in Table 4.11; note that a value greater than 1.0 indicates that the Orangun equation is conservative. Using the maximum bundle perimeter in the computation results in an average ratio of 1.15, with a standard deviation of 0.21. Computations using the minimum value of perimeter give a mean ratio of 1.43, with a standard deviation of 0.24.

Given this information, it seems that the maximum perimeter represents behavior as represented by the Orangun formula more accurately. While the appearance of the four bar bundle after failure was that of a "square bar" (See Figure 4.12), corresponding to minimum perimeter, it was not clear what failure mechanism was involved. The "wedges" of concrete between adjacent bars which gave the bundle a square appearance could have been produced as the bars failed, and not the failure mechanism itself.

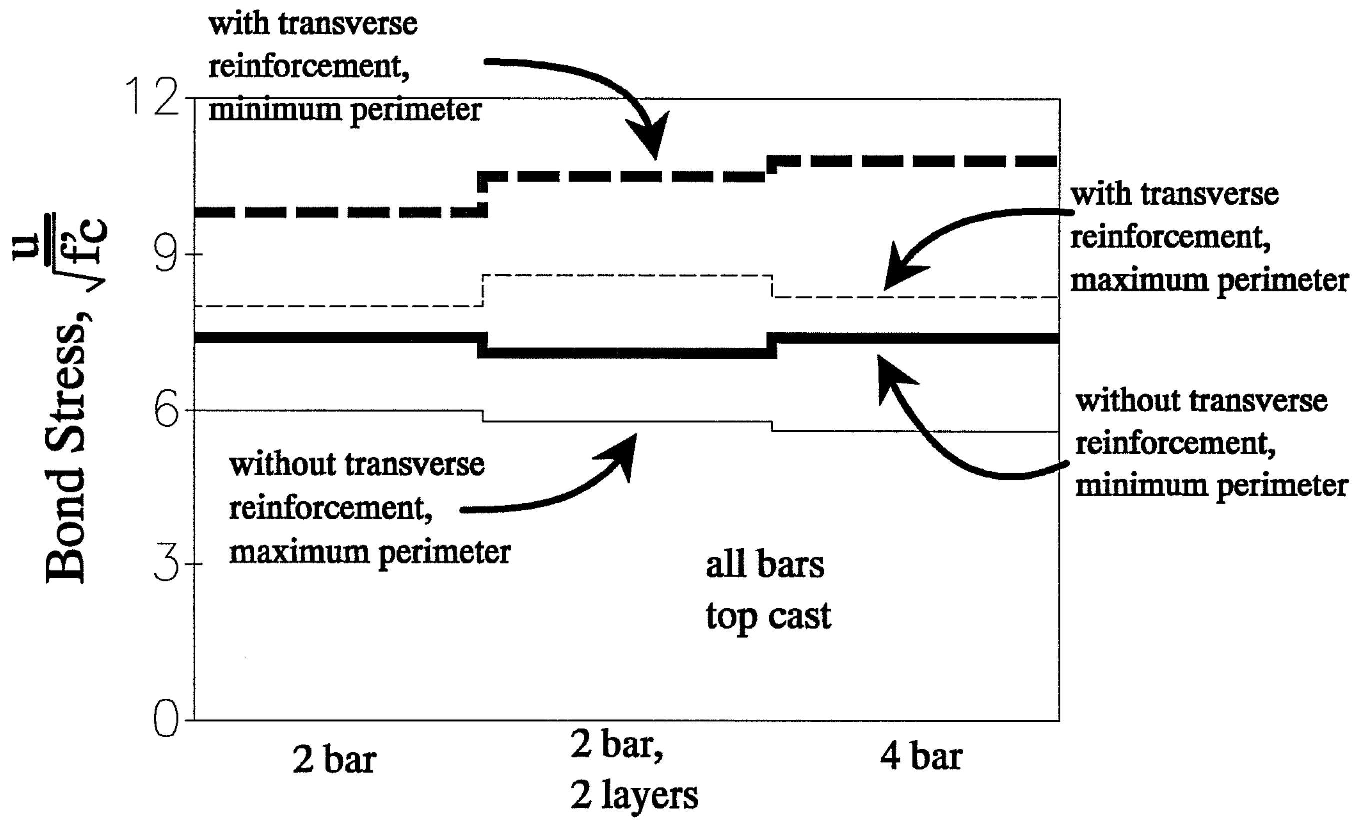


Figure 4.10 Ultimate Bond Stress

Test	$\frac{u_{test}}{\sqrt{f_c'}}$		$\frac{u_{Orangun}}{\sqrt{f_c'}}$ top cast reduction: 1.3	test/ Orangun maximum perimeter	test/ Orangun minimum perimeter
	maximum perimeter	minimum perimeter			
2-16 T	8.0	9.8	6.4	1.25	1.53
2-16 B	12.6	15.4	11.2	1.13	1.38
2-24 T	6.0	7.4	4.0	1.5	1.85
2-24 B	6.1	7.5	7.3	.84	1.03
3-16 B	14.0	17.9	12.2	>1.15	>1.47
3-24 B	8.4	10.7	6.3	1.33	1.7
4-16 T	8.2	10.8	8.6	.95	1.26
4-24 T	5.6	7.4	6.0	.93	1.23
2x2-16 T	8.6	10.5	6.5	1.32	1.62
2x2-24 T	5.8	7.1	5.15	1.13	1.38
			mean	**1.15**	**1.43**
			standard deviation	**.21**	**.24**

Table 4.11: Bond Stress Values from the Orangun Equation

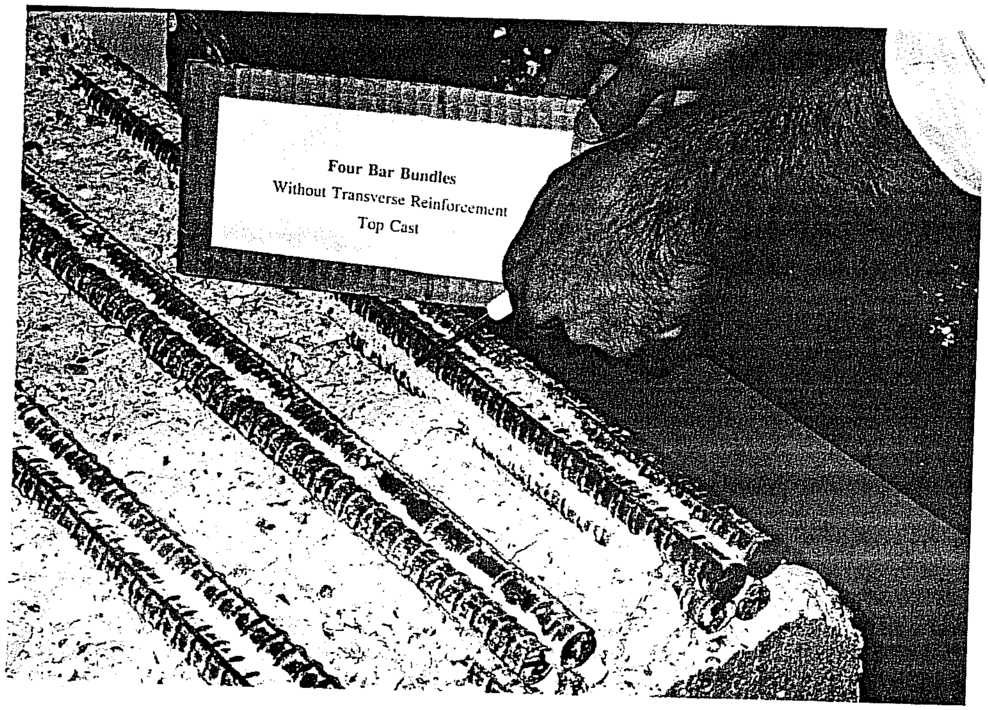


Figure 4.12 Four Bar Bundle After Bond Failure

4.4.2 Distribution of Stress Within a Bundle

A significant aspect of the behavior of bundles of bars is how the stresses are distributed within the bundle. The data collected in this program showed no consistent trend in the distribution of stress within a bundle between bars located in the same plane--that is, bars at the same depth within the section. In most cases, the stress in two bar bundles was distributed about equally between the bars. However, there are some interesting effects in larger bundle sizes. Figure 4.13 shows the three and four bar geometries, and the average stress for the bars at the same depth in the section. The three bar bundle exhibits a significant difference between the stress in the outer two bars and that in the inner bar. As indicated, the ratio of the stress of the outer bars to that of the inner is about 0.8, in both test cases. Based on the bars' depth in the section and strain compatibility, the ratio should be 1.03. Note that the four bar bundle exhibits no such trend.

The higher stress in the inner bar of the three bar bundle is probably a result of the fact that the inner bar effectively has a larger clear spacing than the two outer bars. In section 4.2.2, the existence of two splitting planes in the failure of the four bar bundle was noted. In the four bar geometry, the planes are identical. But in the three bar case, the planes are quite different. The clear spacing of the inner layer of bars (measured between adjacent inner bars) is $3\frac{3}{8}$ inches, while the clear spacing in the outer layer is $2\frac{5}{8}$ inches, a ratio, outer to inner, of 0.79. Figure 4.14 illustrates the difference in the width of the splitting planes in the three bar bundle test. The outer plane is much weaker than the inner plane, and therefore a failure surface first develops there. More of the stress is distributed to the stronger, inner plane, leading to a higher stress in the inner bars.

This observation begins to explain the difference in ultimate bond stress between the three bar bundle and the other geometries. Only the two bar bundle is available for direct comparison, due to casting position effects. The influence of the inner bar of the three bar bundle can be reduced by re-computing ultimate bond stress, taking the stress in the outer layer of bars as the average stress for all bars in the bundle. Since the test of three bar bundles with transverse reinforcement resulted in most of the bars yielding, the unreinforced case is the only one for which this computation can be done confidently. In the latter case, the normalized bond stress becomes 7.7

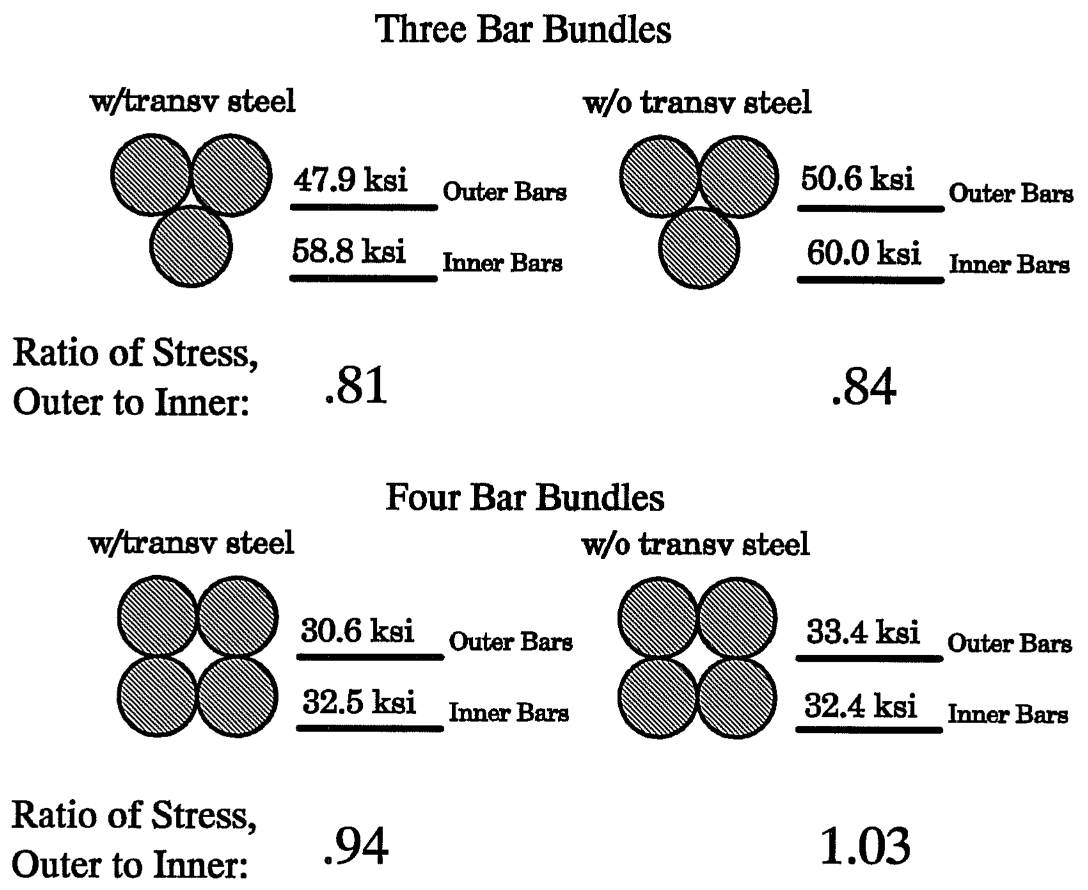


Figure 4.13 Stress Distribution Within a Bundle

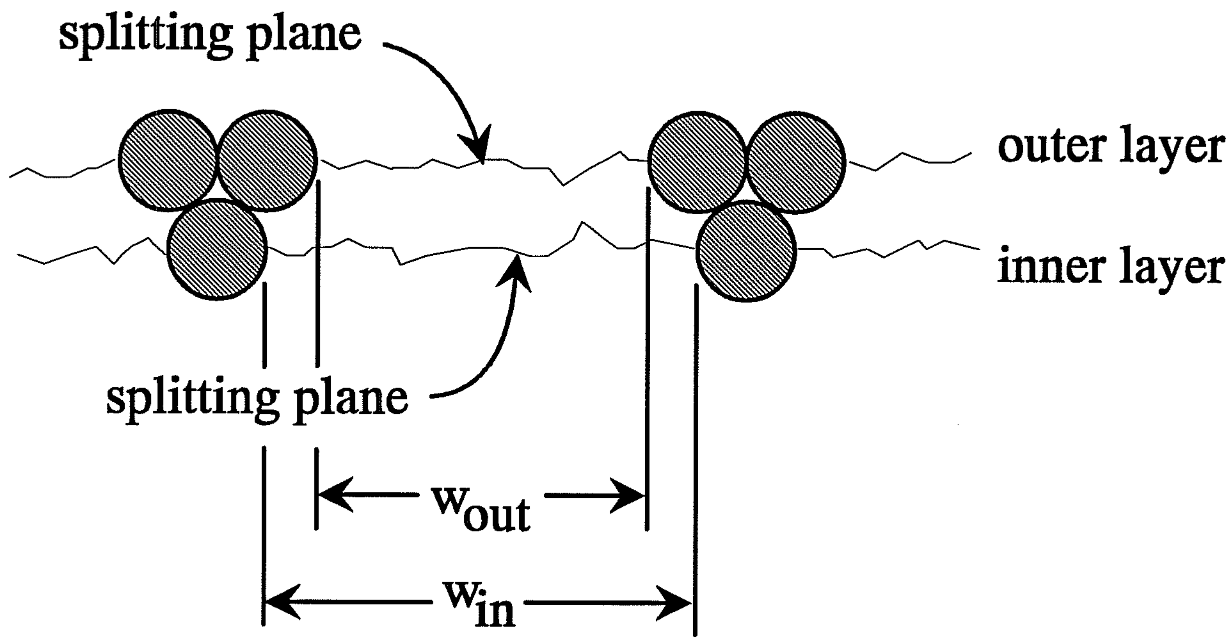


Figure 4.14 Splitting Planes of Different Widths

(as opposed to 8.4) for the three bar bundle, while that of the two bar bundle is 6.1. The three bar bundle still exhibits a higher bond stress, but the difference between the values drops from 37% to 26%.

4.4.3 Equivalent Bars

As mentioned in Section 2.3.1, the AASHTO and ACI documents require the use of an "equivalent bar" in the spacing provisions of bundled bars. For example: a #6 bar has a diameter of 0.75 inches; a bundle of two has a cross-sectional area of 0.88 square inches. The "equivalent bar" would have the same area, but a diameter of 1.06 inches. Spacing requirements would have to be satisfied on the basis of the 1.06 inch diameter. At issue, then, is correlation between the behavior of a bundle and a "round" bar of equivalent area.

4.4.3.1 Two Bar Bundle Versus an Equivalent Bar

The two bar bundles and the corresponding equivalent bars were constructed with the same cover and center to center spacings. But while these aspects of the geometry were constant, the relative spacing in terms of db changed. The clear spacing of the two bar bundles was 2.625 inches, which translates to 2.48 d_b of the equivalent bar. In the comparison test, single #8 bars were placed on the same centers as the bundles; the clear spacing of these bars was 2.95 equivalent bar diameters. The ultimate bond stress for the #8 bar, which is used here as the equivalent bar, is given in Table 4.15. Included in the table is the bond stress for the two bar bundles. In light of the discussion in Sec 4.4.1.3, only the value computed using maximum perimeter is tabulated.

The bond stress of the equivalent bar is higher than that of the 2 bar bundle in both cases. Because the equivalent bar tests yielded, the ultimate bond stress of the equivalent bars will be even higher.

Transverse Reinforcement	2 Bar Bundle: Max Perimeter	#8 Bar	% increase
Yes	12.6	16.3	29%
No	6.1	10.9	79%

Table 4.15: Normalized Bond Stress, $u/\sqrt{f'_c}$, of 2 Bar Bundle Vs. "Equivalent" #8 Bar

Transverse Reinforcement	4 Bar Bundle Max Perimeter	#11 Bar	% increase
Yes	8.2	12.6	54%
No	5.6	7.8	39%

Table 4.16: Normalized Bond Stress, $u/\sqrt{f'_c}$, of 4 Bar Bundle Vs. "Equivalent" #11 Bar

4.4.3.2 Four Bar Bundle Versus an Equivalent Bar

The four bar bundles, and the #11 bars with which they were compared, had the same cover and center to center distance as the bundles and bars in the other tests. The four bar bundle, in terms of equivalent bar diameters, had a clear spacing of 1.75 d_b. The #11 bar had a spacing, based on the dimensions of the equivalent bar, of 1.81 d_b. The variation in spacing is about 0.1 inches, which, in practical terms, is not significant. For purposes of comparison, the equivalent bar can be regarded to have the same spacing, as well as area, as the 4 bar bundles.

The ultimate bond stress of the four bar bundles and the #11 bars is given in Table 4.16. As in the previous case, the equivalent bars reach higher ultimate bond stresses than the bundled bars.

4.4.3.3 Overall Trend

The results of all the equivalent bar tests are shown in Figure 4.17. The equivalent bars have a higher ultimate bond stress in each case. The amount of increase over the bundled bar geometries ranges from roughly 30% to 80%.

4.4.4 Development Length Computations

The principal focus of this research is the safety of current design provisions for the anchorage of bundled reinforcement. Their reliability can be measured both in terms of design strengths and the rationality of the design approach. A method which is not solidly based upon an understanding of actual behavior may confuse or mislead engineers in the design process.

4.4.4.1 Current Code Provisions

The reliability (or accuracy) of the AASHTO specification, ACI 318 building code, and Orangun equations is measured by determining the ratio of calculated development length to measured development length for each test. A ratio greater

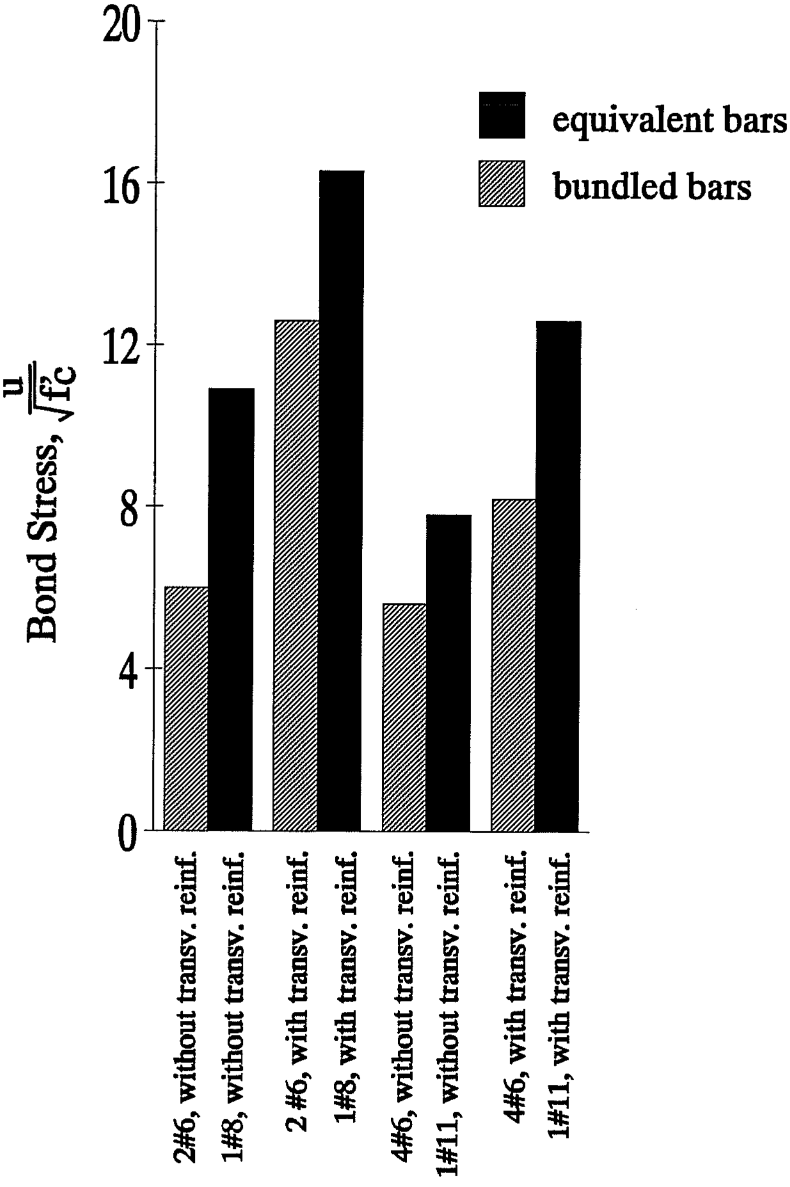


Figure 4.17 Bond Stress of Bundled Bars Vs. Equivalent Bars

than 1.0 indicates that the code results in a longer development length than may be required and is therefore conservative. Statistical analysis of a set of ratios provides a measure of how conservative a given equation is.

Table 4.18 presents the ratio of calculated to measured development lengths for the three equations. The mean and median values for each set of ratios is given, as well as the standard deviation.

4.4.4.1.1 Orangun Equation

The Orangun equation is the most accurate of the methods being considered, though that is perhaps not surprising since it is also the most complex. The average strength ratio is 1.15, and the standard deviation is 0.21. Note that this is the same result discussed in section 4.4.1.3, comparing the bond stress predicted by the Orangun equation and that measured in the tests. The values have simply been converted from bond stress to development length.

4.4.4.1.2 AASHTO Specification

The AASHTO specification is the least accurate of the three equations, and appears to be significantly unconservative. The average ratio of strengths is 0.95, with a standard deviation of 0.24. This indicates that in half of the cases, the AASHTO equations specify below 95% of the embedment length needed to develop nominal yield in the reinforcement. Steel detailed this way would reach less than 95% of yield strength in these cases. This is clearly an unsatisfactory result, and indicates a need for some adjustment to the current provisions contained in the code.

4.4.4.1.3 ACI Code

The ACI code yields very acceptable accuracy in the computation of development lengths. The average strength ratio is 1.49, with a standard deviation of 0.53. Application of the ACI code equations results, on average, in a development length 1.5 times that required (as indicated by test). The tests show that the use of the ACI code to design bundled bar embedments is conservative.

test	ratio of development lengths		
	AASHTO/ test	ACI/ test	Orangun/ test
2-16 T	1.06	1.37	1.25
2-16 B	1.19	1.66	1.12
2-24 T	0.79	1.03	1.50
2-24 B	0.58	0.81	0.84
3-16 B	1.32	2.64	1.15
3-24 B	0.79	1.58	1.33
4-16 T	1.08	2.00	0.95
4-24 T	0.74	1.37	0.93
2x2-16 T	1.12	1.47	1.31
2x2-24 T	0.76	0.99	1.12
mean	.94	1.49	1.15
median	.92	1.42	1.14
standard deviation	.24	0.54	0.21

Table 4.18: Strength Ratios Based on Development Lengths

4.4.4.2 Rationality of Design Approaches

The rationality of a given design method is a rather qualitative measure, given the level of uncertainty in the current understanding of bond mechanics, but is important nonetheless. There is also a necessary compromise between accuracy and complexity in the selection of equations and specifications. The evaluation of design approaches must consider that reliability comes both from an accurate representation of behavior and simplicity of application for the designer.

The AASHTO specification seems to be in error on the side of oversimplification, leading to serious inaccuracies. Current specifications contain a basic design equation, which, when applied to the details of the test specimens considered here, is modified only to account for casting position and bundling of reinforcement. If effects of spacing and transverse reinforcement were to be included, the factor of safety of the AASHTO development length equations could be improved substantially.

The ACI code does just that. Its approach is more rational in that it incorporates more of the known influences on bond strength. In particular, factors for cover, spacing, and transverse reinforcement are combined in a single step function. The step function is not ideal from a behavioral perspective; real behavior is not constant over fairly broad ranges, with sudden changes in-between. The location of the steps may seem to be somewhat arbitrary, and be overly conservative at or just above the point where the function increases. And while the specifications may seem sensitive in that regard, the combination of spacing, reinforcement, and cover into one function also tends to mask individual influences. For instance, the ACI code specifies the same development length for the three bar bundle pattern used in this test, regardless of how much transverse reinforcement is present. However, it must be noted that the equation appears to produce conservative designs without being overly cumbersome to apply.

The Orangun equation predicted development lengths most accurately, but has been considered to be burdensome for use in design. It is valuable, however, because it is considered to be the most accurate representation of the effects of cover, spacing, and transverse reinforcement. Note that the Orangun equation was used to predict bond stress, not development length directly, and that the bond stress was converted to a development length for the bundle as described in section 4.3.3.2, incorporating the maximum effective perimeter of the bundles.

Chapter V:
Conclusions: Bundled Bar Behavior

5.1 Perimeter of a Bundle

The tests conducted in this program indicate that the behavior of a bundle is best approximated by assuming a uniform bond stress applied to the maximum effective perimeter of the bundle. This perimeter is taken as the entire circumference of the bars exposed to direct contact with the concrete; or, stated another way, as the circumference of all the bars minus that part occluded within the interior of the bundle. This is the approach currently taken by both the AASHTO and ACI documents, in section 8.28 and 12.4.1 respectively. Development length is increased 20% for a two bar bundle, and 33% for a four bar bundle. The codes do not explicitly state how the factors were derived, but they are based on the change in effective perimeter, applied to the computation of development length. This is illustrated in Figure 5.1.

5.2 Behavior of a Bundle

Bars within a bundle act as a single unit. Stress is distributed equally between bars within a bundle as long as the potential splitting planes through the bars are identical. When the splitting planes are not equal, the failure surface will be through the weaker plane, that being the layer with lesser clear spacing. In such asymmetrical geometries, there is the potential for redistribution of stress to the bar or bars outside the splitting plane, as evidenced by the three bar bundle tests.

Designers could make use of this behavior, but a note of caution is in order. Figure 5.2 demonstrates that in the three bar bundle test, the bar outside the failure plane was located in monolithic concrete. Stress can be redistributed from the weaker, outer plane by transferring force to the inner bar, which is bonded directly to the rest of the beam. If the bundle is turned upside down, then stress redistribution is no longer possible. The splitting plane would then separate the bar in question from the rest of the concrete, and all the force in that bar would have to

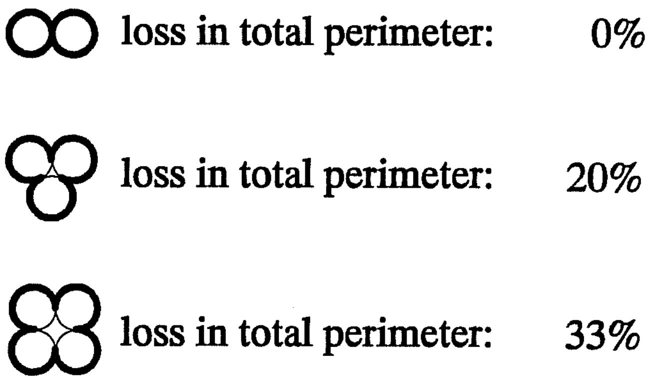


Figure 5.1 Origin of Bundled Bar Factors

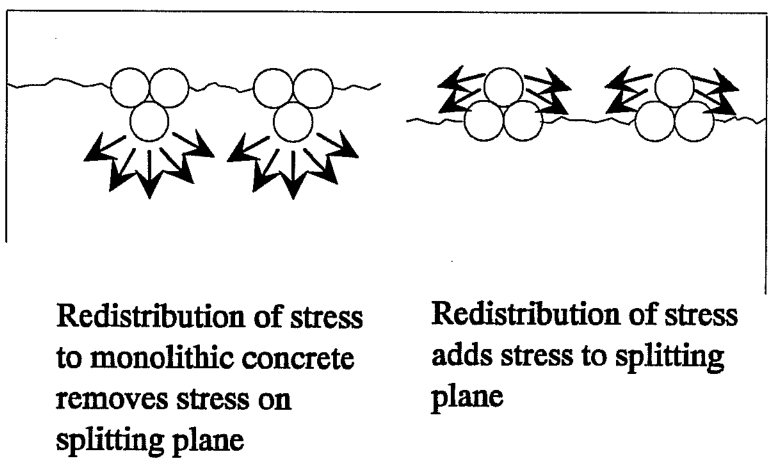


Figure 5.2 Redistribution of Stress

be transferred through the weak plane to the rest of the beam, thereby increasing the stress on the splitting plane.

5.3 Equivalent Bars

Standard round bars consistently reached higher ultimate bond stresses than bar bundles of equivalent cross sectional area. The use of a round equivalent bar to approximate bundled bar behavior may therefore be on the unconservative side. Present code equations specify use of an equivalent bar in place of bundles when considering cover and spacing requirements. The ACI code uses these parameters in computing development length, so the influence of the equivalent bar is substantial. A more accurate representation of bundled bar behavior might improve the accuracy and confidence level of development length calculations.

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