BOND OF EPOXY-COATED REINFORCEMENT TO CONCRETE: BAR PARAMETERS

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ABSTRACT

The effects of coating thickness, deformation pattern, and bar size on the reduction in bond strength between reinforcing bars and concrete caused by epoxy coating are described. Tests include beam-end and splice specimens containing No. 5, No. 6, No. 8, and No. 11 bars with average coating thicknesses ranging from 3 to 17 mils. Three deformation patterns are evaluated. All bars are bottom-cast. Beam-end specimens have covers of 2 bar diameters, while splice specimens have covers that depend on bar size and are less than 2 bar diameters. The results are compared with the splice tests that were used to establish the epoxy-coated bar provisions in the 1989 ACI Building Code and 1989 AASHTO Bridge Specifications. Epoxy coatings are found to significantly reduce bond strength, but the extent of the reduction is less than used to select the development length modification factors in the ACI Building Code and AASHTO Bridge Specifications. Coating thickness has little effect on the amount of bond strength reduction for No. 6 bars and larger. However, the thicker the coating, the greater the reduction in bond strength for No. 5 bars and smaller. In general, the reduction in bond strength caused by an epoxy coating increases with bar size. The magnitude of the reduction depends on the deformation pattern: bars with relatively larger rib-bearing areas are affected less by the coating than bars with smaller bearing areas. This is the first in a series of reports. Subsequent reports will address the effects of concrete cover, bar position, concrete strength, and transverse reinforcement.

INTRODUCTION

Epoxy-coated reinforcing steel has been in general use for approximately the last fifteen years. Its role in reducing the corrosion damage to reinforcing steel in new construction is increasing each year. While epoxy coating acts to protect the steel, it has been widely suspected that the coating also would decrease the bond between the steel and concrete.

The reduction in bond strength has been demonstrated in the two principal studies that have taken place over the past eight years. The studies, by Johnston and Zia (1982) and Treece and Jirsa (1987, 1989), were relatively small in scope but did indeed show that the bond strength of epoxy-coated reinforcement is reduced in comparison to uncoated steel.

Using beam-end specimens containing transverse reinforcement, Johnston and Zia (1982) observed a 15 percent reduction in bond strength with the use of epoxy-coated bars. Using splices without transverse reinforcement, Treece and Jirsa (1987, 1989) reported an average reduction of 34 percent. Largely based on the recommendations of Treece and Jirsa, ACI Committee 318 (1989) adopted modification factors to increase the development length for epoxy-coated bars. The factor is 1.5 (50 percent increase) for bars with cover less than 3 bar diameters or clear spacing between bars less than 6 bar diameters and 1.2 for all other conditions. AASHTO (1989) has adopted factors of 1.5 and 1.15 based on the same criteria. The new ACI and AASHTO provisions include no recognition of the effect of confining reinforcement on the strength reduction obtained with epoxy coatings.

The test results upon which the 1.5 factor is based are quite limited, representing a total of only 21 specimens, of which 12 contained epoxy-coated reinforcement. A single deformation pattern was evaluated, and no specimens were replicated. The deformation pattern used for these tests is no longer used for epoxy-coated bars because of difficulties in coating application.[1] Considering the high variability exhibited in bond tests, there exists a question as to whether these limited experiment results provide an accurate picture of the effect of epoxy coating on

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[1] Florida Steel Corporation, personal communication

bond strength.

This is the first in a series of reports that describe a large-scale study to determine the effect of epoxy coating on bond strength. This report addresses the effects of parameters associated with the bars themselves: coating thickness, deformation pattern, and bar size. This report also addresses the effects of embedment length on the strength of epoxy-coated bars relative to uncoated bars as a means of establishing the applicability of the specimen configurations used in the study. The overall study also considers the effects of concrete cover, bar position, concrete strength, and transverse reinforcement. These topics will be covered in subsequent reports.

EXPERIMENTAL PROGRAM

The overall experimental program consists of 645 test specimens. This report deals with those specimens used to evaluate the effects of parameters which are associated with the bars themselves – the thickness of the epoxy coating, the deformation pattern of the bars, and the bar size. Tests to validate the specimens are also presented.

In these tests, No. 5, No. 6, No. 8, and No. 11 bars with average coating thicknesses ranging from 3 to 17 mils (1 mil = 0.001 in.) were tested. Three deformation patterns, shown in Fig. 1, were evaluated.

Test Specimens:

Two types of test specimens, beam-end specimens and splice specimens, were used. Beam-end specimens containing No. 5, No. 6, and No. 8 bars were 9 in. wide by 24 in. long. For No. 11 bars, the width was increased to 10 in. Specimen depth was adjusted to provide 15 in. of concrete above the bars and 2 bar diameters of cover below the bar (all bars discussed in this report were bottom-cast). A typical test specimen and test bar installation are illustrated in Fig. 2.

The bars projected 22 in. out from the face of the test specimen. Two polyvinyl chloride

(PVC) pipes were used as bond breakers to limit the bonded length of the test bar and to prevent a cone type failure on the front face. The inside diameter of the PVC pipe matched the diameter of the bar. The bonded lengths of the test bars were selected to ensure that the bars did not yield before bond failure occurred (Brettmann, Donahey, and Darwin 1984, 1986). Standard bonded lengths of $3^1/_2$ in. for No. 5 bars, $4^1/_2$ in. for No. 6 bars, 8 in. for No. 8 bars, and 9 in. for No. 11 bars were used. The corresponding lengths of bond breaking PVC pipe at the front of the bars (lead lengths) were $2^3/_8$, $2^3/_4$, $3^3/_4$, and $1^1/_2$ in., respectively. Additional specimens were tested to help evaluate the effect of epoxy coating as a function of lead length and bonded length. Beam-end specimens were used for the major portion of the study.

The splice specimens consisted of simply supported beams, similar to those tested by Treece and Jirsa (1987, 1989). They are illustrated in Fig. 3. Splice lengths ranged from 12 in. for No. 5 and No. 6 bars to 16 in. for No. 8 bars and 24 in. for No. 11 bars. Two or three adjacent splices were located within the constant moment region. Three splices were used for the No. 5 bars. An additional beam with two splices of uncoated No. 5 bars was used to evaluate the usefulness of double splice specimens for later tests. The strength of the double and triple splice specimens were nearly proportional to the number of splices. Based on this evidence (admittedly limited), double splice beams were used for No. 6, No. 8, and No. 11 bars. A cover of 1 in. was used for No. 5 and No. 6 bars, $1^1/_2$ in. for No. 8, and 2 in. for No. 11 bars. The clear spacing between splices was equal to 4 in. and side cover was equal to 2 in. for all beams. Additional dimensions and data are included in Fig. 3. The spliced bars were all bottom-cast, in contrast to the Treece /Jirsa specimens, which primarily used top-cast bars.

Materials

Reinforcing Steel-ASTM A 615 (1987), Grade 60, No. 5, No. 6, No. 8, and No. 11 bars were used. Bars with 3 deformation patterns, designated S, C, and N, were tested (Fig. 1). Deformation pattern S consisted of ribs perpendicular to the axis of the bar. Deformation pattern C consisted of diagonal ribs inclined at an angle of 60° with respect to the axis of the bar. Deformation pattern N consisted of diagonal ribs inclined at an angle of 70° with respect to the axis of the bar. Bars of each size and deformation pattern were from the same heat of steel. Yield strengths and deformation properties are shown in Table 1.

Epoxy coatings were applied in accordance with ASTM A 775 (1988) and ranged in thickness from 3 to 17 mils as measured by a pull-off type thickness gauge. Readings were taken at 6 points around the circumference of the bar between each set of deformations within the bonded length. Average readings within the bonded lengths are reported. A wide range in coating thickness, outside of the ASTM A 775 limits (5 to 12 mils), was used to help evaluate the effects of coating thickness on bond strength.

Concrete-Non-air-entrained concrete was supplied by a local ready mix plant. Type I portland cement and 3/4 in. nominal maximum size coarse aggregate were used. Water-cement ratios from 0.41 to 0.55 were used to obtain concrete with nominal strengths of 5,000 or 6,000 psi. 6,000 psi concrete was used for the majority of the specimens. Mix proportions are shown in Table 2. Concrete properties for individual specimen groups are given in Table 3.

Placement Procedure

Concrete was placed in two lifts. The first lift was placed in all specimens in a group before any specimen received a second lift. Each lift in the beam-end specimens was vibrated at 6 evenly spaced points. Each lift in the splice specimens was vibrated on each side of the beams at staggered 1 ft intervals.

Standard 6 x 12 in. test cylinders were cast in steel molds and cured in the same manner as the test specimens. Forms were stripped after the concrete had reached a strength of at least 3,000 psi.

Test Procedure

Tests were made at nominal concrete strengths of 5,000 or 6,000 psi. The beam-end specimens were tested using an apparatus developed by Donahey and Darwin (1983, 1985) and modified by Brettmann et al (1984, 1986). Specimens from a group were tested within a 12 hour period (except for groups 18-20, for which tests were completed over a 48 hour period) at ages ranging from 3 to 10 days. No. 5 and No. 6 bars were loaded at approximately 3.0 kips per minute. No. 8 and No. 11 bars were tested at about 6.0 kips per minute.

Splice specimens were inverted and tested as illustrated in Fig. 3. Loads were placed on the ends of the cantilever regions, resulting in a constant moment region between the two supports. Specimens were loaded monotonically. Crack locations and widths were recorded during the progress of the tests. Crack measurements ceased at a load below the expected failure load to insure that the balance of the test would not be interrupted and provide a consistent measure of member strength. Two specimens, C-pattern No. 6 coated and S-pattern No. 8 uncoated, however, failed immediately after crack measurements were taken. Splice tests lasted 20 to 25 minutes.

Results and Observations

Beam-end Specimens - The test variables and ultimate bond forces of the bars in the beam-end specimens are listed in Table 4.

Fig. 4 illustrates typical load-slip curves for No. 5 bars. Slip at the unloaded end of the bars is shown. Uncoated bars obtained a higher strength than bars with a nominal 5 mil coating, which in turn had a greater bond strength than bars with a 12 mil coating. The initial slope of the load-slip curve decreases as the coating thickness increases. As will be discussed later in the report, No. 5 bars were the only bars to exhibit a marked sensitivity to coating thickness.

A splitting type bond failure occurred in all tests. On the front surface of the beam-end specimens, one crack ran up through the cover from the test bar to the top surface. The top surface crack continued parallel to and above the test bar over the bonded section of the bar and fanned out over the rear PVC bond breaker (Fig. 5). On the front surface, one or two cracks ran down below the test bar, similar to the crack patterns observed by Brettmann et al. (1984, 1986). Although two different crack patterns were observed, the concrete around the bar always split into three parts: wedges on either side of the bar, and the remaining specimen below the bar.

Splice Specimens - The load-deflection curves for the splice specimens (Fig. 6) indicate little difference in the response of the members, with the principal exception that epoxy-coated bar specimens consistently failed at a lower load than uncoated bar specimens.

Crack widths were measured within a region spanning 12 in. on either side of the splice. The number of cracks and maximum crack widths are summarized in Table 5. For three out of seven pairs, the specimens with epoxy-coated reinforcement exhibited a greater maximum crack width than the specimens with uncoated bars. For two pairs, the maximum crack widths were identical, and for two pairs the specimens with uncoated bars had the greater maximum crack width. For four pairs, the specimens with the uncoated bars exhibited a greater number of cracks, while in one case the two specimens had an identical number of cracks and in two cases the specimens with the epoxy-coated bars had the greater number of cracks.

Table 5 also summarizes the strengths obtained for the splice specimens in terms of bending movement and bar stress. Bar stress is calculated using the usual expression for flexural strength.

Splice specimens with epoxy-coated bars were uniformly weaker than specimens with uncoated bars, with the relative strengths ranging between 0.94 (S-pattern No. 6 bars) and 0.71 (S-pattern No. 11 bars). At failure, splice specimens exhibited extensive longitudinal and transverse cracking in the region of the splices (Fig. 7). Concrete above the splices was easily removed with a hammer, exposing a nearly horizontal crack running the full width of the beam in the plane of the splices.

Bar appearance - The test bars were examined following the tests by removing the concrete cover. Uncoated bars showed evidence of good adhesion to the concrete. Particles of concrete were left on the shaft of the bar and on the sides of the deformations. Wedges of compacted concrete powder were lodged in the front of the ribs, adhering to the ribs on the pull side only.

As observed in earlier tests of epoxy-coated reinforcement (Johnston and Zia 1982, Treece and Jirsa 1987, 1989), there was virtually no evidence of adhesion between the epoxy-coated bars and the surrounding concrete. No concrete particles were left on the deformations or the shaft of the coated bars. The concrete in contact with the epoxy-coated bars had a smooth, glassy surface. In a few cases, there were signs of the epoxy-coating being crushed against the concrete, but in general the epoxy was undamaged.

EVALUATION OF EXPERIMENTAL RESULTS

This report emphasizes the role of bar properties on the bond strength of epoxy-coated reinforcement. Specifically, the roles of coating thickness, deformation pattern, and bar size are studied. In addition, tests designed to validate the test specimen itself are discussed. The ratio of the bond strength of coated bars to the bond strength of uncoated bars, or relative bond strength C/U, will be used as the chief measure of the effects of epoxy coating.

To obtain the best possible comparisons, adjustments in bond strengths are made to account for deviations in actual concrete cover from the standard of two bar diameters, 2 d_b (ACI Committee 318 1989). This adjustment is obtained by plotting all beam-end specimen strengths for bars of a given size versus the actual cover. Covers ranging from 1 to 3 d_b are used (note, the effect of cover will be addressed in a subsequent report). It is observed that the best fit lines for different groups of specimens are nearly parallel for bars of the same size, independent of deformation pattern or bar surface condition. Using the technique of dummy variables (Draper and Smith 1981), parallel best fit lines are obtained based on the assumption that changes in cover cause the same incremental change in bond force for bars of the same size, independent of deformation pattern or test group. Thus, each group of specimens is represented by a separate line. A typical plot, in this case for No. 11 bars, is shown in Fig. 8. Individual specimen strengths are corrected by shifting the measured bond strength parallel to the best fit line to a value corresponding to 2 d_b cover. The impact of this correction is small. An analysis using No. 5 and No. 6 bar data that was uncorrected for cover altered no conclusions obtained with the cover-corrected data. This is fortunate because a cover correction cannot be made for the No. 8 bars in groups 2 through 6, since actual cover was not measured for these specimens.

For the epoxy-coated No. 5 bars, a similar correction is necessary based on coating thickness (9 mils is taken as the standard), due to the sensitivity of the bond strength of these bars to the thickness of the epoxy. As will be demonstrated, larger bars do not require a coating thickness correction, because the bond strength of No. 6 bars and larger is not sensitive to coating thickness.

In addition to the cover and coating thickness corrections, test results are normalized with respect to a nominal concrete strength of 6,000 psi using the assumption that, within the concrete strength range used, bond strength is proportional to the square root of the compressive strength. Thus, bond strengths are multiplied by $(6000/f'_c)^{1/2}$ to obtain the final modified values. Both the original and modified values of bond force are summarized in Table 4. The average modified values of bond force are summarized by bar size, deformation pattern and group in Table 6.

Splice test results are not modified for cover, coating thickness or concrete strength.

Beam-end Specimens

Specimen Evaluation-Due to the large number of variables in the overall study, it was considered desirable to use a single bonded length in the beam-end specimens for each bar size. At the outset, however, it was not clear what effect either the bonded length or the lead length had on the reduction in bond strength caused by the epoxy coating. To answer these questions, No. 5 bar beam-end specimens with a constant bonded length, $3\frac{1}{2}$ in., and lead lengths ranging from 0 to $3^3/_4$ in., and No. 5, No. 6, and No. 8 bar beam-end specimens with non-standard bonded and lead lengths were evaluated. In these latter groups, the non-standard specimens had longer bonded lengths (No. 5, $l_b = 8^1/_2$ in.; No. 6, $l_b = 10^1/_2$ in.; No. 8, $l_b = 14$ in.) and a shorter lead length ($l_l = ^1/_2$ in.) than the standard test specimens described earlier.

Fig. 9 shows the variation in ultimate bond force as a function of lead length for N-pattern No. 5 bars with a bonded length of $3^1/_2$ in. (groups 7, 8, 11, and 12). As illustrated, bond strength increases nearly linearly with increasing lead length for both the coated and uncoated bars. Based on the best fit lines, C/U varies from only 0.936 to 0.934 for lead lengths of 0.0 and 3.75 in., respectively. Thus, lead length does not appear to play a role in the *relative* bond strengths of coated and uncoated bars.

Fig. 10 compares the ultimate bond forces of N-pattern No. 5, No. 6, No. 8 bars and S-pattern No. 5 bars as a function of bonded length plus lead length. The data points for the longer total embedment (all from group 16) represent the average of at least 3 test specimens. The data points for the shorter embedment represent the average of the standard specimens of each type (corrected to a $2d_b$ cover and No. 5 bars corrected to a nominal 9 mil coating). As illustrated, the ultimate bond force increases with increasing total embedment for No. 5 bars and No. 6 bars, but decreases with increasing total embedment for No. 8 bars. This reduction, occurs for both coated and uncoated No. 8 bars. Although not a key aspect of this study, Figs. 9 and 10 show that maximum anchorage capacity does not depend solely on the length of bar in contact with concrete.

Fig. 10 also shows that the bond strengths of coated and uncoated bars respond similarly to changes in specimen geometry, resulting in only small changes in C/U. For the N-pattern No. 8 bars, C/U increases from 0.84 for the standard embedment length to 0.88 for the longer embedment length. For the N-pattern No. 6 bars, C/U increases from 0.93 for the standard embedment length to 1.01 for the longer embedment length. For the N-pattern No. 5 bars, C/U increases from 0.91 for the standard embedment length to 0.98 for the longer embedment length, while for the S-pattern No. 5 bars, C/U decreases from 0.83 to 0.76. When both deformation patterns are considered for No. 5 bars, C/U remains virtually unchanged for the two embedment lengths, with mean values of 0.87 for both standard and longer embedments.

Overall, these results might be used to suggest that C/U tends to increase with embedment length. However, considering the small number of nonstandard specimens tested, none of these variations is statistically significant. Thus, the evidence is just as strong that the effect of epoxy coating is independent of both the bonded length and the lead length. These observations contrast with the conclusion of Cleary and Ramirez (1989) that C/U drops with increasing anchorage length. However, their conclusion was based on an even smaller sampling of test data than considered here.

Having established that the reduction in bond strength caused by an epoxy coating is independent of lead length and bonded length, the balance of this report is dedicated to answering the question: Does the effect of the epoxy coating depend on coating thickness, deformation pattern, or bar size? To answer these questions, 20 groups of specimens (groups 2-15, 17-22) were tested. No. 5, No. 6, and No. 8 bars are used to evaluate the effect of coating thickness. No. 5, No. 6, No. 8, and No. 11 bars are used to evaluate the effects of deformation pattern and bar size.

Coating Thickness - The effect of coating thickness is illustrated in Figs. 11, 12, and 13, for No. 8, No. 6, and No. 5 bars, respectively. In these figures, C/U is plotted as a function of the epoxy coating thickness for each deformation pattern. Each data point represents the ratio of the bond strength of an individual epoxy-coated bar to the average bond strength of uncoated bars with the same deformation pattern and bar size in the same group of specimens. Using the technique of dummy variables (Draper and Smith 1981), the best fit lines for each deformation pattern are obtained using the assumption that there may be differences in the effect of the coating due to deformation pattern, but that the effect of coating thickness is the same for all deformation patterns.

Figs. 11 and 12 show that coating thickness plays virtually no role in the magnitude of strength reduction caused by the epoxy coating for No. 8 and No. 6 bars. This observation matches similar observations made by Johnston and Zia (1982) and Treece and Jirsa (1987, 1989). The best fit lines in Figs. 11 and 12 for No. 8 and No. 6 bars, in fact, have very slight negative slopes, which result in decreases in C/U of 0.012 and 0.002, respectively, as the coating thickness increases from 5 to 12 mils. In contrast to these observations, Fig. 13 shows that coating thickness does play a role for No. 5 bars, with C/U dropping, on the average, by 0.090 as the coating thickness increases from 5 to 12 mils. This observation does not conflict with earlier studies (Johnston and Zia 1982, Treece and Jirsa 1987, 1989), since those studies included no bars smaller than No. 6. On reflection, the conclusion that C/U depends on coating thickness for small bars seems completely reasonable, because as bar size decreases coating thickness becomes more significant in relation to the height of the bar ribs.

Deformation Pattern-A second look at Figs. 11-13 provides convincing evidence that the effect of the epoxy coating varies considerably with deformation pattern. For the three bar sizes illustrated, the S pattern is affected the most. The values of C/U for the C and N patterns are very close for the No. 6 and No. 5 bars. Also, it can be observed that smaller bars are affected, on the average, less than larger bars. Some smaller bars, however, exhibit lower values of C/U than do larger bars of different deformation patterns. Mean values of C/U based on group, deformation pattern and bar size are summarized in Table 6. For a 9 mil coating, the mean values of C/U for the S, C and N deformation patterns are, respectively, 0.83, 0.91 and 0.91 for No. 5 bars, 0.81, 0.91 and 0.93 for No. 6 bars, and 0.74, 0.90 and 0.84 for No. 8 bars. [Note: As will be explained later in this section, these values of C/U do not give a fair comparison of the deformation patterns.]

At this point, one might ask: Is there any parameter that will tie the observed results together?

In Europe, researchers have long felt that the so-called "related rib area" (really the ratio of the bearing area of the ribs to the shearing area between ribs), R_r, is an important predictor of the bond strength of deformed bars (Rehm 1961, Soretz and Holzebein 1979). The average values of C/U for individual groups of No. 5, No. 6, No. 8, and No. 11 bars are compared with R_r in Fig. 14. The comparison shows that, in general, C/U decreases as R_r decreases.

An alternative parameter, the bearing area ratio, R_b, equal to the ratio of the rib-bearing area per inch of length to the nominal cross-sectional area of the bar, provides a similar correlation with C/U, as shown in Fig. 15. For both R_r and R_b, the general correlation cuts across bar size, but the relative order of the bars in terms of R_r and R_b is not constant. Based on these comparisons R_r provides slightly better correlation with C/U, but comparisons with R_b have the advantage that bars of a given size are more closely spaced than if R_r is used (for example, see the data points representing No. 5 bars in Figs. 14 and 15). With additional analysis, it is likely that other parameters, such as rib orientation, will be found to play a role.

The results shown in Figs. 11-15 do not give a completely equitable comparison of the deformation patterns, because the values of C/U are evaluated individually by deformation pattern. Thus, a coated bar may have a low C/U based on uncoated bars of the same deformation pattern, but, in fact, have a higher bond strength than another coated bar that has a high value of C/U because its uncoated bars have a low bond strength. It is fairer to base the values of C/U on the mean strengths of *all* uncoated bars of the same size. This is done in Table 6 and Figs. 16 and 17. For a 9 mil coating, the mean values of C/U calculated on this basis for the S, C and N patterns are, respectively, 0.85, 0.93, and 0.87 for No. 5 bars, 0.80, 0.89 and 0.97 for No. 6 bars, 0.73, 0.83 and 0.90 for No. 8 bars, and 0.90, 0.80 and 0.78 for No. 11 bars. Table 6 and Figs. 16 and 17 also show the ratios of the mean strengths of uncoated bars in each group to the mean strength of all uncoated bars of the same size, U/U. The mean values of U/U for the S, C and N patterns are, respectively, 1.03, 1.02 and 0.95 for No. 5 bars, 0.99, 0.97 and 1.04 for No. 6 bars, 0.98, 0.96 and 1.06 for No. 8 bars, and 0.98, 0.97 and 1.05 for No. 11 bars. It is worth noting that not only is the order of relative strength different for coated and uncoated bars of the same size, but the range in the mean values of C/U significantly exceeds the range in the mean values of U/U, except for No. 5 bars where the range of relative strengths is identical. The wider spread in the bond strengths of coated bars emphasizes the strong dependance of bond strength reduction on deformation pattern.

Unlike the coated bars, there is no clear relationship between R_b or R_r and the relative strengths of uncoated bars of the same size.

Bar Size - The effect of epoxy coating on bond strength as a function of bar size is illustrated in Fig. 18, which compares the relative bond strengths of coated and uncoated bars by deformation pattern. As with Figs. 16 and 17, the relative strengths are expressed in terms of the mean strength of uncoated bars of the same size.

For the coated bars, the overall trend is a reduction in C/U with increasing bar size. The mean values of C/U are 0.88, 0.89, 0.83 and 0.83 for No. 5, No. 6, No. 8, and No. 11 bars, respectively. Based on deformation pattern, the lowest mean values of C/U for each bar size are 0.85, 0.80, and 0.73, for S-pattern No. 5, No. 6, and No. 8 bars, respectively, and 0.78 for N-pattern No. 11 bars.

The C/U values for No. 6 and No. 11 bars contrast sharply with the mean values obtained by Treece and Jirsa (1987, 1989) for splices: 0.74 for No. 6 bars and 0.64 for No. 11 bars.

Splice Specimens

Splice test specimens are larger and more costly than beam-end specimens. Therefore, it is desirable to run fewer splice tests than beam-end tests in a study. The question arises: Why run splice tests at all? The reasons are two-fold. Splice tests may provide a more realistic model of what happens in an actual structure, and the development length provisions for epoxy-coated bars in ACI 318-89 are based on the splice tests run by Treece and Jirsa (1987, 1989). With this in mind, it is important to know (1) if beam-end specimens give the same results as splice specimens, and (2) if the tests in the current study, both beam-end and splice tests, match the earlier splice tests (Treece and Jirsa 1987, 1989).

Before these questions are answered, the variability that is inherent in bond tests should be considered. Bond tests exhibit a great deal of scatter, as shown in Figs. 11-13. However, the scatter shown in these figures is only one-half of the picture, since the values of C/U are based on mean bond strengths of uncoated bars.

Imagine if the bond strength of each coated bar is divided by the bond strength of *each* uncoated bar in the same test group. Clearly, the scatter in C/U will increase. The extent of the scatter is illustrated in Fig. 19, where these individual values of C/U are compared as a function of the bearing-area ratio, R_b. Since the splice tests in this study, as well as those performed by Treece and Jirsa (1987, 1989), were executed with individual coated and uncoated bar specimens, i.e. no replications, the expected scatter in C/U for splices should be like that shown for the beam-end specimens in Fig. 19.

The C/U values for the splice tests in this study and those from Treece and Jirsa (1987, 1989) also appear in Fig. 19. As illustrated, the splice tests generally lie within the scatter band obtained from the beam-end tests. A summary of the splice tests in the current study is presented in Table 5.

For the current study, some splice results are on the high side of the scatter band (S-pattern No. 6, 0.94, S-pattern No. 8, 0.90, and N-pattern No. 8, 0.85) and some are on the low side (N-pattern No. 5, 0.75, C-pattern No. 6, 0.76, and S-pattern No. 11, 0.71). Overall, the key aspects of bond strength reduction caused by epoxy coating appear to be the same for both beam-end and splice specimens.

The mean value of C/U for the current splice tests, 0.82 is slightly lower than the mean for all beam-end tests, 0.85. However, the mean value of C/U from Treece and Jirsa (1987, 1989), 0.66 if weighted by test group or 0.69 if weighted by individual specimen, is considerably below the mean for the beam-end tests. The lower relative strength of the splices can be traced to the fact that most of the splices had a cover that was less than the 2 d_b used for the beam-end specimens, and a lower strength is statistically expected for unconfined multiple splice specimens than for single splice or single bar specimens. Detailed consideration of these effects will be included in the next report.

Implications for Design

Although this report presents only a portion of the results from the University of Kansas study, the results described here have important implications for design.

The major observation is that the bond strength of epoxy-coated bars, relative to uncoated bars, is considerably higher than the value of 0.66 used to calculate the 1.5 development length modification factor for bars with less than 3 d_b cover in the 1989 ACI Building Code and 1989 AASHTO Bridge Specifications. The lowest average value of C/U obtained for any bar size or deformation pattern, 0.73 for S-pattern No. 8 bars, translates into a modification factor of 1.37. No. 5, No. 6, and No. 11 bars are affected even less, with modification factors of 1.18, and 1.25, and 1.28, respectively, based on the deformation pattern with the lowest value of C/U. And these values are all based on a cover of $2\ d_b$.

These results suggest that a lower penalty is necessary for bars with a 2 d_b cover than recommended by Treece and Jirsa (1987, 1989) and implemented by ACI (1989) and AASHTO (1989) for bars with a cover less than 3 d_b. It appears that development length modification factors can safely be reduced to 1.25 for No. 6 bars and smaller and 1.35 or 1.40 for No. 7 bars and larger (care should be taken in selecting values for No. 14 and No. 18 bars since no tests have been performed on these bar sizes). A modification factor of 1.25 for No. 5 bars and smaller is more than needed, based on a 9 mil coating, but will help to take into account the lower bond strengths obtained by small bars with thicker coatings.

The results also suggest that development length modification factors can be reduced further by (1) altering deformation patterns to improve the bond strength of epoxy-coated bars or (2) standardizing on "strong" deformation patterns on an industry wide basis. Modification factors for each bar size should be based on the deformation pattern with the lowest mean C/U value, rather than the mean value of C/U for all bars of a given size, since deformation is clearly a controllable parameter. As noted earlier, the deformation pattern tested by Treece and Jirsa (1987, 1989) is no longer used for epoxy-coated bars because of difficulties in coating.

The insensitivity to coating thickness of bars larger than No. 5 indicates that coatings thicker than 12 mils could be used on larger bars to improve corrosion protection. This improved protection could be obtained with little reduction in bond strength beyond that currently observed. Additional study is necessary, however, before new limits on coating thickness can be established.

CONCLUSIONS

The following conclusions are based on the results and analyses presented in this report.

1. Epoxy coatings in the range of 5 to 12 mils significantly reduce the bond strength of deformed reinforcing bars to concrete. However, the extent of the reduction is less than used to select development length modification factors in the 1989 ACI Building Code and 1989 AASHTO Bridge Specifications.
2. For coatings between 5 and 12 mils in thickness, differences in coating thickness have little effect on the amount of the bond strength reduction for No. 6 bars and larger. Thicker coatings cause a greater reduction in bond strength than thinner coatings for No. 5 bars and smaller.
3. In general, the reduction in bond strength caused by epoxy coating increases with bar size.
4. The magnitude of the reduction depends on deformation pattern. Bars with relatively larger rib bearing areas are affected less by the coating than bars with smaller bearing areas.

FUTURE REPORTS

Research on the effect of epoxy coating on the bond strength of reinforcing steel is continuing at the University of Kansas. Future reports will address the effects of cover, bar position, concrete strength, and confinement, as well as presenting proposed revisions to the development length provisions of the ACI Building Code (ACI Committee 318 1989) and the AASHTO Bridge Specifications (1989).

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Table 1 Average Test Bar Data

Bar Size	Def. Pattern	Yield Str. (ksi)	Def. Spacing (in.)	Def. Gap (in.)	Def. Angle (deg.)	Bearing Area per Inch * (in.)	Related Rib Area *	Bearing Area Ratio * ($in.^{-1}$)
5	S	70.6	0.423	0.159	90	0.113	0.057	0.361
5	C	72.3	0.413	0.140	60	0.143	0.074	0.471
5	N	68.4	0.379	0.158	70	0.166	0.086	0.545
6	S	63.8	0.502	0.154	90	0.139	0.060	0.320
6	C	70.9	0.467	0.122	60	0.188	0.079	0.420
6	N	64.2	0.462	0.151	70	0.201	0.084	0.448
8	S	67.0	0.674	0.176	90	0.202	0.064	0.256
8	C	**	0.656	0.195	60	0.241	0.077	0.305
8	N	63.8	0.602	0.160	70	0.250	0.080	0.316
11	S	64.6	0.945	0.217	90	0.313	0.071	0.202
11	C	63.1	0.840	0.196	60	0.302	0.069	0.196
11	N	64.3	0.914	0.195	70	0.287	0.065	0.185

* Bearing area based on closely spaced measurements of ribs; bar perimeters and areas based on nominal dimensions.

** Yield strength is greater than 70.0 ksi.

Table 2 Concrete Mixture Proportions (Cubic Yard Batch Weights)

Group	Nominal Strength (psi)	W/C ratio	Cement (lb)	Water (lb)	Aggregate Fine+ (lb)	Aggregate Coarse* (lb)
2	6000	0.41	756	310	1245	1575
3-7	6000	0.45	622	280	1437	1575
8-17,21 22,SP2-SP4	6000	0.45	733	330	1213	1575
18-20,SP1	5000	0.55	600	330	1324	1575

+ Kansas River Sand - Lawrence Sand Co., Lawrence, KS, bulk specific gravity = 2.62, absorption = 0.5%, fineness modulus = 3.0.

* Crushed limestone - Hamm's Quarry, Perry, KS, bulk specific gravity = 2.52, absorption = 3.5%, maximum size = 3/4 in., unit weigth = 97.2 lb/cubic ft.

Table 3 Concrete Properties

Group	Slump (in.)	Concrete Temperature (F)	Age at Test (days)	Average Compressive Strength (psi)
2	2 1/2	60	3	5700
3	1 1/4	65	5	6090
4	1 1/4	73	4	6130
5	1 1/2	60	4	5920
6	1 1/2	70	5	5870
7	1	68	6	6000
8	3	80	4	5800
9	4	89	6	5650
10	4 1/2	85	7	5990
11	3 1/4	89	6	5970
12	3 1/4	92	7	5940
13	3 1/4	93	9	5840
14	4	88	7	5800
15	4 1/4	74	8	6000
16	3 1/2	72	4	6240
17	5 3/4	78	9	5850
18	4 1/4	57	3	4790
			4	5010
			5	5430
19	3 3/4	68	4	5070
			5	5270
20	2 3/4	89	9	5290
			10	5260
21	4	92	5	5990
22	4 1/2	64	7	6300
SP1 *	4 3/4	70	11	5360
SP2	2 3/4	78	6	6010
SP3	5 1/2	74	6	5980
SP4	3 1/2	87	7	5850

* SP = Splice groups

Table 4 Beam-end Tests

Group	Specimen Label *	Average Coating Thickness (mils)	Cover (in.)	Concrete Strength (psi)	Ultimate Bond Force (lb)	Modified Bond Force (lb)	Lead Length (if non-standard) (in.)
7	5N 9- 3.5	9.5	1 1/4	6000	16000	16000	3.75
	5N 9- 3.5A	10.1	1 1/4	6000	16080	16080	3.75
	5N 9- 3.5B	8.9	1 5/8	6000	16200	16200	3.75
	5N 0- 3.5	0.0	1 9/32	6000	16890	16890	3.75
	5N 0- 3.5A	0.0	1 1/4	6000	15930	15930	3.75
	5N 0- 3.5B	0.0	1 9/16	6000	17100	17100	3.75
8	5N 0- 3.5	0.0	1 1/4	5800	18110	18419	3.75
	5N 9- 3.5	5.6	1 9/32	5800	15860	16131	3.75
	5N 0- 3.5	0.0	1 5/16	5800	14580	14578	
	5N 9- 3.5	7.0	1 11/32	5800	14100	13635	
	5N 0- 3.5	0.0	1 1/4	5800	10850	11035	1.50
	5N 9- 3.5	5.1	1 1/4	5800	11180	11371	1.50
9	5S 5- 3.5	6.9	1 5/16	5650	11160	10903	
	5S 5- 3.5A	5.5	1 5/16	5650	11910	11446	
	5S 5- 3.5B	4.4	1 5/16	5650	13590	12995	
	5S12- 3.5	14.5	1 5/16	5650	10520	11495	
	5S12- 3.5A	17.1	1 3/8	5650	11340	12517	
	5S12- 3.5B	11.8	1 5/16	5650	10630	11164	
	5S 0- 3.5	0.0	1 5/16	5650	14770	14969	
	5S 0- 3.5A	0.0	1 5/16	6310	14870	14249	
	5S 0- 3.5B	0.0	1 11/32	5650	13220	13246	
10	5C 9- 3.5	9.3	1 3/16	5990	12660	12970	
	5C 9- 3.5A	10.1	1 1/4	5990	12950	13141	
	5C 9- 3.5B	8.7	1 1/4	5990	12880	12841	
	5C 5- 3.5	3.0	1 5/16	5990	14700	13473	
	5C 5- 3.5A	4.5	1 1/4	5990	13370	12640	
	5C 5- 3.5B	3.7	1 5/16	5990	14110	12997	
	5C 0- 3.5	0.0	1 9/32	5990	13660	13545	
	5C 0- 3.5A	0.0	1 1/4	5990	13340	13351	
	5C 0- 3.5B	0.0	1 3/8	5990	14340	13849	

* Specimen Label

#D T- LR

# = bar size : 5,6,8,11
D = deformation pattern : S,C,N
T = nominal coating thickness : 0,5,9,12 mils
L = bonded length in inches
R = replication I.D. : blank, A, B

Table 4 Beam-end Tests (continued)

Group	Specimen Label	Average Coating Thickness (mils)	Cover (in.)	Concrete Strength (psi)	Ultimate Bond Force (lb)	Modified Bond Force (lb)	Lead Length (if non-standard) (in.)
11	5N 9- 3.5	9.6	1 7/32	5970	12180	12435	
	5N 9- 3.5A	10.0	1 1/4	5970	11630	11824	
	5N 9- 3.5B	9.9	1 11/32	5970	11930	11731	
	5N 0- 3.5	0.0	1 9/32	5970	12180	12085	
	5N 0- 3.5A	0.0	1 1/4	5970	12800	12832	
	5N 0- 3.5B	0.0	1 1/4	5970	13940	13974	
	5N 0- 3.5	0.0	1 9/32	6090	7050	6997	0.00
	5N 0- 3.5A	0.0	1 3/16	6090	7000	6948	0.00
12	5N 0- 3.5	0.0	1 1/4	5940	15320	15397	
	5N 0- 3.5A	0.0	1 1/4	5940	13830	13899	
	5N 0- 3.5B	0.0	1 1/4	5940	12650	12713	
	5N 9- 3.5	9.8	1 3/16	5940	12080	12523	
	5N 9- 3.5A	10.5	1 3/16	5940	12570	13131	
	5N 9- 3.5B	9.3	1 11/32	5940	11890	11622	
	5N 0- 3.5	0.0	1 1/4	5940	10460	10512	1.50
	5N 0- 3.5A	0.0	1 1/4	5940	11250	11306	1.50
	5N 9- 3.5	8.3	1 1/4	5940	10690	10743	1.50
	5N 9- 3.5A	9.8	1 1/8	5940	11350	11407	1.50
	5N 0- 3.5	0.0	1 1/4	5940	9550	9598	1.00
	5N 0- 3.5A	0.0	1 5/16	5940	10730	10784	1.00
	5N 9- 3.5	9.0	1 9/32	5940	9260	9306	1.00
	5N 9- 3.5A	9.4	1 7/32	5940	10520	10572	1.00
	5N 0- 3.5	0.0	1 9/32	5940	9930	9980	0.50
	5N 0- 3.5A	0.0	1 1/16	5940	8720	8763	0.50
	5N 0- 3.5B	0.0	1 3/16	5940	9290	9336	0.50
	5N 9- 3.5	9.2	1 7/32	5940	8310	8351	0.50
	5N 9- 3.5A	9.6	1 5/16	5940	8360	8402	0.50
	5N 9- 3.5B	8.8	1 7/16	5940	8150	8191	0.50
	5N 0- 3.5	0.0	1 9/32	5940	7980	8020	0.00
	5N 0- 3.5A	0.0	1 3/16	5940	7980	8020	0.00
	5N 9- 3.5	9.8	1 5/16	5940	6870	6904	0.00
	5N 9- 3.5A	8.1	1 7/32	5940	7950	7990	0.00
13	5N 0- 3.5	0.0	1 9/32	5844	12170	12205	
	5N 0- 3.5A	0.0	1 1/4	5844	13660	13841	
	5N 0- 3.5B	0.0	1 3/16	5844	12850	13271	
	5N 5- 3.5	7.1	1 9/32	5844	13110	12845	
	5N 5- 3.5A	6.2	1 1/4	5844	12000	11698	
	5N 5- 3.5B	6.2	1 1/4	5844	11700	11394	
16	5N 0- 8.5	0.0	1 1/4	6240	18400	18042	0.50
	5N 0- 8.5A	0.0	1 9/32	6240	15800	15493	0.50
	5N 0- 8.5B	0.0	1 9/32	6240	19400	19023	0.50
	5N 9- 8.5	7.0	1 5/32	6240	17600	17258	0.50
	5N 9- 8.5A	5.6	1 7/32	6240	16600	16277	0.50
	5N 9- 8.5B	6.5	1 11/32	6240	18500	18140	0.50

Table 4 Beam-end Tests (continued)

Group	Specimen Label	Average Coating Thickness (mils)	Cover (in.)	Concrete Strength (psi)	Ultimate Bond Force (lb)	Modified Bond Force (lb)	Lead Length (if non-standard) (in.)
	5S 0- 8.5	0.0	1 11/32	6240	18200	17846	0.50
	5S 0- 8.5A	0.0	1 5/16	6240	17400	17062	0.50
	5S 0- 8.5B	0.0	1 5/16	6240	17700	17356	0.50
	5S 9- 8.5	9.6	1 9/32	6240	11200	10982	0.50
	5S 9- 8.5A	9.0	1 1/4	6240	17000	16669	0.50
	5S 9- 8.5B	10.3	1 1/4	6240	12100	11865	0.50
21	5C 0- 3.5	0.0	31/32	5990	14180	15321	
	5C 0- 3.5A	0.0	1 3/16	5990	14530	14793	
	5C 0- 3.5B	0.0	1 3/16	5990	14850	15113	
	5C 5- 3.5	4.3	1 7/32	5990	12880	12242	
	5C 5- 3.5A	5.0	1 7/32	5990	13030	12507	
	5C 5- 3.5B	4.7	1	5990	12990	13296	
	5C12- 3.5	11.2	1 3/8	5990	12940	12810	
	5C12- 3.5A	11.3	1 1/4	5990	12670	13059	
	5C12- 3.5B	10.8	1 1/4	5990	13900	14207	
	5S 0- 3.5	0.0	7/8	5990	12790	14306	
	5S 0- 3.5A	0.0	1 1/4	5990	14750	14762	
	5S 0- 3.5B	0.0	1 3/16	5990	14460	14723	
	5S 5- 3.5	4.7	1 1/4	5990	12460	11762	
	5S 5- 3.5A	5.3	1 1/8	5990	12850	12753	
	5S 5- 3.5B	5.6	1 1/4	5990	12880	12330	
	5S12- 3.5	13.8	1 1/4	5990	10220	11019	
	5S12- 3.5A	10.0	1 1/32	5990	11340	12392	
	5S12- 3.5B	11.7	1 3/8	5990	11820	11772	
14	6S 0- 4.5	0.0	1 15/32	5800	20130	20660	
	6S 0- 4.5A	0.0	1 15/32	5800	20210	20741	
	6S 0- 4.5B	0.0	1 1/2	5800	16410	16690	
	6S 5- 4.5	4.1	1 9/16	5800	15630	15524	
	6S 5- 4.5A	4.8	1 1/2	5800	16140	16415	
	6S 5- 4.5B	4.2	1 1/2	5800	14560	14808	
	6S12- 4.5	11.8	1 1/2	5800	15430	15693	
	6S12- 4.5A	10.9	1 9/16	5800	15250	15137	
	6S12- 4.5B	11.6	1 17/32	5800	15330	15405	
	6N 0- 4.5	0.0	1 1/2	5800	18000	18307	
	6N 0- 4.5A	0.0	1 7/16	5800	18340	19026	
	6N 0- 4.5B	0.0	1 1/2	5800	20240	20586	
	6N 9- 4.5	7.2	1 9/16	5800	20680	20660	
	6N 9- 4.5A	8.8	1 23/32	5800	19880	18915	
	6N 9- 4.5B	8.0	1 9/16	5800	17760	17690	
	6C 0- 4.5	0.0	1 1/2	5800	18850	19172	
	6C 0- 4.5A	0.0	1 19/32	5800	17960	17707	
	6C 0- 4.5B	0.0	1 1/2	5800	19000	19324	
	6C 5- 4.5	4.7	1 9/16	5800	17290	17212	
	6C 5- 4.5A	4.2	1 19/32	5800	18460	18216	
	6C 5- 4.5B	4.1	1 9/16	5800	16970	16887	

Table 4 Beam-end Tests (continued)

Group	Specimen Label	Average Coating Thickness (mils)	Cover (in.)	Concrete Strength (psi)	Ultimate Bond Force (lb)	Modified Bond Force (lb)	Lead Length (if non-standard) (in.)
	6C12- 4.5	9.5	1 1/2	5800	18750	19070	
	6C12- 4.5A	10.2	1 1/2	5800	18930	19253	
	6C12- 4.5B	11.4	1 17/32	5800	17900	18019	
16	6N 0-10.5	0.0	1 9/16	6240	25200	24710	0.50
	6N 0-10.5A	0.0	1 15/32	6240	26500	25985	0.50
	6N 0-10.5B	0.0	1 9/16	6240	22900	22455	0.50
	6N 9-10.5	7.2	1 1/2	6240	26300	25789	0.50
	6N 9-10.5A	8.9	1 1/2	6240	23600	23141	0.50
	6N 9-10.5B	9.5	1 17/32	6240	25300	24808	0.50
17	6C 0- 4.5	0.0	1 1/2	5850	17900	18128	
	6C 0- 4.5A	0.0	1 9/16	5850	19800	19679	
	6C 0- 4.5B	0.0	1 7/16	5850	17870	18470	
	6C 5- 4.5	7.1	1 9/16	5850	16020	15851	
	6C 5- 4.5A	5.9	1 1/2	5850	16740	16953	
	6C 5- 4.5B	6.5	1 1/2	5850	16100	16305	
	6C12- 4.5	9.3	1 1/2	5850	15890	16092	
	6C12- 4.5A	10.5	1 1/2	5850	14570	14755	
	6C12- 4.5B	10.9	1 1/2	5850	16160	16365	
	6S 0- 4.5	0.0	1 15/32	5850	17400	17808	
	6S 0- 4.5A	0.0	1 7/16	5850	18300	18905	
	6S 0- 4.5B	0.0	1 1/2	5850	19200	19444	
	6S 5- 4.5	5.7	1 1/2	5850	15130	15322	
	6S 5- 4.5A	3.8	1 17/32	5850	15800	15814	
	6S 5- 4.5B	3.6	1 17/32	5850	14900	14903	
	6S12- 4.5	12.9	1 15/32	5850	15900	16288	
	6S12- 4.5A	11.5	1 17/32	5850	16900	16928	
	6S12- 4.5B	11.1	1 17/32	5850	13900	13890	
22	6N 0- 4.5	0.0	1 3/8	6300	19290	19570	
	6N 0- 4.5A	0.0	1 1/2	6300	19970	19488	
	6N 0- 4.5B	0.0	1 1/2	6300	19440	18971	
	6N 0- 4.5C	0.0	1 5/8	6300	24530	23193	
	6N 0- 4.5D	0.0	1 5/16	6300	19880	20519	
	6N 0- 4.5E	0.0	1 1/2	6300	21080	20571	
	6N 9- 4.5	9.8	1 13/32	6300	18390	18505	
	6N 9- 4.5A	8.0	1 7/16	6300	19330	19236	
	6N 9- 4.5B	9.7	1 5/16	6300	16140	16869	
	6N 9- 4.5C	8.6	1 3/8	6300	19560	19834	
	6N 9- 4.5D	8.9	1 15/32	6300	17870	17625	
	6N 9- 4.5E	8.0	1 9/32	6300	17960	18831	
2	8C12- 8.0	13.3	2	5700	38300	39294	
	8C 9- 8.0	10.0	2	5700	36760	37714	
	8C 5- 8.0	5.3	2	5700	35990	36924	
	8C 0- 8.0	0.0	2	5700	45990	47184	

Table 4 Beam-end Tests (continued)

Group	Specimen Label	Average Coating Thickness (mils)	Cover (in.)	Concrete Strength (psi)	Ultimate Bond Force (lb)	Modified Bond Force (lb)	Lead Length (if non-standard) (in.)
3	8S12- 8.0	12.8	2	6090	27030	26829	
	8S12- 8.0A	13.0	2	6090	32040	31802	
	8S12- 8.0B	12.3	2	6090	29110	28894	
	8S 9- 8.0	9.7	2	6090	29940	29717	
	8S 9- 8.0A	10.2	2	6090	28140	27931	
	8S 9- 8.0B	10.2	2	6090	31100	30869	
	8S 5- 8.0	5.4	2	6090	28990	28774	
	8S 5- 8.0A	6.4	2	6090	28580	28368	
	8S 5- 8.0B	6.5	2	6090	32280	32040	
	8S 0- 8.0	0.0	2	6090	43480	43157	
	8S 0- 8.0A	0.0	2	6090	40960	40656	
	8S 0- 8.0B	0.0	2	6090	40640	40338	
4	8N 9- 8.0	8.6	2	6130	35820	35438	
	8N 9- 8.0A	8.5	2	6130	42030	41581	
	8N 9- 8.0B	8.8	2	6130	34970	34597	
	8N 0- 8.0	0.0	2	6130	45220	44737	
	8N 0- 8.0A	0.0	2	6130	50000	49466	
	8N 0- 8.0B	0.0	2	6130	44580	44104	
5	8C12- 8.0	13.8	2	5920	37370	37621	
	8C12- 8.0A	13.2	2	5920	30590	30795	
	8C12- 8.0B	12.7	2	5920	34560	34792	
	8C 9- 8.0	9.5	2	5920	36070	36312	
	8C 9- 8.0A	10.0	2	5920	33560	33785	
	8C 9- 8.0B	9.4	2	5920	34290	34520	
	8C 5- 8.0	5.5	2	5920	33440	33665	
	8C 5- 8.0A	4.6	2	5920	35550	35789	
	8C 5- 8.0B	3.7	2	5920	35560	35799	
	8C 0- 8.0	0.0	2	5920	34550	34782	
	8C 0- 8.0A	0.0	2	5920	34740	34973	
	8C 0- 8.0B	0.0	2	5920	39490	39755	
6	8S 9- 8.0	7.9	2	5870	35430	35820	
	8S 9- 8.0A	10.8	2	5870	32840	33201	
	8S 0- 8.0	0.0	2	5870	46500	47012	
	8S 0- 8.0A	0.0	2	5870	42710	43180	
	8C 9- 8.0	10.7	2	5870	33790	34162	
	8C 9- 8.0A	9.1	2	5870	36630	37033	
	8C 0- 8.0	0.0	2	5870	43930	44413	
	8C 0- 8.0A	0.0	2	5870	46820	47335	
	8N 9- 8.0	9.2	2	5870	36620	37023	
	8N 9- 8.0A	10.4	2	5870	45070	45566	
	8N 0- 8.0	0.0	2	5870	38000	38418	
	8N 0- 8.0A	0.0	2	5870	47670	48194	

Table 4 Beam-end Tests (continued)

Group	Specimen Label	Average Coating Thickness (mils)	Cover (in.)	Concrete Strength (psi)	Ultimate Bond Force (lb)	Modified Bond Force (lb)	Lead Length (if non-standard) (in.)
15	8S 0- 8.0	0.0	1 15/16	6000	41800	42650	
	8S 0- 8.0A	0.0	2	6000	42700	42700	
	8S 5- 8.0	4.1	2	6000	29050	29050	
	8S 5- 8.0A	4.7	2	6000	33340	33340	
	8S 5- 8.0B	6.8	1 15/16	6000	34730	35580	
	8S12- 8.0	16.5	2	6000	30500	30500	
	8S12- 8.0A	11.7	2 1/16	6000	29100	28249	
	8S12- 8.0B	14.1	1 15/16	6000	32000	32850	
	8N 0- 8.0	0.0	2	5830	40600	41187	
	8N 0- 8.0A	0.0	2	5830	42800	43419	
	8N 0- 8.0B	0.0	2	5830	45140	45793	
16	8N 0-14.0	0.0	2 1/32	6240	36800	36085	0.50
	8N 0-14.0A	0.0	2	6240	38800	38046	0.50
	8N 0-14.0B	0.0	2 1/32	6240	37800	37065	0.50
	8N 9-14.0	10.3	2	6240	31900	31280	0.50
	8N 9-14.0A	7.7	2	6240	36100	35398	0.50
	8N 9-14.0B	10.0	2	6240	31900	31280	0.50
18	8N 0- 8.0	0.0	1 7/8	5060	45600	51357	
	8N 0- 8.0A	0.0	1 15/16	5060	42400	47021	
	8N 0- 8.0B	0.0	1 7/8	5060	41040	46391	
	8N12- 8.0	12.2	1 31/32	5060	33700	37122	
	8N12- 8.0A	9.3	1 31/32	5060	35700	39300	
	8N12- 8.0B	8.6	1 15/16	5060	35950	39997	
	8S 0- 8.0	0.0	1 31/32	5440	36920	39199	
	8S 0- 8.0A	0.0	2 1/32	5440	43540	45300	
	8S 0- 8.0B	0.0	2 1/32	5440	37940	39419	
	8S12- 8.0	8.1	2 1/16	5440	32660	33448	
	8S12- 8.0A	9.7	1 29/32	5440	29510	32268	
	8S12- 8.0B	11.6	1 29/32	5440	33510	36468	
19	11N 0- 9.0	0.0	2 13/16	5070	36000	38666	
	11N 0- 9.0A	0.0	2 7/8	5270	46100	48195	
	11N 0- 9.0B	0.0	2 9/16	5270	36100	40009	
	11N 9- 9.0	10.3	2 3/4	5270	32000	34144	
	11N 9- 9.0A	8.5	2 3/4	5070	29600	32200	
	11N 9- 9.0B	8.1	2 3/4	5270	28200	30089	
	11S 0- 9.0	0.0	2 11/16	5270	38600	41683	
	11S 0- 9.0A	0.0	2 25/32	5270	36300	38484	
	11S 0- 9.0B	0.0	2 13/16	5070	34400	36925	
	11S 9- 9.0	11.0	2 3/4	5270	27600	29449	
	11S 9- 9.0A	10.9	2 5/8	5070	27700	31127	
	11S 9- 9.0B	12.6	2 3/4	5270	36400	38839	
	11C 0- 9.0	0.0	2 1/2	5070	37500	42781	
	11C 0- 9.0A	0.0	2 23/32	5270	37800	40581	
	11C 0- 9.0B	0.0	2 11/16	5270	35100	37948	

Table 4 Beam-end Tests (continued)

Group	Specimen Label	Average Coating Thickness (mils)	Cover (in.)	Concrete Strength (psi)	Ultimate Bond Force (lb)	Modified Bond Force (lb)	Lead Length (if non-standard) (in.)
	11C 9- 9.0	12.1	2 3/4	5070	29000	31547	
	11C 9- 9.0A	13.1	2 3/4	5270	27700	29556	
	11C 9- 9.0B	12.4	2 13/16	5270	29100	30553	
20	11N 0- 9.0	0.0	2 13/16	5290	47380	49962	
	11N 0- 9.0A	0.0	3	5260	39500	40200	
	11N 0- 9.0B	0.0	2 11/16	5260	41330	44638	
	11N 9- 9.0	10.4	2 7/8	5290	29300	30210	
	11N 9- 9.0A	8.7	2 15/16	5260	33700	34502	
	11N 9- 9.0B	9.2	2 13/16	5260	32910	34652	
	11S 0- 9.0	0.0	2 13/16	5290	36480	38354	
	11S 0- 9.0A	0.0	2 13/16	5260	43990	46485	
	11S 0- 9.0B	0.0	2 11/16	5260	38060	41145	
	11S 9- 9.0	10.9	2 13/16	5290	41780	43998	
	11S 9- 9.0A	9.4	2 3/4	5260	36030	38481	
	11S 9- 9.0B	9.7	2 3/4	5260	39560	42251	
	11C 0- 9.0	0.0	2 7/8	5290	41580	43289	
	11C 0- 9.0A	0.0	2 13/16	5260	34500	36350	
	11C 0- 9.0B	0.0	2 13/16	5260	39440	41626	
	11C 9- 9.0	9.4	2 3/4	5290	28320	30160	
	11C 9- 9.0A	8.2	2 11/16	5260	38600	41722	
	11C 9- 9.0B	8.4	2 11/16	5260	33800	36596	

Table 5 Splice Tests

Group	Bar No.	Def. pattern	Splice length (in.)	Average Coating Thickness (mils)	No. of cracks	Widest crack (mils)	Bar stress for crack comparison (ksi)	Ultimate moment (k-in)	Ultimate stress (ksi)	+ C/U
SP1	5	N	12	0.0	7	9	40.9	521	58.7	
	5*	N	12	0.0	8	7	42.1	813	61.2	
	5*	N	12	9.5	6	7	42.1	609	45.5	0.74
SP2	6	S	12	0.0	6	7	36.7	543	43.2	
	6	S	12	8.3	3	9	36.7	511	40.6	0.94
	6	C	12	0.0	5	5	36.7	610	48.7	
	6	C	12	8.8	6	5	36.7	466	36.9	0.76
SP3	8	S	16	0.0	6	7	25.9	854	40.1	
	8	S	16	9.4	4	5	25.9	768	35.9	0.90
	8	N	16	0.0	5	9	25.9	858	40.3	
	8	N	16	9.5	7	7	25.9	737	34.4	0.85
SP4	11	S	24	0.0	5	7	24.0	1459	37.6	
	11	S	24	9.3	5	9	24.0	1053	26.6	0.71
	11	C	24	0.0	7	7	24.0	1372	35.2	
	11	C	24	10.3	6	10	24.0	1128	28.6	0.81
	Mean =									0.82

* These beams contained 3 splices

\+ C/U = Ratio of bond strengths of coated to uncoated bars

1 mil = 0.001 in.

Table 6 Summary of Beam-end Tests

Bar size	Def. pattern	Group No.	No. of uncoated bars	Uncoated bars bond force (lb)	No. of coated bars	Coated bars bond force (lb)	C/U+ group	U/U++ all	C/U++ all
5	S	9	3	14154	6	11753	0.83	1.01	0.84
5	S	21	3	14598	6	12005	0.82	1.04	0.86
Average =				14376		11879	0.83	1.03	0.85
5	C	10	3	13580	6	13009	0.96	0.97	0.93
5	C	21	3	15078	6	13020	0.86	1.08	0.93
Average =				14329		13014	0.91	1.02	0.93
5	N	11	3	12964	3	11998	0.93	0.92	0.86
5	N	12	3	14003	3	12425	0.89	1.00	0.89
5	N	13	3	13107	3	11977	0.91	0.93	0.85
Average =				13358		12133	0.91	0.95	0.87
Average of all No. 5 bars * =				14021		12342	0.88	1.00	0.88
6	S	14	3	19363	6	15498	0.80	1.00	0.80
6	S	17	3	18720	6	15525	0.83	0.97	0.81
Average =				19041		15511	0.81	0.99	0.80
6	C	14	3	18733	6	18112	0.97	0.97	0.94
6	C	17	3	18760	6	16056	0.86	0.97	0.83
Average =				18746		17084	0.91	0.97	0.89
6	N	14	3	19309	3	19089	0.99	1.00	0.99
6	N	22	6	20385	6	18486	0.91	1.06	0.96
Average =				20026		18687	0.93	1.04	0.97
Average of all No. 6 bars * =				19271		17094	0.89	1.00	0.89

\+ Numerator and denominator based on group average

++ Numerator based on group average. Denominator based on average for three deformation patterns for each bar size; each deformation pattern weighted equally

* Each deformation pattern weighted equally

** Each bar size weighted equally

Table 6 Summary of Beam-end Tests (continued)

Bar size	Def. pattern	Group No.	No. of uncoated bars	Uncoated bars bond force (lb)	No. of coated bars	Coated bars bond force (lb)	C/U+ group	U/U++ all	C/U++ all
8	S	3	3	41384	9	29472	0.71	0.96	0.68
8	S	6	2	45104	2	34512	0.77	1.05	0.80
8	S	15	2	42680	6	31600	0.74	0.99	0.73
8	S	18	3	41312	3	34064	0.82	0.96	0.79
Average =				42365		31303	0.74	0.98	0.73
8	C	2	1	47184	3	37976	0.80	1.10	0.88
8	C	5	3	36504	9	34784	0.95	0.85	0.81
8	C	6	2	45880	2	35600	0.78	1.07	0.83
Average =				41409		35584	0.90	0.96	0.83
8	N	4	3	46104	3	37208	0.81	1.07	0.86
8	N	6	2	43304	2	41296	0.95	1.01	0.96
8	N	15	3	43464	0	0	0.00	1.01	0.00
8	N	18	3	48256	3	38800	0.80	1.12	0.90
Average =				45461		38827	0.84	1.06	0.90
Average of all No. 8 bars * =				43078		35238	0.83	1.00	0.82
11	S	19	3	39033	3	33138	0.85	0.94	0.80
11	S	20	3	41994	3	41580	0.99	1.01	1.00
Average =				40513		37359	0.92	0.98	0.90
11	C	19	3	40437	3	30555	0.76	0.97	0.74
11	C	20	3	40419	3	36162	0.89	0.97	0.87
Average =				40428		33358	0.83	0.97	0.80
11	N	19	3	42291	3	32148	0.76	1.02	0.77
11	N	20	3	44937	3	32625	0.73	1.08	0.79
Average =				43614		32386	0.74	1.05	0.78
Average of all No. 11 bars * =				41518		34367	0.83	1.00	0.83
Average of all bars ** =							0.86	1.00	0.85

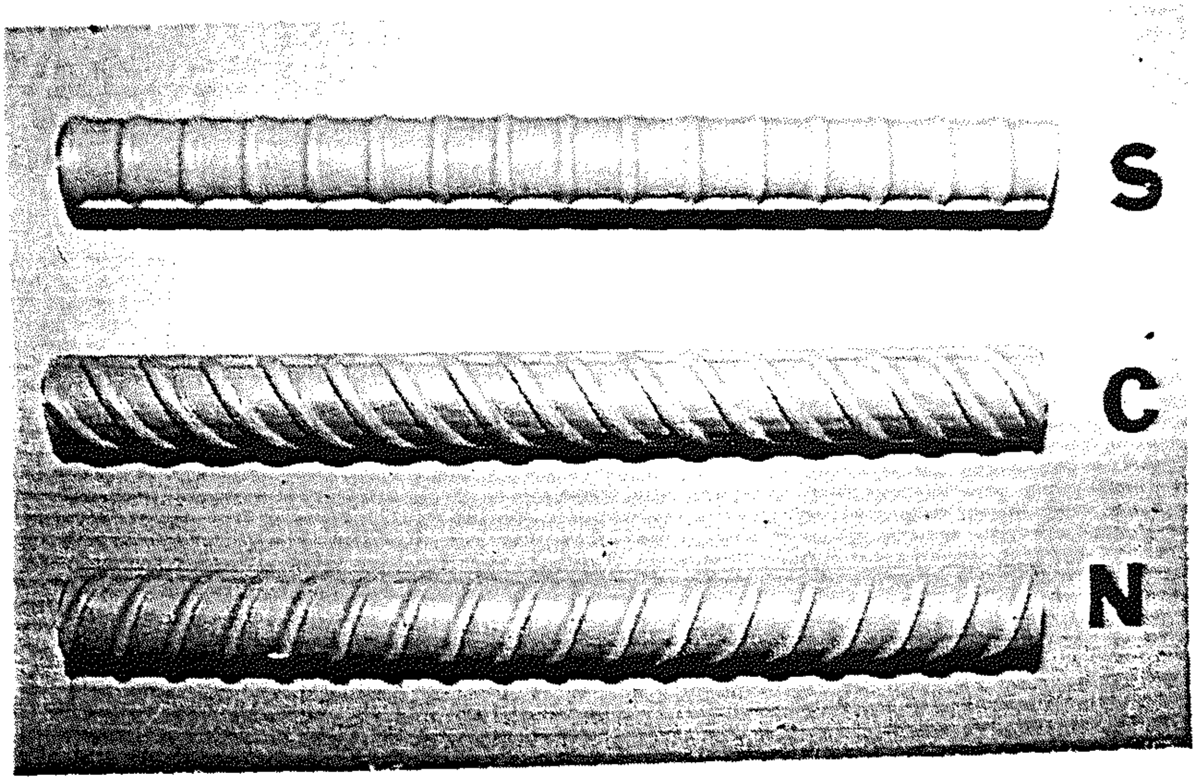


Fig. 1 Reinforcing Bar Deformation Patterns

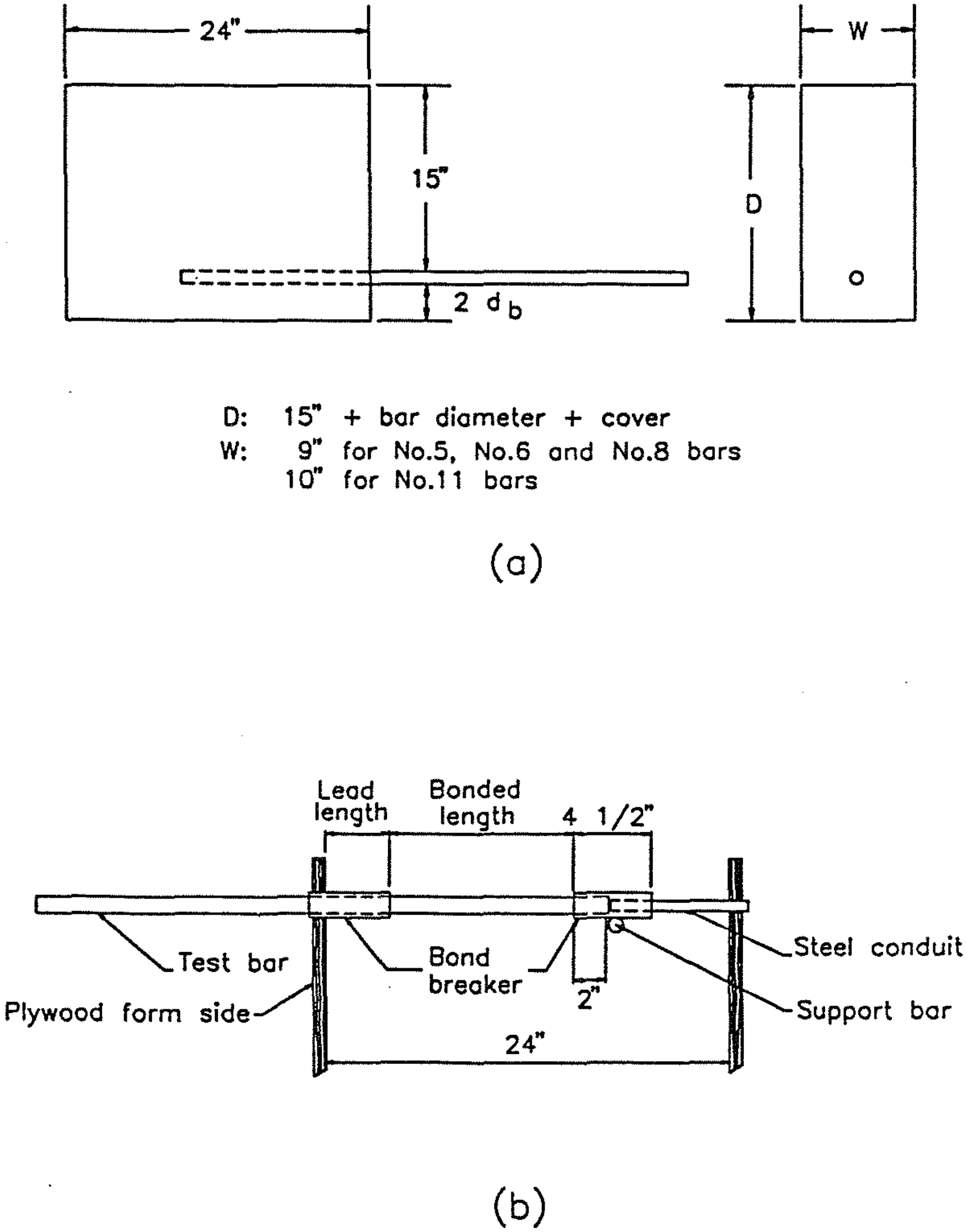
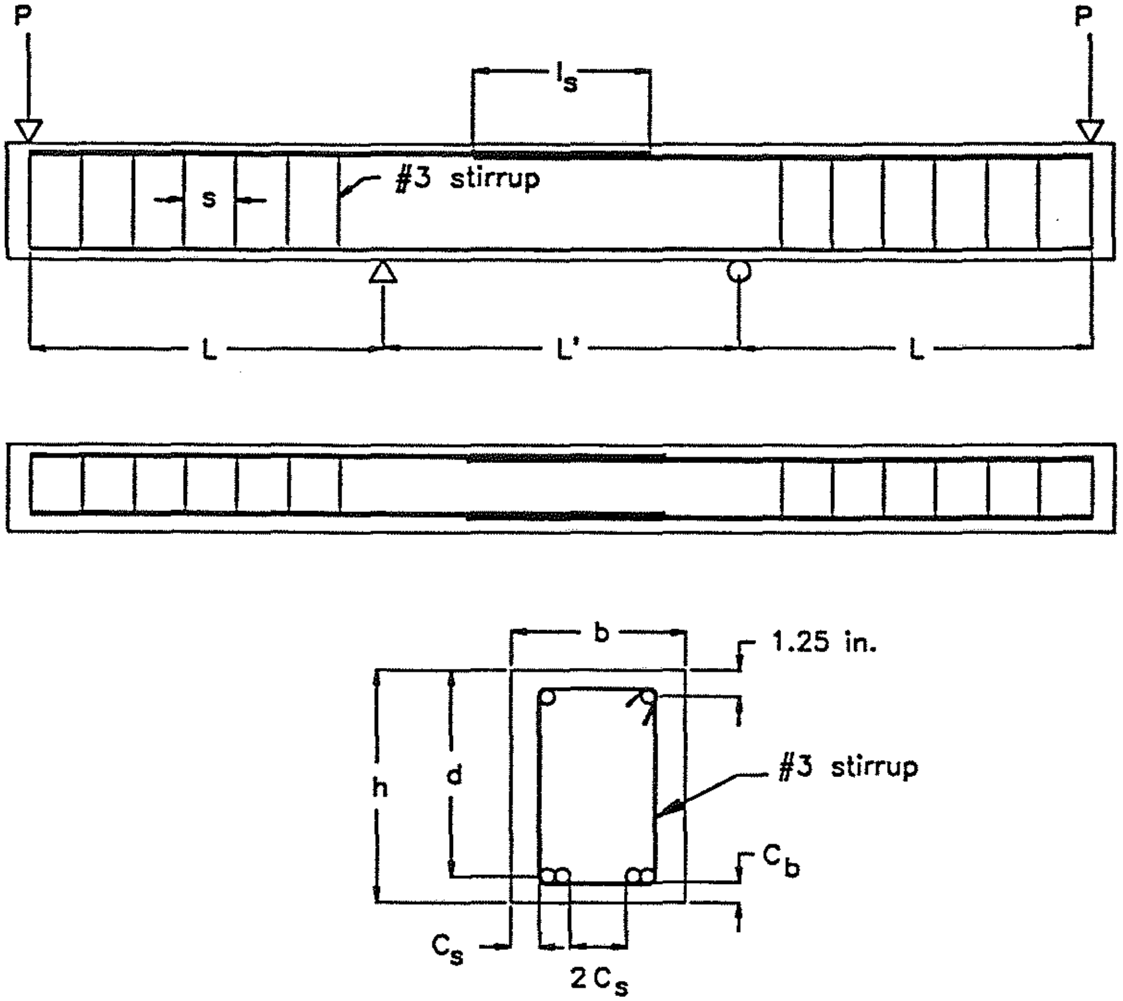


Fig. 2 (a) Beam-end Specimen Dimensions. (b) Test Bar Installation



Bar Size	L (ft.)	L' (ft.)	l_s (in.)	No. of splices	s (in.)	b (in.)	d (in.)	h (in.)	Cs (in.)	Cb (in.)
#5	4	4	12	3	6	15.75	14.69	16	2	1
#5	4	4	12	2	6	10.5	14.69	16	2	1
#6	4	4	12	2	7	11	14.63	16	2	1
#8	4	4	16	2	7	12	14	16	2	1.5
#11	4.5	6	24	2	6	13.65	13.30	16	2	2

Fig. 3 Splice Specimens

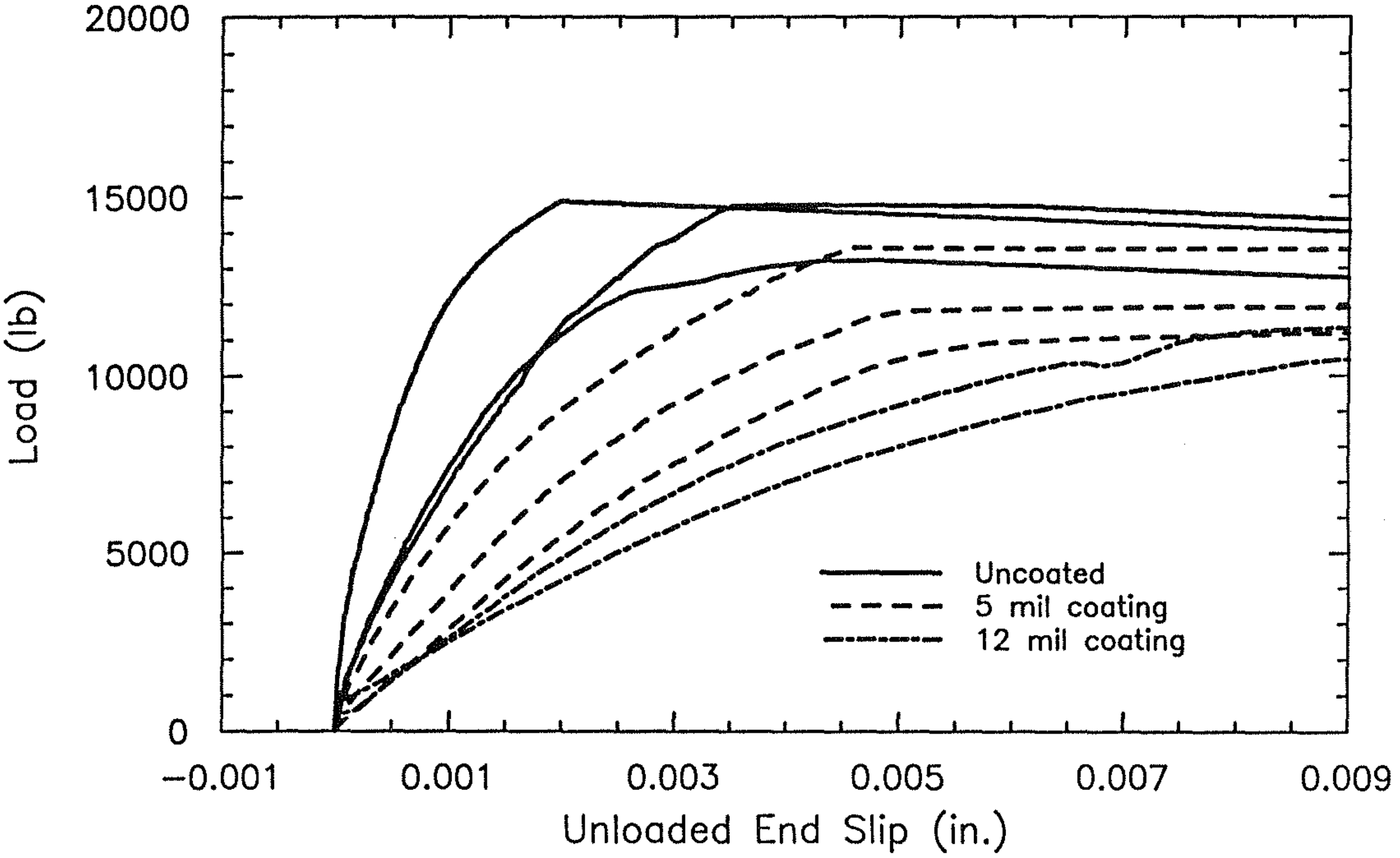


Fig. 4 Load-Slip Curves for S-Pattern No. 5 Bars

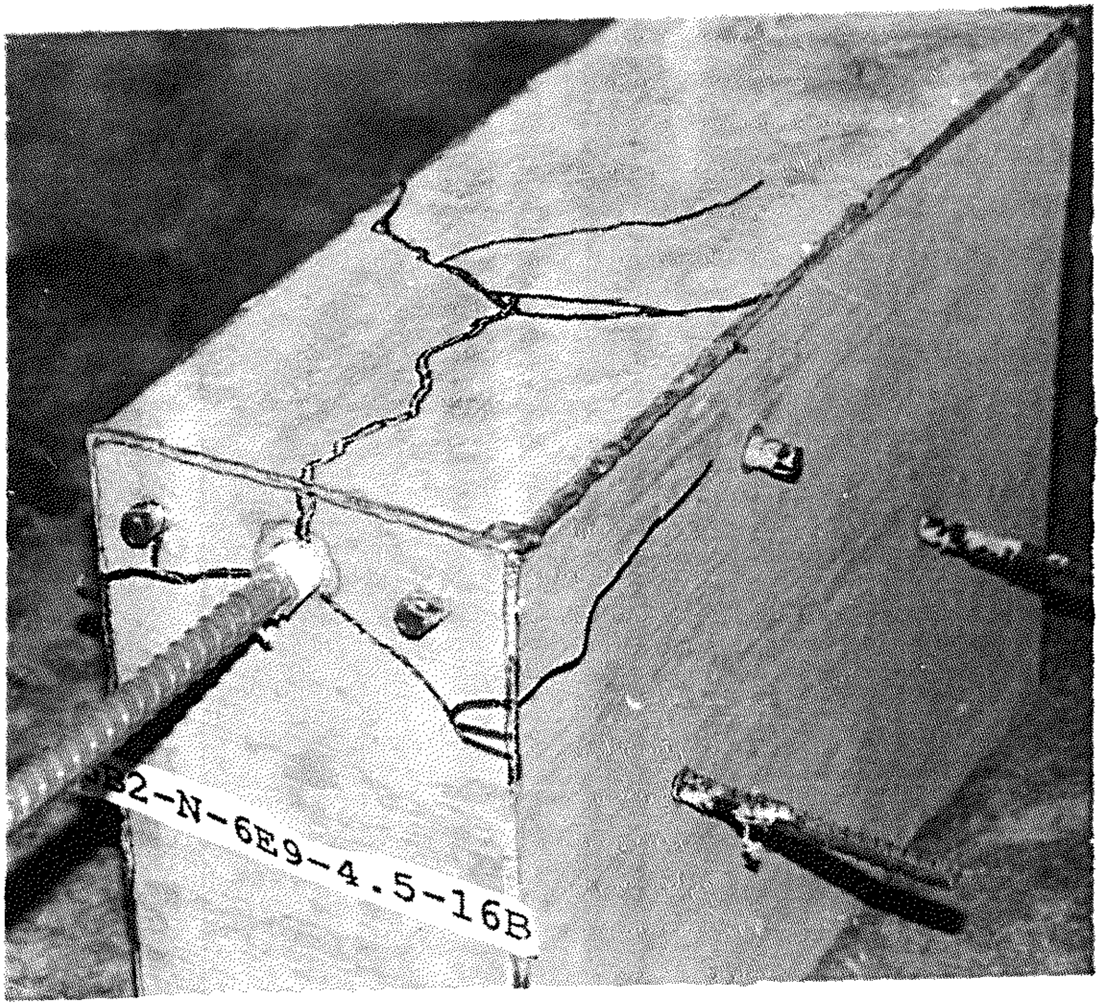


Fig. 5 Cracked Beam-end Specimen after Failure

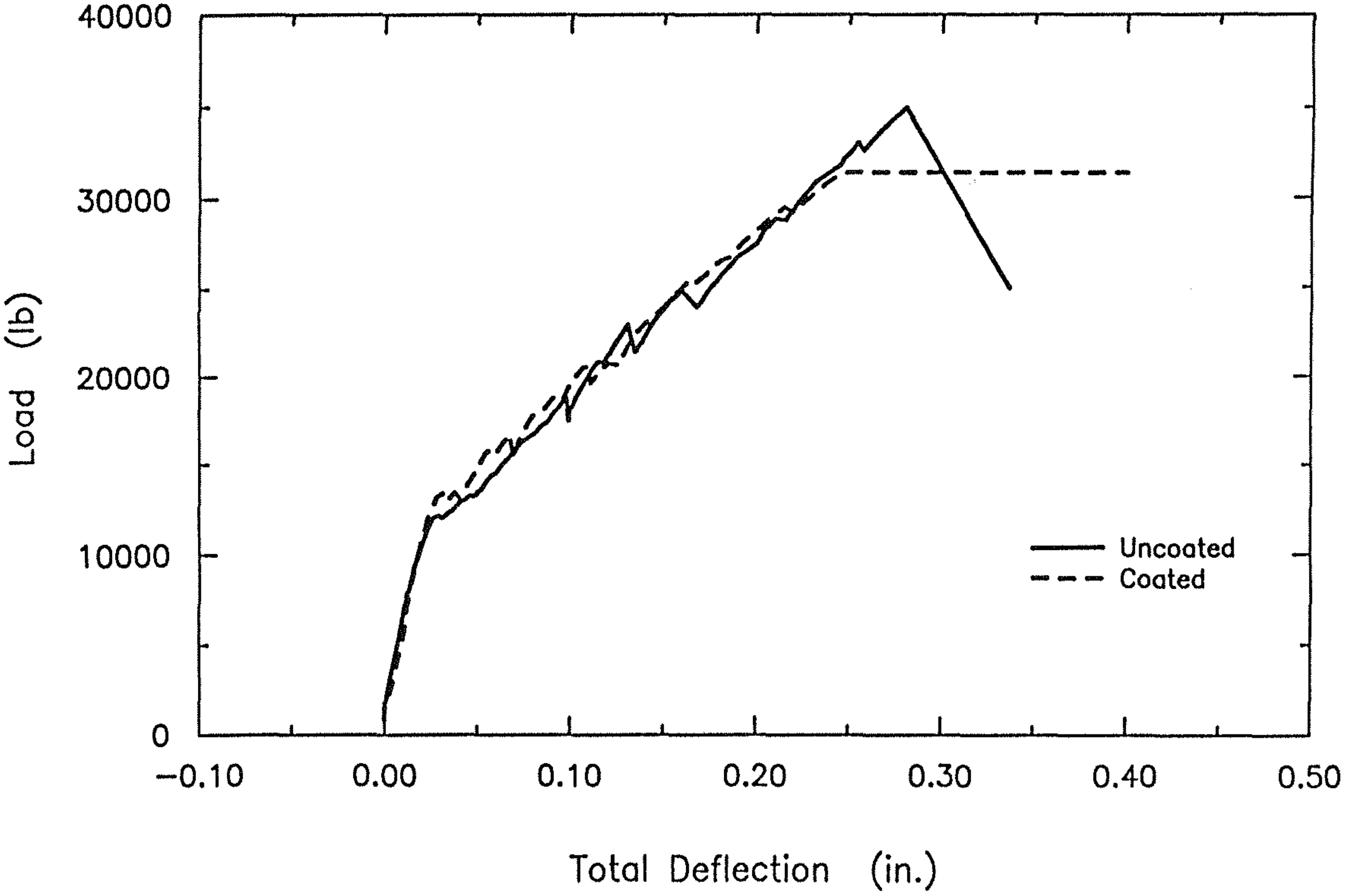


Fig. 6 Load-Deflection Curves for S-Pattern No. 8 Bar Splice Specimens

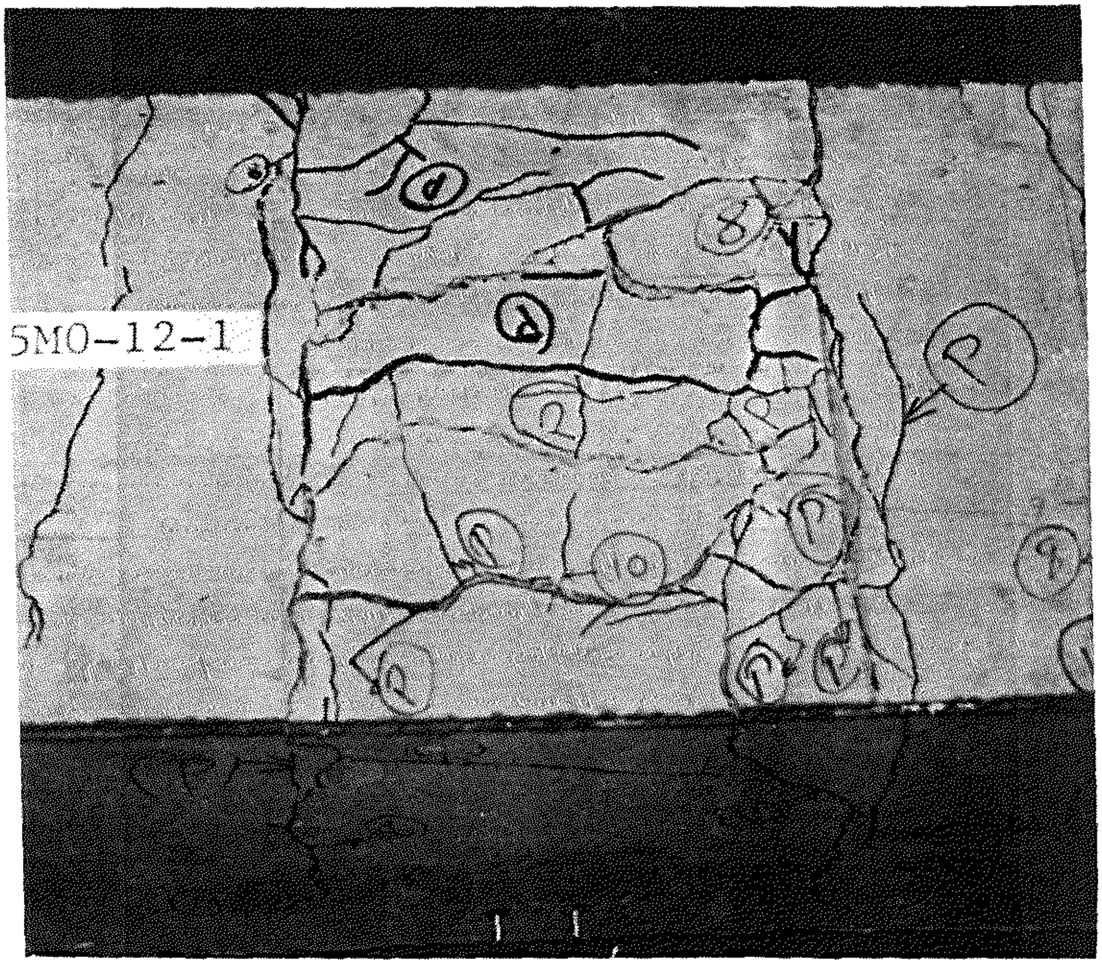


Fig. 7 Cracked Splice Specimen after Failure

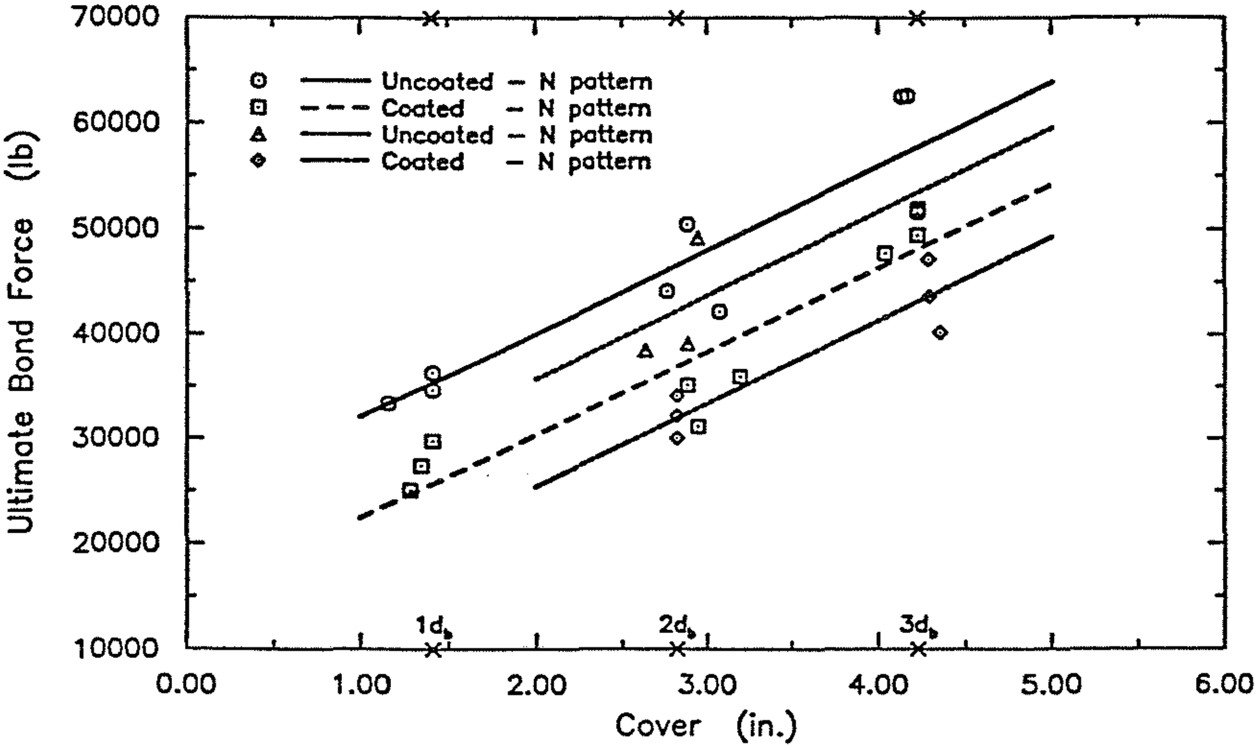


Fig. 8 Ultimate Bond Force versus Cover for No. 11 Bars

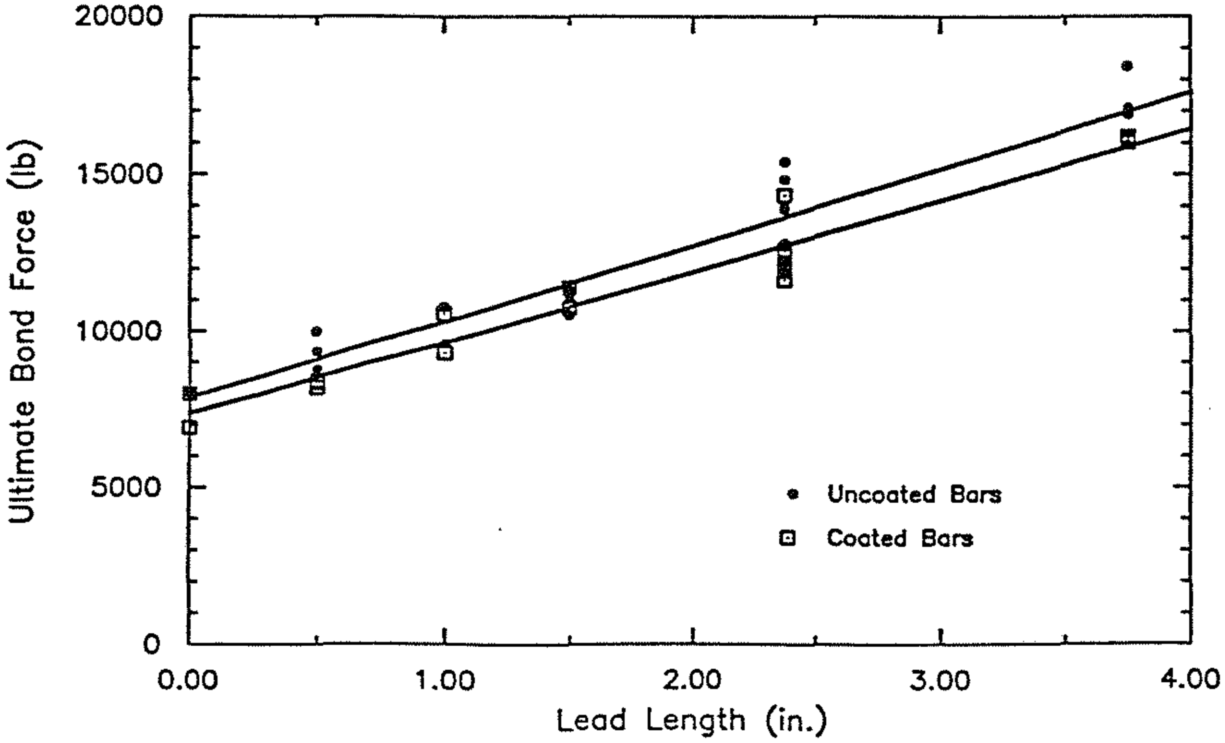


Fig. 9 Ultimate Bond Force versus Lead Length for N-Pattern No. 5 Bars. Bonded length = $3^1/_2$ in.

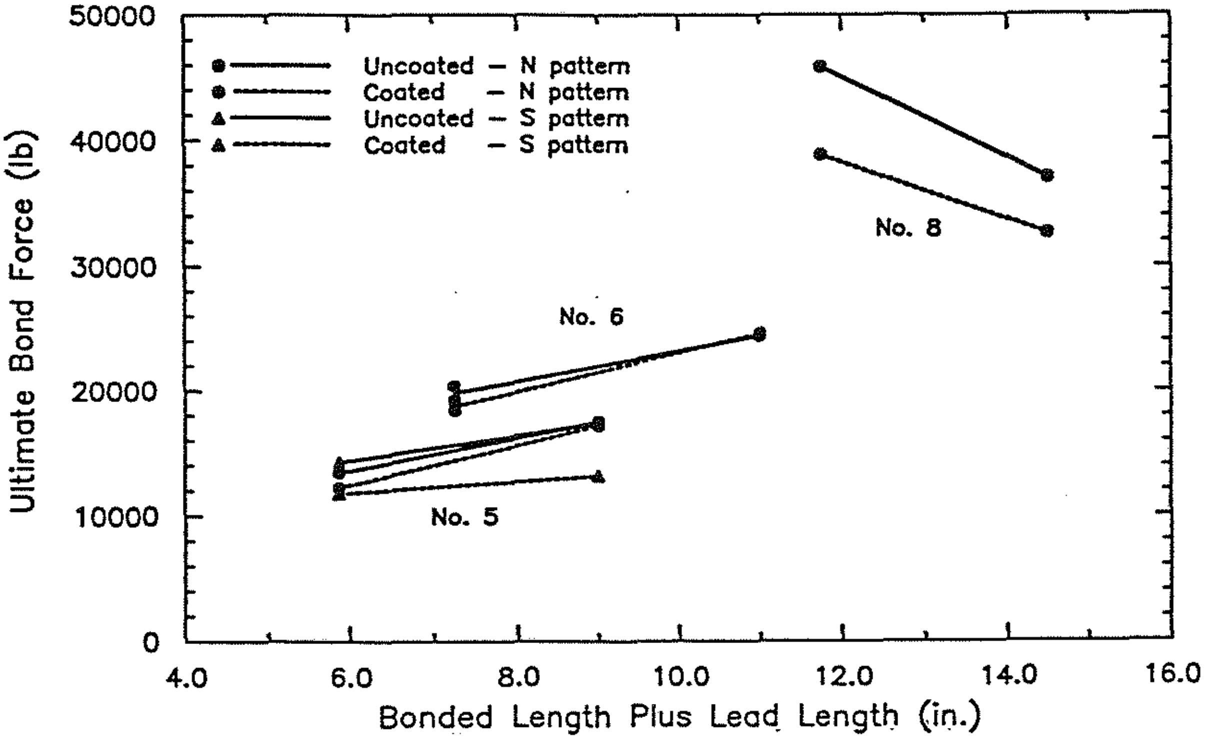


Fig. 10 Ultimate Bond Force versus Bonded Length Plus Lead Length for N-Pattern No. 5, No. 6, and No. 8 Bars and S-Pattern No. 5 Bars

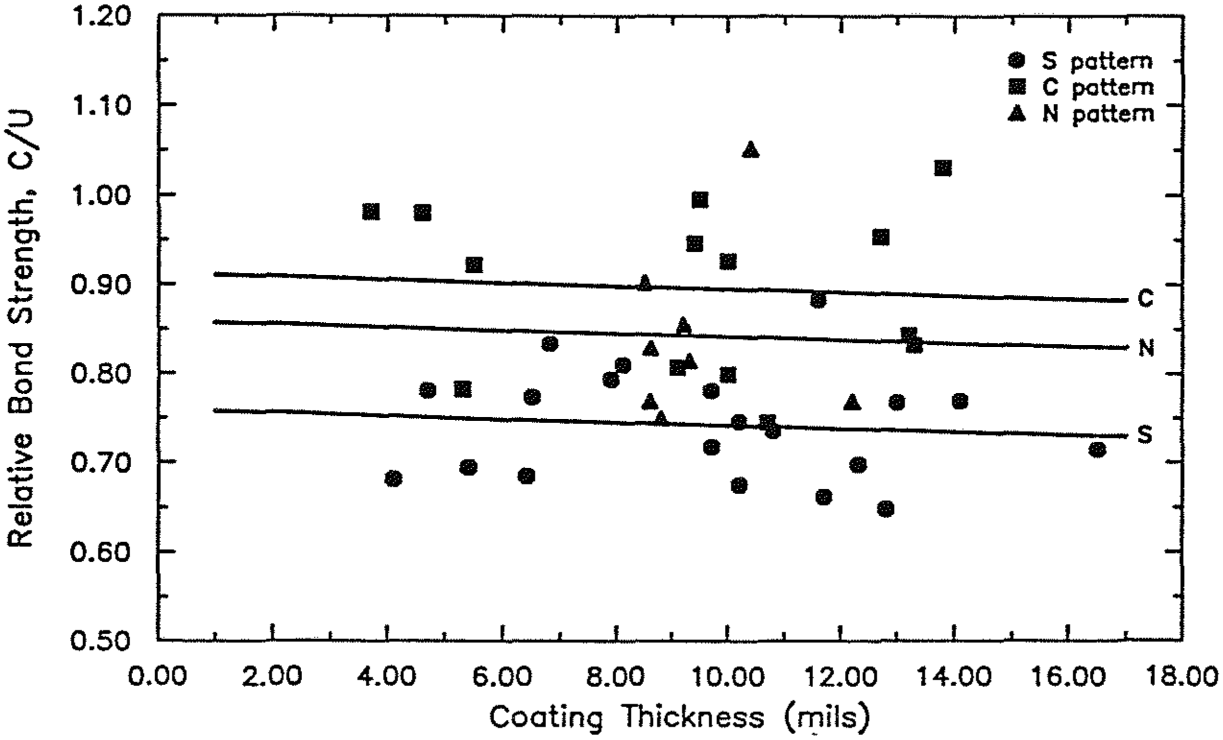


Fig. 11 Relative Bond Strength, C/U, versus Coating Thickness for No. 8 Bars

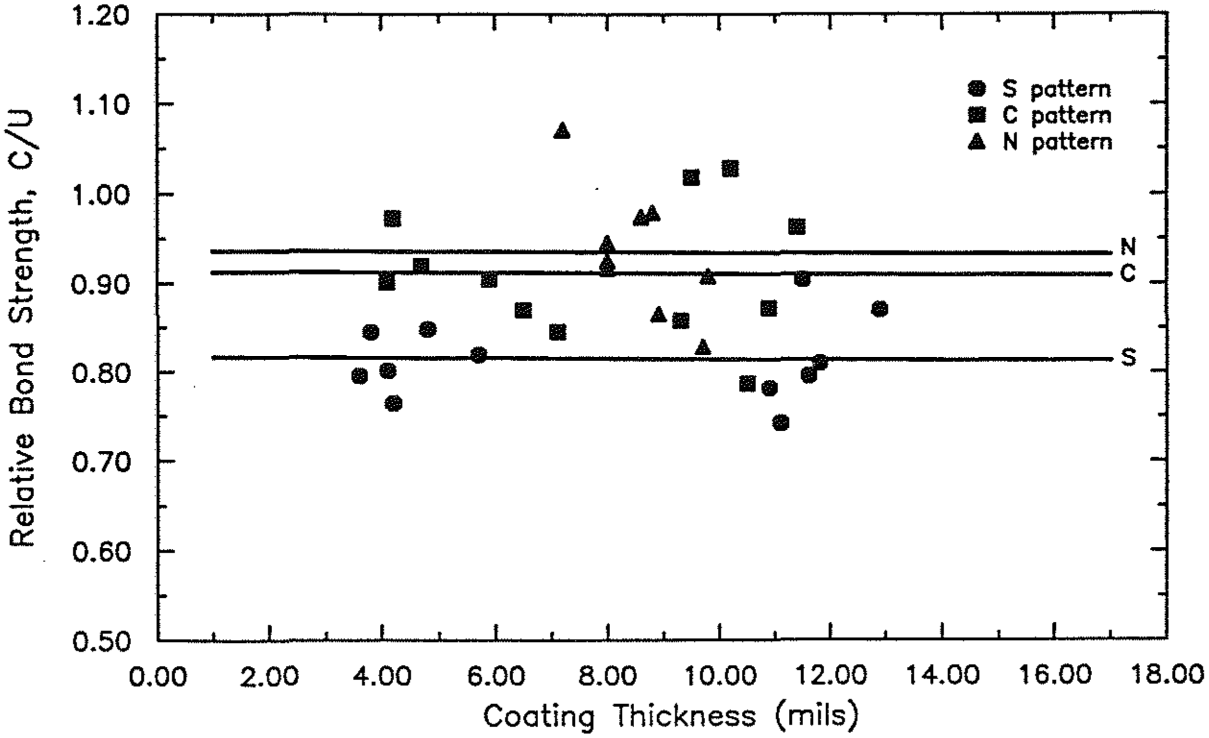


Fig. 12 Relative Bond Strength, C/U, versus Coating Thickness for No. 6 Bars

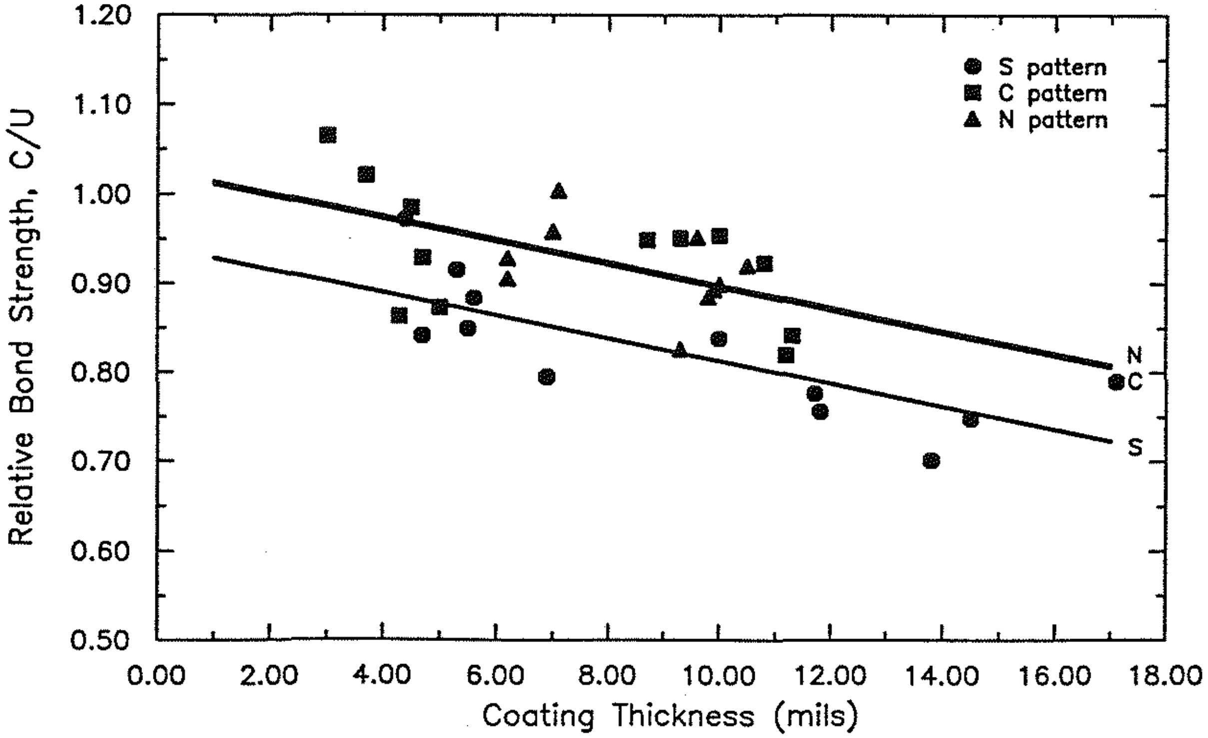


Fig. 13 Relative Bond Strength, C/U, versus Coating Thickness for No. 5 Bars

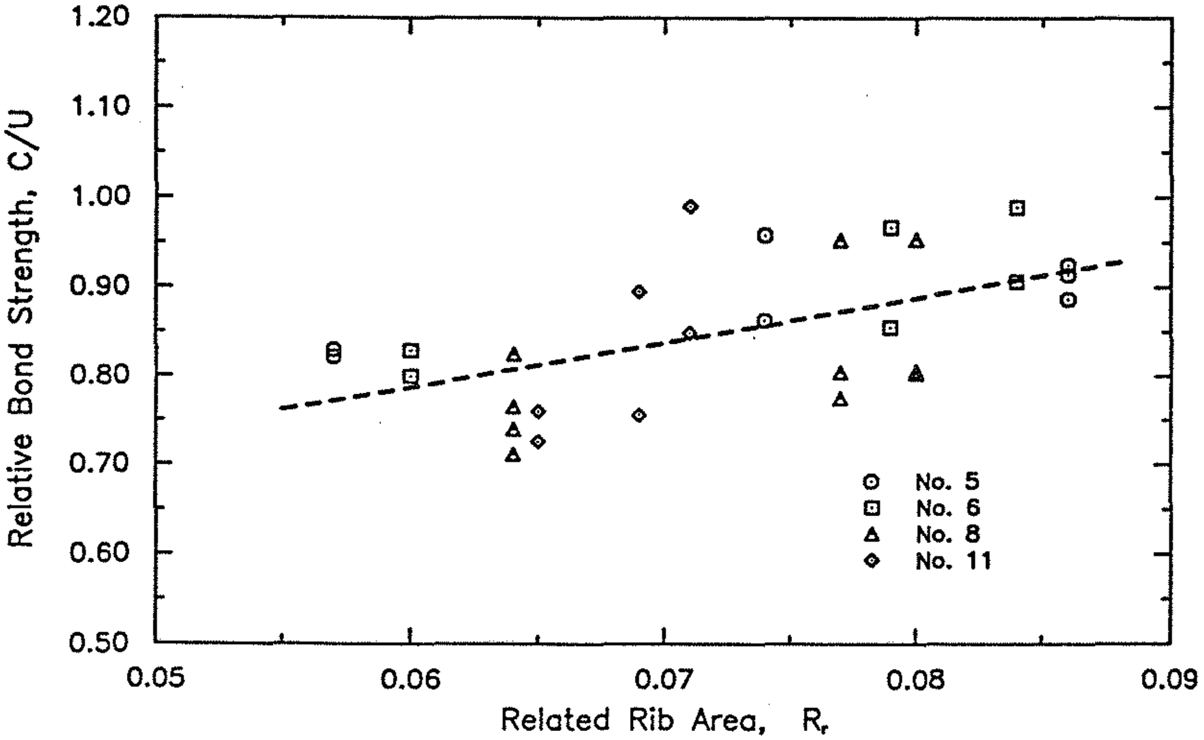


Fig. 14 Relative Bond Strength, C/U, versus Related Rib Area, R_r. C and U based on mean bond strength for coated and uncoated bars for each group.

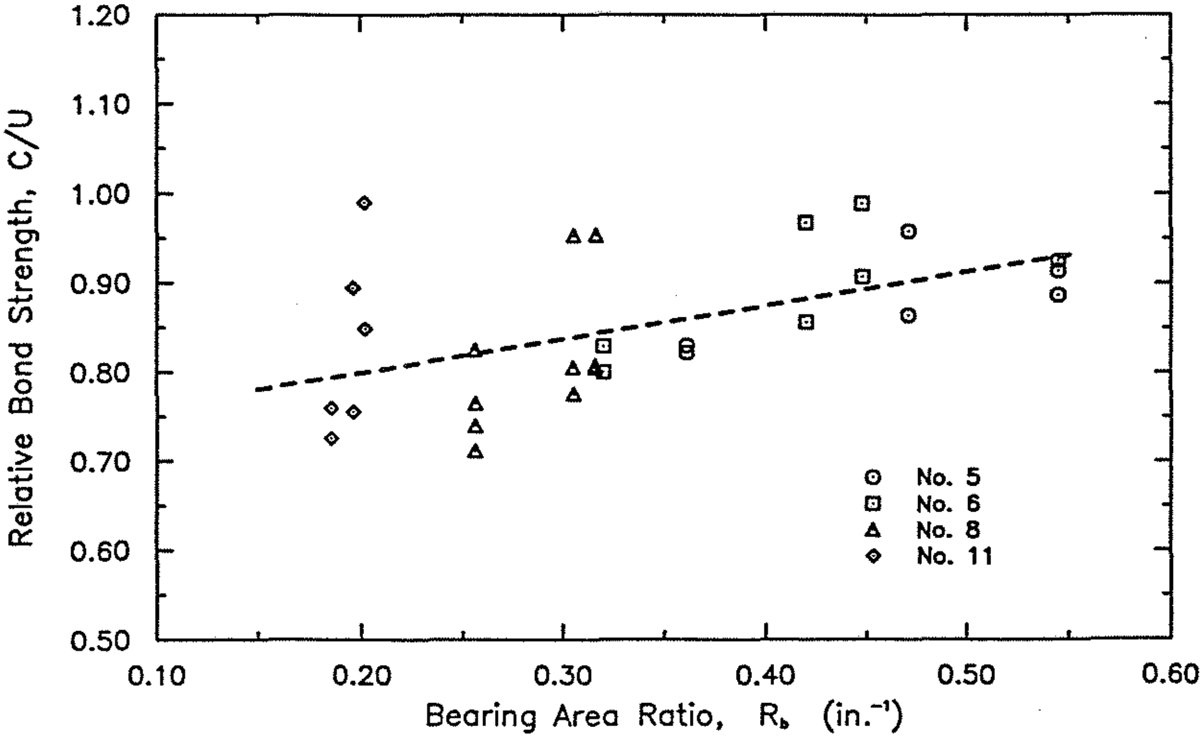


Fig. 15 Relative Bond Strength, C/U, versus Bearing Area Ratio, R_b. C and U based on mean bond strength for coated and uncoated bars for each group.

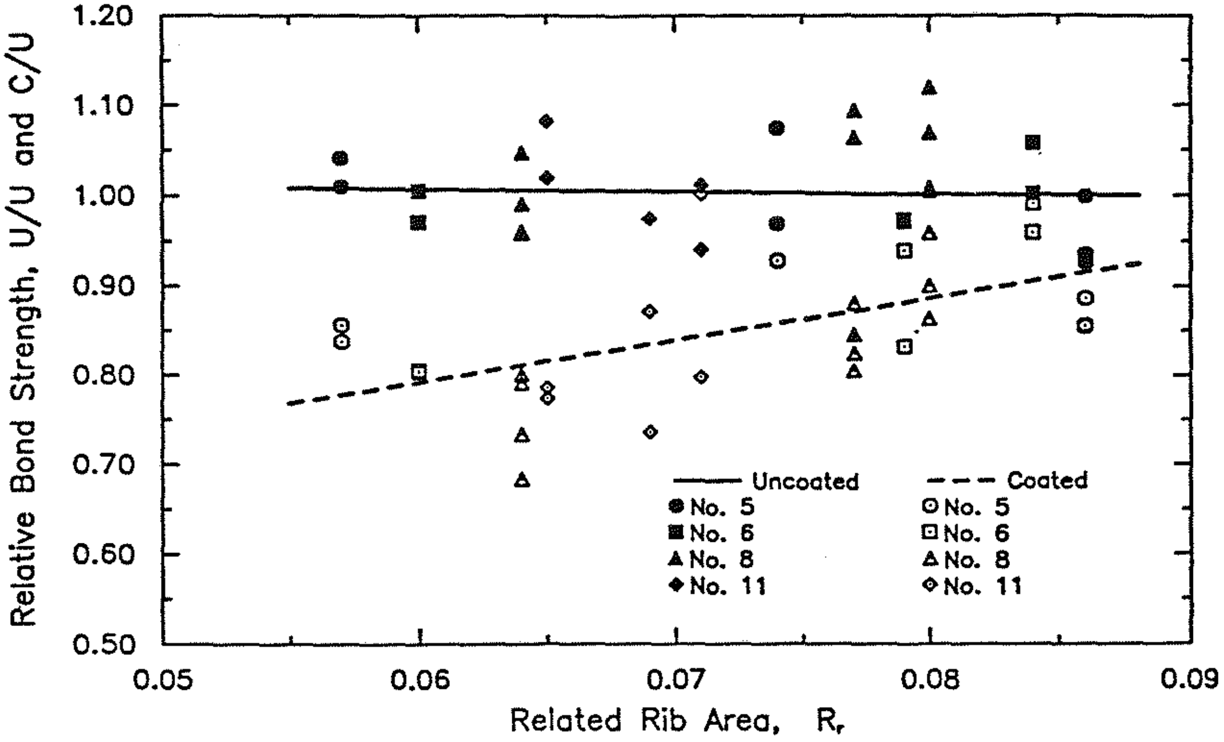


Fig. 16 Relative Bond Strengths, U/U and C/U, versus Related Rib Area, R_r. Numerator of ratio based on mean bond strength for each group. Denominator based on mean bond strength of all bars of the same size.

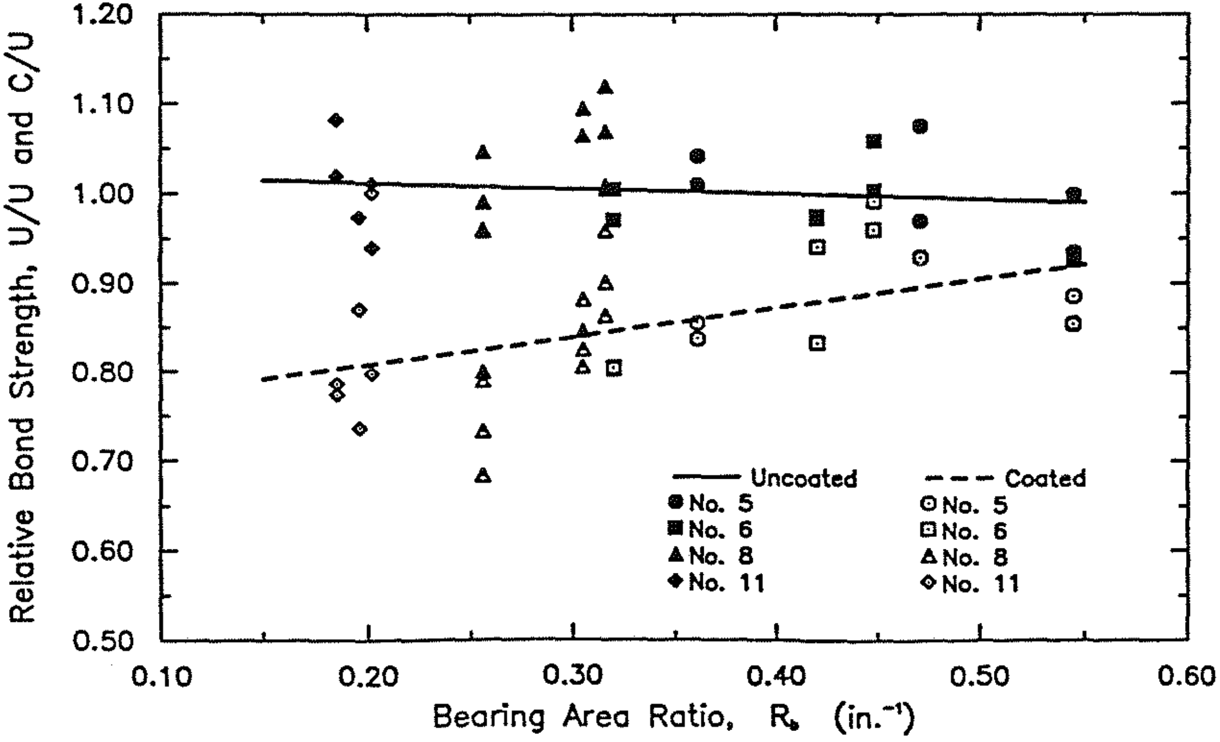


Fig. 17 Relative Bond Strengths, U/U and C/U, versus Bearing Area Ratio, R_b. Numerator of ratio based on mean bond strength for each group. Denominator based on mean bond strength of all bars of the same size.

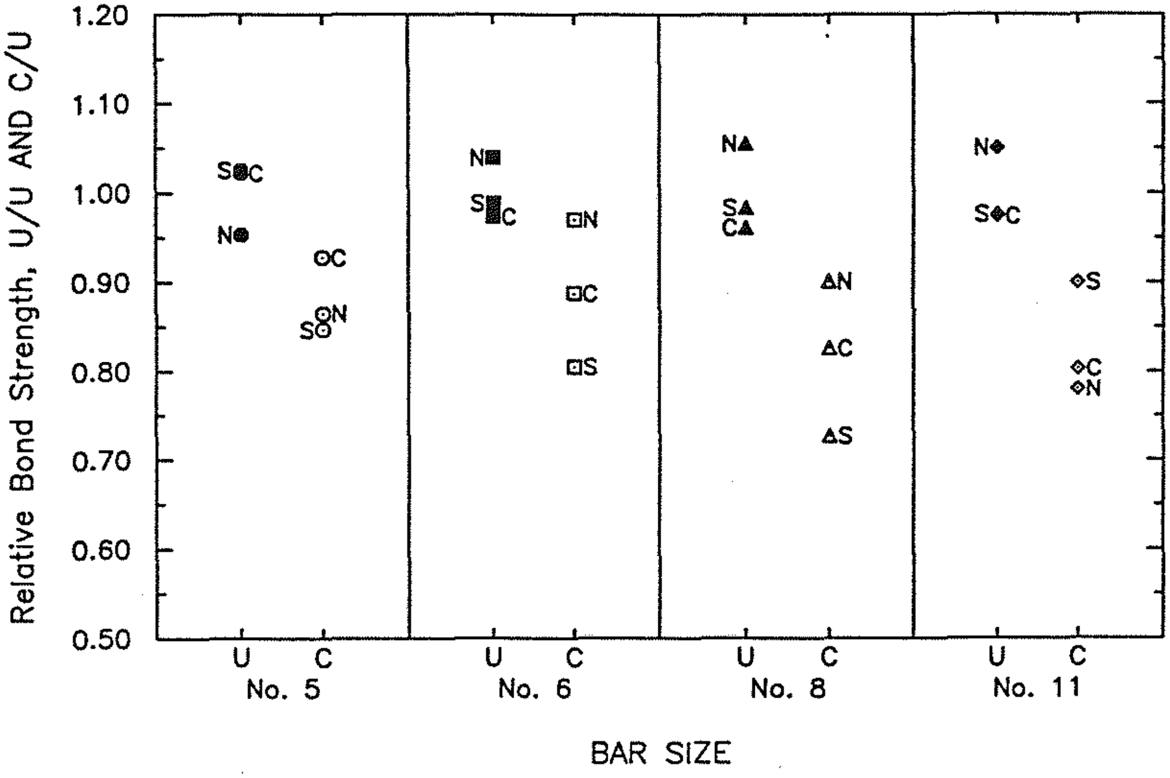


Fig. 18 Relative Bond Strengths, U/U and C/U, versus Bar Size

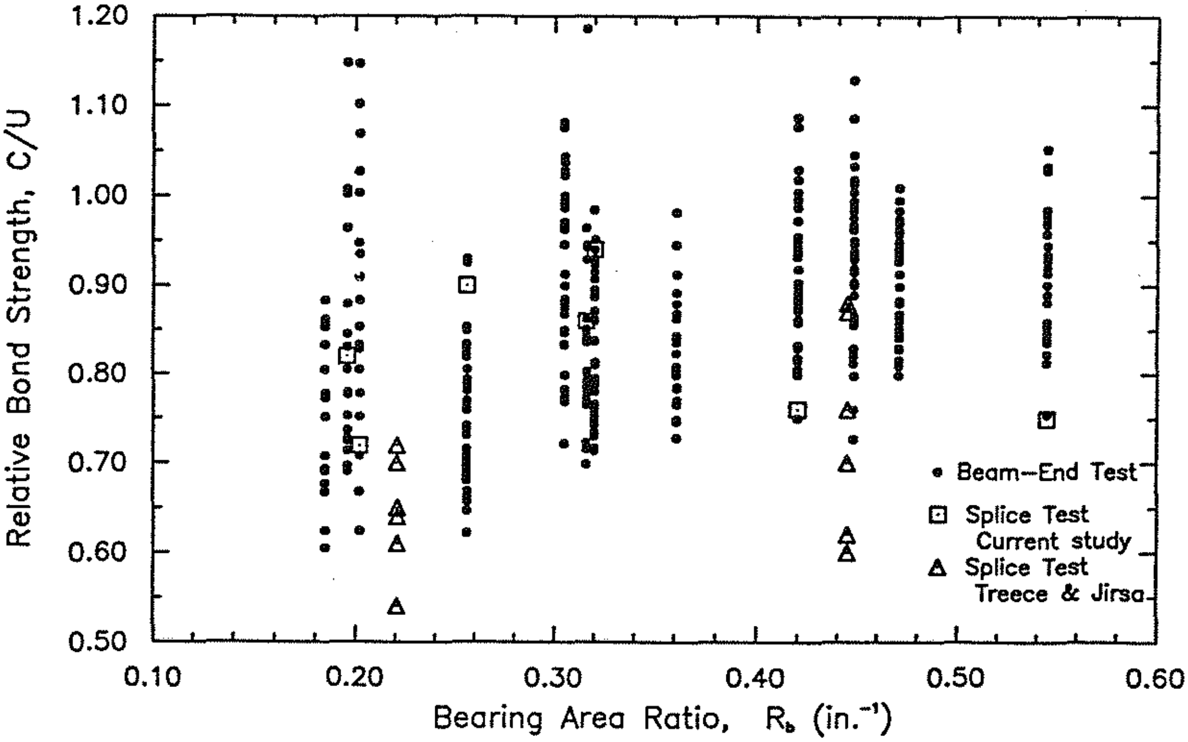


Fig. 19 Relative Bond Strength, C/U versus Bearing Area Ratio, R_b. Beam-end and splice specimens from the current study and splice specimens tested by Treece and Jirsa (1987, 1989).