EFFECT OF DEFORMATION HEIGHT AND SPACING ON BOND STRENGTH OF REINFORCING BARS

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ABSTRACT

The effect of deformation pattern on bond strength is studied using 1 in. diameter machined bars with deformation heights of 0.05, 0.075, and 0.10 in. and deformation spacings ranging from 0.26 in. to 2.2 in. The combinations of rib height and spacing produce relative rib areas (ratio of projected rib area normal to bar axis to product of nominal bar perimeter and center-to-center rib spacing) of 0.20, 0.10, and 0.05 for each deformation height. Conventional reinforcing bars, with a relative rib area of 0.07, are also studied. The effect of deformation pattern is evaluated using beam-end specimens with varying degrees of confinement provided to the test bars. Degrees of confinement are: 1) 2 in. cover without transverse stirrups, 2) 2 in. cover with confining transverse stirrups, and 3) 3 in. cover without confining transverse stirrups. Bars with 2 in. cover have an initial unbonded length of $^1/_2$ in. and a bonded length of 12 in. Bars with 3 in. cover have an initial unbonded length of 4 in. and a bonded length of $8^1/_2$ in.

The bond force-slip response of reinforcing bars is a function of the relative rib area of the bars, independent of the specific combination of rib height and rib spacing. Under all conditions of bar confinement, the initial stiffness of load-slip curves increases with an increase in the relative rib area. Under conditions of relatively low confinement, in which bond strength is governed by splitting of the concrete, bond strength is independent of deformation pattern. Under conditions in which additional bar confinement is provided by transverse reinforcement or higher cover, bond strength increases compared to the bond strength of bars with less confinement. The magnitude of the increase in bond strength increases with an increase in the relative rib area.

INTRODUCTION AND BACKGROUND

There is widely conflicting evidence on the effect of deformation pattern on the bond strength between reinforcing bars and concrete. Some studies indicate that deformation pattern has a strong influence on bond strength. Other studies show that deformation pattern has little influence, and it is not uncommon for bars with different patterns to produce nearly identical development and splice strengths.

The current criteria for reinforcing bar deformation patterns in the United States are based on research carried out more than forty years ago by Arthur P. Clark (1946, 1949) at the National Bureau of Standards (now the National Institute of Standards and Technology) under a fellowship from the American Iron and Steel Institute. Clark evaluated seventeen reinforcing bar patterns. Based on his study, Tentative Specification ASTM A 305-47T was developed and later modified (ASTM A 305-49) to include a maximum average spacing of deformations, or ribs, equal to 70 percent of the nominal diameter of the bar and a minimum height of deformations equal to 4 percent for bars with a nominal diameter of $^1/_2$ in. or smaller, 4.5 percent for bars with a nominal diameter of $^5/_8$ in., and 5 percent for larger bars. These provisions constitute the major deformation requirements in use today (ASTM A 615-90, A 616-90, A 617-90, A 706-90).

Clark's work was based primarily on pullout tests, but included some beam tests. His evaluation of bar performance was based on bond behavior throughout the usable range of bond stress, rather than on bond strength. Clark averaged the bond stresses at loaded end slips of 0.0005, 0.001, 0.002, 0.003, 0.004, 0.005, 0.0075, and 0.01 in. for each bar. He then averaged the values for top and bottom-cast bars to obtain a single representative bond stress for each deformation pattern. His reports (Clark 1946, 1949) do not include the peak stresses obtained in the tests.

At the time Clark made his recommendations on rib spacing and height, he also recommended that the ratio of the shearing area (bar perimeter times distance between ribs) to the rib bearing area (projected rib area normal to the bar axis) be limited to a maximum of 10, and if possible 5 or 6. Today this criterion is usually described in terms of the inverse ratio, that is the ratio of the bearing area to the shearing area, which is known alternately as the "rib area", "related rib area", or "relative rib area" (DIN 1986, Soretz and Holzenbein). Relative rib area, R_r, will be used as the descriptive term in this report.

$$R_r = \frac{\text{projected rib area nomal to bar axis}}{\text{nominal bar perimeter} \times \text{center–to–center rib spacing}} \tag{1}$$

Clark's recommendations then become a minimum relative rib area, R_r, of 0.10, with desirable values of 0.20 or 0.17. It is interesting to note that Clark's rib area recommendations were not included in ASTM A 305-49 and that current deformation patterns in the U.S. (ASTM A 615), Europe (DIN 1986, ISO 1990) and Japan (JIS 1975) do not provide the relatively high bearing areas recommended by Clark. Typical values of R_r for bars manufactured in the U.S. range from 0.057 to 0.084 (Choi et al. 1990). In 1949, the best performing deformation patterns were not used as the industry standard largely because of a desire on the part of the reinforcing bar producers only to remove the weakest patterns, rather than establish the best possible anchorage to concrete (Wildt 1991). In his studies, Clark also observed that the face angle of the rib with respect to the longitudinal surface of the bar had an important effect on slip. The more gradual the inclination of the rib face, the greater the slip for a given force.

Since the time of Clark's efforts, a great deal has been learned about the bond performance of deformed reinforcing bars. It is generally agreed that the bond between reinforcing steel and concrete consists of a chemical adhesion, friction, and mechanical interlock. For regular deformed bars, the effect of the mechanical interaction has long been believed to be the major contributor to bond strength (Menzel 1939, Lutz et al. 1966, Lutz and Gergely 1967).

During the late 1950's and the 1960's, Rehm (1957, 1961) and Lutz et al. (1966, 1967) demonstrated that, as reinforcing steel moves with respect to concrete, one of two failure modes can occur. Either the concrete in front of the ribs gradually crushes, resulting in a "plow-through" or pullout-type failure, or the ribs and/or crushed concrete in front of the ribs acts as a wedge, introducing tensile stresses perpendicular to the bar axis, which result in a splitting type failure of the concrete. Rehm (1957, 1961) found that if the ratio of rib spacing to rib height is less than 7 and if the rib face angle (or rib flank inclination, as it is called in Europe) is greater than 40°, then the concrete in front of the ribs undergoes gradual crushing, followed by a pullout failure. If the ribs have a spacing to height ratio greater than 10, for a rib face angle greater than 40°, the concrete in front of the ribs first crushes and then forms wedges that induce tensile stresses that, in turn, cause transverse cracking and longitudinal splitting of the concrete. In general, the higher the confinement, the more likely a pullout failure. However, in most structural applications, a splitting failure is more common (Clark 1949, Menzel 1952, Chinn et al. 1955, Ferguson and Thompson 1962, Losberg and Olsson 1979, Soretz and Holzenbein 1979, Johnston and Zia 1982, Treece and Jirsa 1989, and Choi et al. 1991, to list but a few).

Slip of a reinforcing bar with respect to the concrete has the effect of crushing the concrete in front of the ribs, producing a rib with an effective angle of 30 to 40° (Lutz and Gergely 1967), which, rather than the steel itself, acts as the wedge. Lutz et al. (1966, 1967) showed that a rib-face angle below 30° considerably softens the load-slip relationship. Work by Skorobogatov and Edwards (1979) on bars with face angles of 48.5° and 57.8° supports these observations. Skorobogatov and Edwards concluded that, in the range tested, the face angle does not affect bond strength since the high rib face angle is flattened by the crushed concrete wedge which reduces the effective face angle to a smaller value.

Losberg and Olsson (1979), in a study of three deformation patterns commonly used in Sweden, came to the conclusion that traditional pullout tests, of the type used by Clark, are not useful for predicting the response of reinforcing bars in actual structures, because the state of stress around the bars in pullout specimens is considerably different from the state of stress in actual structures, largely due to the additional confinement provided in pullout tests. Losberg and Olsson found that the three deformation patterns produced considerably different bond strengths when they were evaluated using a pullout test. However, in tests where splitting governed, they found little difference for the three patterns, with the possible exception that bars with ribs that were oriented obliquely to the longitudinal axis caused greater splitting and thus provided a slightly lower strength than bars with ribs at a right angle to the bar. They also tested some specially machined bars, with different deformation spacings, and found that splitting strength was not sensitive to rib spacing. Their tests indicated that bond capacity actually decreased once ribs became closer than about two-thirds of the bar diameter.

Soretz and Holzenbein (1979) studied a number of bar parameters, including the height and spacing of ribs, the inclination of the ribs with respect to the bar axis, and the cross-sectional shape of the ribs along the longitudinal direction of the bar.

In one portion of their study, keeping the rib-bearing area per unit length constant while changing the spacing and height of the ribs, they found little difference in behavior, up to a slip of 1 mm. However, for slips greater than 1 mm, the bar with the lowest rib height exhibited 20 percent lower strength than the other two patterns tested. They also observed that the bar with the highest ribs caused more splitting. They concluded, somewhat in opposition to the observations of Losberg and Olsson (1979), that the optimum geometry would be rib spacings of 0.3 bar diameter and rib heights of 0.03 bar diameter to give the best combination of increased bond strength and limited splitting. In tests of the effect of rib inclination on bond strength, Soretz and Holzenbein observed that the more perpendicular the rib to the longitudinal axis, the higher the bond strength. However, they found rib inclination to be a relatively small factor compared to rib bearing area. In studying the effect of rib face angle, they observed that ribs with a lower face angle exhibit more slip, but provide the same strength as bars with equal rib heights and steeper rib-face angles. They concluded that requirements for a minimum rib face inclination are not needed. Soretz and Holzenbein also studied the fabrication performance of bars using rebend tests and observed that the lower the rib height and the closer the inclination of the ribs to being parallel with the longitudinal axis of the bar, the better the performance (the lower the frequency of failure) in the rebend tests.

A recent study by Kimura and Jirsa (1992) using pullout specimens supports many of the earlier observations, including an increase in bond strength with increasing relative rib area.

The work by Clark (1946, 1949), Losberg and Olsson (1979), and Soretz and Holzenbein (1979), and Kimura and Jirsa (1992) indicates that, at least under some conditions, an increase in relative rib area will increase bond strength. However, under other conditions it will have no effect (Losberg and Olsson 1979). Ribs that are more perpendicular to the longitudinal axis provide the highest bond strength, but the effect of rib inclination is relatively minor. Work by Rehm (1957, 1961), Lutz et al. (1966, 1967) and Soretz and Holzenbein (1979) indicates that increasing the rib face angle above about 40° will not improve bond strength. Other than these observations, there is little agreement on precise criteria for rib spacing and height.

In addition to research specifically addressed to the effect of deformation pattern, statistical studies covering a wide range of splice and development data have shown that bond strength increases with increasing cover, bar spacing, and confinement provided by transverse reinforcement (Orangun et al. 1975, 1979, Darwin et al. 1992a, 1992b). For members without transverse reinforcement, the relationship observed between bond strength and development/splice length, cover, bar spacing, and bar size shows relatively little scatter (Darwin et al. 1992a, 1992b) and appears to be independent of deformation pattern. In contrast, the relationship for members with transverse reinforcement exhibits large scatter (Orangun et al. 1975, 1979). That large scatter may be due to the need for a better characterization of bond strength, which may need to include the effect of the deformation pattern, a parameter that has not yet been incorporated in the statistical analyses.

The work described in this report represents the first major experimental effort in a large-scale study to improve the development characteristics of reinforcing bars. It is the purpose of this study to specifically determine the effect of rib height, spacing, and relative rib area on bond strength, including the conditions under which changes in deformation pattern play a role. The results of this study are being used as guidance for the design of a new series of reinforcing bar patterns that are being placed in production as part of the overall research program.

This study also includes the modification of previous test specimen designs and test methods (Brettmann et al. 1986, Choi et al. 1991) to provide a more realistic measure of bond performance.

EXPERIMENTAL PROGRAM

The experimental program consists of 156 test specimens. The first portions of the test series were used to modify the configuration of the test specimen and test setup. The modifications were made in accordance with the results of an unpublished finite element study (Niwa 1991) that indicated that the stress fields adjacent to the reinforcing bars would be closer to those obtained in flexural members if the compressive reaction on the front of the specimen were moved further away from the reinforcing bar than in previous tests (Brettmann et al. 1984, 1986, Choi et al. 1990, 1991). As will be described, modification of the test configuration also required, the addition of shear reinforcement to the test specimen. While these changes in test configuration are described, the report emphasizes the effect of deformation pattern on bond strength.

The principal parameters in this study are rib height, rib spacing, relative rib area and degree of confinement provided by concrete and transverse reinforcing steel. The study was carried out using specially machined reinforcing bars along with bars with standard deformation patterns for comparison.

Test Specimens

The beam-end test specimens illustrated in Figs. 1a and b were used for most of the tests. The specimen contains a 1 in. nominal diameter bottom-cast test bar with a 2 in. cover and 15 in. of concrete above the bar. The specimen contains four closed stirrups to provide shear strength. The stirrups are oriented parallel, rather than perpendicular, to the sides of the test specimen to limit their effect on a splitting bond failure. The test specimen also contains two No. 6 bars, with $1\,^1/_2$ in. bottom and side cover, to serve as flexural reinforcement. The overall dimensions are 9 x 18 x 24 in. The specimen contains three transverse No. 5 bars that are used to aid in fabrication and testing. The specimen configuration is altered for Group 9 which is used to evaluate the effect of additional concrete confinement. This is obtained by raising the test bar and the No. 6 bar flexural reinforcement by 1 in.

As shown in Fig. 1b, some test specimens include four additional No. 3 bar stirrups to determine the effects of confinement provided by transverse reinforcement.

Test bars extended 22 in. out from the face of the specimens. Two polyvinyl chloride (PVC) pipes were used as bond breakers to control the bonded length of the bar and to avoid a localized cone-type failure of the concrete at the loaded end of the specimen. Bonded lengths of 8, $8^1/_2$, 10, 12, and $13^1/_2$ in. were used in different test groups. Lengths of bond breaking PVC pipe in front of the bars (lead lengths) of 0.5 and 4 in. were used in various tests.

During the middle portion of the study, concern was raised about the fact that the ultimate bond forces obtained using the test specimen were limited by the bond strength of the No. 6 bars. In Groups 7 and 8, the straight No. 6 bars were replaced by hooked No. 6 bars. The hooked bars had a $1^1/_2$ in. cover, with the tails of the hooks terminating $1^1/_2$ in. from the upper surface of the test specimen. The addition of the hooks was found to increase the bond strength of some bars but not to materially affect the maximum capacity that could be obtained from the test specimen. Straight No. 6 bars were used as auxiliary flexural reinforcement in the balance of the tests.

The first two test groups were exploratory in nature. They were tested in a different manner from the later groups and did not contain side stirrups.

Materials

Reinforcing steel.–The principal test bars were fabricated from 110 ksi yield strength ASTM A 311 (1990) cold-rolled steel. The minimum diameter of all bars was 1.0 in. Three test specimens each of 9 different deformation patterns were fabricated. As illustrated in Fig. 2a, three rib heights, 0.05 in., 0.075 in., and 0.10 in., were used with spacings ranging from 0.263 in. to 2.20 in. to produce relative rib areas, R_r (Eq. 1), of 0.20, 0.10, and 0.05. The patterns were selected to produce all three values of relative rib area for each deformation height. The bars with 0.05 in. ribs were machined from $1^1/_8$ in. diameter bars. The other bars were machined from $1^1/_4$ in. diameter bars.

A 60° face angle was used on the machined bars. The rib width for each test bar is shown in Fig. 2a.

In addition to the machined bars, ASTM A 615 (1990) Grade 60 No. 8 bars were evaluated to compare the prototype test bars to standard reinforcement. Two patterns, designated S and N, were evaluated. Deformation pattern S, $R_r = 0.070$, consisted of ribs perpendicular to the axis of the bar. Deformation pattern N, $R_r = 0.078$, consisted of diagonal ribs inclined at 70° with respect to the axis of the bar. The S-pattern bars, shown in Fig. 2b, were used for most comparisons. No. 3 bars, with ribs perpendicular to the axis of the bar, were used as stirrups. Reinforcing bar properties are summarized in Table 1.

Concrete.–Air-entrained concrete was supplied by a local ready mix plant. Portland cement, 3/4 in. nominal maximum size crushed limestone, and Kansas river sand were used. A water-cement ratio of 0.41 was used to produce strengths of 4,500 to 6,000 psi at the time of test for Groups 3-9. Mix proportions and concrete properties are given in Tables 2a and 2b.

Placement Procedure

Forms were fabricated using plywood, 2 x 4 in. studs, and all-thread rods. Joints in the forms were sealed with flexible caulk to prevent leakage. Joints between the reinforcing bar, PVC pipe, steel conduit, and formwork were sealed with modeling clay.

The 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 was vibrated at six evenly spaced points. To minimize the effects of differences in concrete properties within a batch on test results, test specimens with similar test parameters were placed at different points during the fabrication of each group.

Most test groups were placed at one time. However, Groups 6 and 9 were placed on three and two different days, respectively, to reduce logistical problems.

To ascertain what effect, if any, the location of the test bars within the bonded length had on bond strength, three configurations were evaluated in Groups 5 and 6. For configuration A, a constant distance of $^{1}/_{4}$ in. was used between the face of the first rib within the bonded length and the adjacent bond-breaking PVC pipe. For configuration B, a constant distance of $^{1}/_{4}$ inch was maintained between the bearing face of the last rib within the bonded length and the adjacent PVC pipe. For configuration C, an equal distance was provided between the bearing face of the first rib and the adjacent PVC pipe and the bearing face of the last rib and the adjacent PVC pipe. Each configuration was used for one-third of the test bars in Groups 5 and 6. The results show that the positioning of the bars did not affect bond strength.

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 the strength of at least 3,000 psi.

Test Procedure

The tests were carried out at concrete strengths of 4,500 to 6,000 psi. The specimens were tested using an apparatus developed by Donahey and Darwin (1983, 1985) and modified by Brettmann et al. (1984, 1986). Further modifications were carried out to increase the distance between the test bar and the compressive reaction plate (Fig. 3). In previous studies (Brettmann et al. 1986, Choi et al. 1990, 1991, Hadje-Ghaffari et al. 1991, 1992), the 4 in. high reaction plate providing the compressive force on the front of the test specimen was centered 7 in. below the center of the test bar. Groups 1 and 2 were tested using this configuration. For Groups 3-8, the reaction plate was positioned to bear on the bottom 3$^{1}/_{2}$ in. of the test specimen, as illustrated in Fig. 3. This arrangement provided a lever arm of approximately 13$^{3}/_{4}$ in. between the centroid of the compressive force and the test bar. For Group 9, the bearing plate was positioned to bear on the bottom 2$^{1}/_{2}$ in. of the test specimen providing a lever arm of approximately 13$^{1}/_{4}$ in.

As shown in Fig. 3, the specimens were tied to the structural floor by two wide flange sections and four tie-down rods. Load was applied at a rate of about 6 kips per minute by two 60-ton hollow-core hydraulic jacks powered by an Amsler hydraulic testing machine, through two 1 in. diameter load rods instrumented as load cells. The hydraulic jacks exerted a pulling force on two yokes through a wedge-grip assembly. The tensile force in the bar was counteracted by the reaction plate.

Bar slip was measured using spring-loaded linear variable differential transformers (LVDTs). Two LVDTs were attached to the test bar with an aluminum yoke, 4 in. from the concrete surface, to measure loaded end slip. A single LVDT was placed in contact with the back end of the test bar through the steel conduit to measure unloaded end slip.

The specimens were tested 7 to 19 days after casting. For specimens cast and/or tested on different days, separate sets of at least 3 test cylinders were used to measure the concrete strength. Following the tests, the test bars were removed for reuse.

RESULTS, OBSERVATIONS, AND EVALUATION

Groups 1-4 were used to modify the test setup and to select the test configurations. Therefore, major emphasis is placed upon results obtained from the 110 specimens evaluated in Groups 5-9. The specimens in Groups 5, 8 and 9 (cover = 2, 2, and 3 in., respectively) contained bars that were not confined by transverse reinforcement. The specimens in Groups 6 and 7 (cover = 2 in.) contained bars that were confined by transverse stirrups. Lead lengths of 0.5 and 4.0 in. were used in Groups 5-8 and Group 9, respectively. Straight auxiliary No. 6 flexural reinforcement was used in Groups 5, 6 and 9. Hooked auxiliary reinforcement was used in Groups 7 and 8.

The test results described in the following sections show that the relative rib area has a dominant effect on the load-slip response of all bars, independent of rib height. An increase in relative rib area results in an increase in the stiffness of the initial portion of the load-slip curve, matching the observations of Clark (1946, 1949). The test results also show that the effect of relative rib area on bond strength depends on the degree of confinement provided to the reinforcing bar. For bars not confined by transverse reinforcement or high concrete cover, differences in relative rib area have little effect on bond strength. However, the addition of transverse reinforcement or an increase in the confinement provided by the concrete results in a significant increase in bond strength with increasing relative rib area. The details of specimen behavior follow.

Test variables and bond strengths are listed in Table 3.

Cracking Patterns

A splitting failure was observed in all tests. The nature of the failure was brittle or ductile, depending on the absence or presence of transverse stirrups. As illustrated in Fig. 3, the specimens were tested in an inverted position. The discussion that follows refers to the specimen as oriented for the test, with the test bar at the top of the specimen.

Specimens without transverse stirrups.–For bars with 2 in. cover, failure was preceded by the initiation of a crack above the test bar, running parallel to the bar, vertically through the cover along the top surface of the specimens (Figs. 4-6). As described below, additional cracking occurred during the test. However, the crack above the test bar was the widest at the completion of the test. For bars with 3 in. cover, a major horizontal crack formed prior to failure (Fig. 7). The crack intercepted the test bar and the two auxiliary No. 6 bars.

Three patterns were observed for specimens with 2 in. cover (Groups 5 and 8):

1. As illustrated in Fig. 4, in addition to the main crack, two cracks were visible on the front face of the specimen, running down and out from underneath the test bar to the midsection of the specimen, forming an inverted V with an enclosed angle of 100-120°. Together with the main crack above the specimen, the three cracks formed an inverted Y.
2. As illustrated in Fig. 5, two horizontal cracks propagated from either side of the test bar to the edge of the specimen. Together with the main crack, these cracks formed an inverted T.
3. As illustrated in Fig. 6, the initial vertical crack ran from the top of the test specimen through the test bar to the midsection of the test specimen before branching out into two diagonal arms, again forming an inverted Y.

On the top of specimens with 2 in cover, the main crack continued towards the back end of the bonded length. The crack then branched out into two arms, propagating towards the sides of the specimen, with an enclosed angle between the two branches of 120 to 180°. In addition to these "major" cracks, smaller transverse cracks were observed on most specimens. Minimal cracking was observed on the sides of the specimens with straight auxiliary reinforcement (Group 5). For the specimens with the hooked auxiliary bars (Group 8), the cracks on the front surface joined with cracks on the sides. The side cracks inclined towards the vertical and joined with transverse cracks on the top of the specimen. These transverse cracks were located about 2 in. from the front surface.

For specimens with 3 in. cover (Group 9) there was, in most cases, no vertical crack through the cover. The crack on the loaded face of the specimen started from the test bar and ran, approximately horizontally, through the auxiliary bars to the sides of the specimen (Fig. 7). These cracks continued horizontally on the sides and toward the rear of the specimen, finally inclining toward the top surface. A transverse crack across the mid-section of the top surface connected the two side cracks, forming a wedge of concrete above the test bar. In some cases, this wedge of concrete completely separated from the rest of the specimen at failure. In addition to the main cracks, some minor cracks were observed on the top surface, usually starting from the main transverse crack, running longitudinally toward the back of the specimen, and branching out into a V. Other minor diagonal cracks formed on the sides of the specimen, starting close to the position of the compressive bearing plate. The diagonal cracks were more noticeable during the latter stages of the loading process than after failure.

Specimens with transverse stirrups.–Cracking patterns for specimens with transverse stirrups (Groups 6 and 7) were similar to those observed for specimens with 2 in. cover, without transverse stirrups (Groups 5 and 8). However, specimens with transverse stirrups exhibited more extensive transverse cracking on the top surface of the specimen (Fig. 8). In addition, the front face of the specimens exhibited more transverse cracking than most specimens without transverse stirrups, largely due to the fact that the front faces of concrete tended to pull out of the specimen at the time of failure. These specimens exhibited higher bond strengths and more ductile behavior at peak loads than the specimens without transverse stirrups. However, in contrast to the specimens without stirrups, which failed rather quietly, these specimens failed with a bang, which was often accompanied by pieces of concrete that separated from the specimen in an explosive manner.

Most failures involved the formation of two steep diagonal cracks on the sides of the specimens. These cracks joined the bottom portion of the inverted Y-shaped cracks on the front face of the specimen and transverse cracks on the top surface of the specimen within about 5 in. of the loaded face.

Crushing of Concrete around Test Bar Ribs

The following observations were made upon removal of concrete after completion of the tests. These observations pertain only to test specimens without transverse stirrups. The process of removing the test bars from specimens with transverse stirrups involved destruction of the concrete and prevented clear observations from being made.

Concrete surrounding the loaded side of the ribs was crushed as the bar slipped under load. For specimens with ribs spacings up to $^1/_2$ in., practically all of the concrete between the ribs was crushed. For specimens with rib spacings greater than $^1/_2$ in., the extent of the crushing varied from $^1/_4$ in. to $^1/_2$ in. in front of the loaded face of the ribs.

As the bars were removed from the concrete, some concrete powder could be found lodged against the loaded face of some of the ribs. Concrete also was observed to form a small truncated cone between the first rib and the bond breaker PVC pipe. The diameter of the cone increased from the diameter of the rib to the outside diameter of the PVC pipe. For the concrete crushed in front of the ribs, the angle between the surface of the concrete powder and the bar shaft ranged between 17° and 40°. The lower angles were observed on the 0.05 in. ribs, while the higher angles were observed for the 0.075 and 0.10 in. ribs.

There was evidence of bonding between the test bars and the concrete, as indicated by the presence of concrete particles on the bar shaft.

Load-Slip Response

Load-slip curves for the specimens in Groups 5-9 are presented in Figs. 9-32. Where more than one specimen has the same combination test parameters, average curves are presented.

As shown in Figs. 9-24, the initial portions of the load-slip curves are not sensitive to the presence of transverse stirrups. As would be expected, the load versus loaded end slip curves exhibit lower initial stiffness than the load-unloaded end slip curves. With increased slip, this observation is also true for specimens with 2 in. cover and straight auxiliary reinforcement, without transverse reinforcement (Group 5). However, for specimens with transverse reinforcement, hooked reinforcement, or 3 in. cover, the load-loaded end slip curves appear to be stiffer at loads above about 30 kips. This apparent stiffening is due to the fact that portions of the front face of the concrete in these specimens tend to move forward as the specimen begins to crack. Thus, the loaded end slip, which is actually measured with respect to the front concrete surface, appears to be less than the unloaded end slip, which is measured with respect to the unloaded end of the concrete. The effect of this behavior is especially clear in the load-loaded end slip curves for Group 7 (Figs. 17-19) which are highly erratic due to separation of concrete on the front face of the specimen.

For bars with 2 in. cover and without transverse reinforcement (Groups 5 and 8), the load versus loaded and unloaded end slip curves (Figs. 9-24) generally rise steeply and then flatten out as the peak load is attained. This description also applies to the load-loaded end slip curves for the specimens with transverse reinforcement (Groups 6 and 7) (Figs. 9-12, 17-20) and the specimens with 3 in. cover without transverse reinforcement (Group 9) (Fig. 25-28). This description does not apply, however, to the load-unloaded end slip curves for Groups 6, 7, and 9 (Figs. 13-16, 21-24, 29-32). For these three groups, the load-unloaded end slip curves initially rise steeply, reach a plateau at a load of 30 to 40 kips and begin to rise again only after significant additional slip, until the peak load is attained. The large increase in slip observed for these specimens may occur in conjunction with the separation of portions of concrete on the front or top surfaces of the test specimens, lowering the effective bond stiffness and allowing the additional bar movement. The separation of the concrete, however, does not represent the maximum capacity of the specimen. The load at which the high increase in unloaded end slip occurs for these specimens approximates the maximum capacity of the test specimens.

A comparison of load-slip response based on relative rib area shows that, for all test groups, the higher R_r, the higher the initial stiffness of the load-slip curve. For similar degrees of confinement, the initial stiffness appears to depend on R_r, independent of rib height. The two higher relative rib areas, in general, produced similar curves, with the 0.20 relative rib area bars producing slightly stiffer curves than those with $R_r = 0.10$. Bars with $R_r = 0.05$ showed significantly more slip than those with the higher relative rib areas. The conventional reinforcing bars, with $R_r = 0.07$, showed greater initial loaded end slips than even the prototype bars with $R_r = 0.05$, but unloaded end slips between those obtained for $R_r = 0.05$ and 0.10. The high stiffness and low slip obtained with higher values of R_r may prove useful in reducing the rate of degradation of reinforced concrete members subjected to severe cyclic loading.

Bond Strength

The bond strengths obtained for test specimens in Groups 5 and 6, 7 and 8, and 9 are presented in Figs. 33, 34, and 35, respectively. Each data point in Fig. 33 represents the average of three test results. The data points in Fig. 34 represent individual test results, and the data points illustrated in Fig. 35 represent one or the average of two or three test specimens. Specific results are presented in Table 3.

Since concrete strengths range from 4,500 to 6,000 psi, the test results are modified to allow individual tests to be compared on an equitable basis. Modified bond strengths are obtained by normalizing the test results with respect to a nominal concrete strength of 5,000 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 $(5000/f'_c)^{1/2}$.

As illustrated in Figs. 33 and 34, the significant difference in load-slip behavior obtained as a function of relative rib area, R_r, does not always translate into higher strength. For specimens without transverse reinforcement, bond strengths are independent of deformation pattern, although most of the prototype bars exhibit higher strengths than the conventional reinforcing bars, marked RV and RH. In these cases, the bars were subject to low confining stresses and appear to have acted as wedges, causing the concrete to split at the time of failure. These results suggest that there is apparently little difference in the wedging effect, as a function of rib height and spacing, based on strength. The lower strength obtained by the conventional bars may be tied to the lower face angle of the ribs, which may cause these bars to act as somewhat more efficient wedges than the machined bars. It can also be observed that the conventional bars with the longitudinal ribs oriented in the vertical position (RV) consistently provide higher bond strengths than the conventional bars with the longitudinal ribs oriented in a horizontal position (RH). This may be due to the fact that the specimens fail principally by vertical cracking and the vertical orientation of the longitudinal ribs brings more of the surface area of the transverse ribs to bear on the concrete at the time of failure.

In contrast to the bars without transverse reinforcement, the bars with transverse reinforcement (Groups 6 and 7) exhibit a significant effect of deformation pattern on bond strength. In all cases, bond strength increases significantly with the addition of transverse reinforcement; however, that increase is generally greater, the greater the relative rib area. For the tests illustrated in Fig. 33, the bars with the lowest value of R_r (0.05) exhibit a 25 percent increase in bond strength due to confinement. As relative rib area increases, the additional bond strength provided by the confinement increases up to 50 percent for $R_r = 0.20$. With the exception of the bars with $R_r = 0.05$ and rib height = 0.10 (rib spacing = 2.20 in.) shown in Fig. 33, relative rib area appears to be the primary controlling factor in the added bond strength, i.e., relative rib area rather than rib height and/or rib spacing appears to be the factor controlling the increase in bond capacity. The added strength obtained for the conventional reinforcement ($R_r = 0.07$) is below that obtained for most of the machined bars with $R_r = 0.05$.

In evaluating the test results for Group 6 (Fig. 33), the observation was made that, for most bars with $R_r = 0.20$, the strength appeared to be controlled by splitting around the auxiliary

No. 6 bars used as tensile reinforcement. For this reason, it is not clear that the maximum strength obtained in the tests with the highest relative rib areas are indicative of what could be obtained. To improve the ability of the specimen to handle test bars with higher bond forces, new sets of specimens were fabricated in which the straight auxiliary bars shown in Figs. 1a and 1b were replaced by hooked bars. The results for these specimens both with (Group 7) and without (Group 8) transverse reinforcement, are illustrated in Fig. 34. The results show that the capacity of all bars was increased by the change in specimen configuration. However, the use of the hooked bars did not greatly alter the maximum capacity of the test specimen. The modification resulted in a 3 kip increase in bond strength for bars without transverse reinforcement and a similar increase in bond strength for bars with transverse reinforcement, up to a maximum of 45 to 48 kips. For bars with transverse reinforcement, the added bond strength appears, in all cases, to be a function of relative rib area. However, the bond strength leveled off for bars with transverse reinforcement and relative rib areas greater than 0.10. This leveling off appears to be due primarily to the test specimen rather than the deformation geometry. As a result, the tests in Group 9 returned to the original reinforcement configuration.

To evaluate the effects of additional concrete confinement, the specimen configuration shown in Fig. 1a was modified by raising the position of the test bar and the auxiliary reinforcement by 1 in. and increasing the lead length to 4 in., while reducing the bonded length to $8^1/_2$ in. (total embedment remained at $12^1/_2$ in.) to limit the total bond force. The results (Fig. 35) illustrate that there is a strong relationship between bond strength and relative rib area if there is added confinement provided by the concrete. The results illustrated in Fig. 35 represent all but two of the test specimens in Group 9. Two specimens, M32-8.5-4C and M33-8.5-4C, are excluded because they had unusually low strengths, 12 and 6 kips, respectively, below other bars with the same test parameters. For completeness, the average results including these bars are shown in Fig. 36.

A comparison of either Fig. 35 or Fig. 36 with the results for Groups 5 and 8 in Figs. 33 and 34 shows that added concrete confinement significantly increases bond strength and that the higher the relative rib area, the greater the increase. For the results illustrated in Fig. 35, the average bond strengths increase by 40, 49, and 58 percent for R_r = 0.05, 0.10, and 0.20, respectively, compared to the specimens in Group 5 (Fig. 33). As observed for the test results shown in Figs. 33 and 34, the bond strengths obtained by the conventional reinforcement are below those obtained by the machined bars, increasing by an average of just 31 percent, compared to similar bars tested in Group 5. In this case, the bond strength obtained by the conventional reinforcement appears to be unaffected by the orientation of the longitudinal ribs, perhaps because the principal failure crack was horizontal.

Overall, comparisons between Figs. 33 and 35 suggest that increasing R_r for bars in practice will result in even greater improvements in bond strength with added cover and bar spacing than can be obtained currently.

DISCUSSION

The results obtained in this study explain many earlier observations. The most important observations in the current study involve 1) the conditions under which deformation pattern plays a role in bond strength and 2) the effect of the relative rib area, R_r, on bond force-slip relationships and bond strength.

Within the range of the deformation parameters evaluated in this study, deformation pattern has virtually no effect on bond strength when a splitting failure of the concrete governs. This matches the earlier observations of Losberg and Olsson (1979), as well as the statistical evaluations by Orangun et al. (1975, 1977) and Darwin et al. (1992a, 1992b). Under these conditions, a deformed reinforcing bar behaves as a wedge, causing the concrete to split. The effectiveness of the wedge is not sensitive to the details of the deformation pattern. Under conditions of increased confinement (as in a standard pullout test or with the addition of transverse reinforcement or higher concrete cover and bar spacing), the greater the rib bearing area, the higher the bond strength. Thus, with additional confinement provided by either transverse reinforcement or additional concrete, bond strength increases significantly with increases in the relative rib area. This matches the observations of Losberg and Olsson (1979), Soretz and Holzenbein (1979), and Kimura and

Jirsa (1992). The current study has not established an upper limit on the relative rib area beyond which no improvement in bond strength occurs; there is likely an upper limit, based on practical considerations of bar production and concrete placement. However, since R_r is typically less than 0.08 (Choi et al. 1990), there clearly is considerable room for improvement.

The close relationship between the shape of the load-slip curve and R_r matches the observations of Clark (1946, 1949); under all conditions, the initial stiffness of the curve increases with increasing relative rib area. As mentioned earlier, the high load-slip stiffness of bars with high values of R_r could prove to be useful for structures subjected to cyclic loading.

The low scatter of test data for development and splice tests (Darwin et al. 1992a, 1992b) is likely due to the insensitivity of bond strength to deformation pattern when splitting of concrete controls. The high scatter of test data for bars confined by transverse reinforcement must be due, at least in part, to unaccounted differences in the deformation patterns of the bars used in the tests.

There are some aspects of the current study that do not agree completely with earlier observations. Rehm (1957, 1961) found a relationship between the ratio of rib spacing to rib height and the nature of bond failure. For spacing/height ratios less than 7, Rehm observed that a pullout failure will occur, while for spacing/height ratios greater than 10, a splitting failure will occur. In the current study, splitting failures occurred in all cases, even down to spacing/height ratios of 5.26.

Losberg and Olsson (1979) observed that bond capacity decreased once ribs become closer than about two-thirds of the bar diameter. This did not occur in the current study. No degradation in bond strength was observed for rib spacings as close as 0.263 bar diameter. The differences in these observations may be due, in part, to the effect of the width of the concrete between the deformations. In the current study, deformation widths are relatively small, allowing adequate concrete strength between deformations. If the deformation width were increased, the amount of concrete available to carry shear stresses would be decreased, which might decrease bond strength. This factor will be the subject of further experimental work at the University of Kansas.

Lutz and Gergely (1967) observed that crushed concrete in front of ribs produced an effective rib face angle of 30 to 40°. In the current study, that angle ranged from 17 to 40°. The lower angles were observed on bars with rib heights of 0.05 in. The higher angles were observed for bars with rib heights of 0.075 and 0.10 in. In spite of the differences in effective face angle, overall response was a function of relative rib area. In the current study, there does not seem to be a relationship between the angle of the crushed concrete and bond behavior.

In addition to the effect of the width of concrete between ribs, there are at least two other questions that have not been answered in the current study. First, it is not clear why the conventional reinforcing provided lower bond strengths than the machined reinforcing bars when confinement was provided by transverse reinforcement or additional concrete cover. Second, since the nominal diameter of the reinforcing bars used in this study was constant, it is not clear whether the observed effect of relative rib area is truly nondimensional or a function of the bearing area of the ribs per unit length of the bar. These questions will also be addressed in continuing research.

SUMMARY AND CONCLUSIONS

The effect of deformation pattern on bond strength was studied using 1 in. diameter machined bars with deformation heights of 0.05, 0.075, and 0.10 in. and deformation spacings ranging from 0.263 in. to 2.2 in. The combinations of rib height and spacing produced relative rib areas of 0.20, 0.10, and 0.05 for each deformation height. Conventional reinforcing bars were also studied. The effect of deformation pattern was evaluated using beam-end specimens with varying degrees of confinement provided to the test bars. Degrees of confinement were: 1) 2 in. cover without confining transverse stirrups, 2) 2 in. cover with confining transverse stirrups, and 3) 3 in. cover without confining transverse stirrups. Test bars with 2 in. cover had an initial unbonded length of $^1/_2$ in. and a bonded length of 12 in. Bars with 3 in. cover had an initial unbonded length of 4 in. and a bonded length of 8 $^1/_2$ in. The study was also used to refine the design and test configuration used for the beam-end test specimen.

The following conclusions are based on the results and analyses presented in this report for the range of the parameters evaluated.

1. The bond force-slip response of reinforcing bars is a function of the relative rib area of the bars, independent of the specific combination of rib height and rib spacing.

2. Under all conditions of bar confinement, the initial stiffness of the load-slip curve increases with an increase in the relative rib area.

3. Under conditions of relatively low confinement, in which bond strength is governed by splitting of the concrete, bond strength is independent of deformation pattern.

4. Under conditions in which additional bar confinement is provided by transverse reinforcement or higher covers and lead lengths, bond strength increases compared to the bond strength of bars with less confinement. The magnitude of the increase in bond strength increases with an increase in the relative rib area.

5. The observed relationships between deformation pattern, degree of confinement, and bond strength appear to explain the large scatter obtained in earlier splice and development tests for bars that are confined by transverse reinforcement.

6. The observations made in this study will be used in the development of reinforcing bars with greater relative rib areas that will substantially decrease the required development lengths of bars confined by transverse reinforcement and/or high concrete covers and bar spacings.

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Table 1: Test Bar Data

Nominal Bar Dia. (in.)	Def. Pattern	Yield Strength (ksi)	Def. Height (in.)	Def. Spacing (in.)	Def. Gap (in.)	Def. Angle (deg.)	Bearing Area per inch (in.)	Relative Rib Area
3/8	B	77.3	0.032*	0.2560*	0.115*	90	**	**
1	S	71.1	0.055*	0.6670*	0.175*	90	0.219	0.070
1	N	63.8	0.060*	0.6040*	0.162*	70	0.245	0.078
1	M11	110	0.050	0.2630	-	90	0.629	0.200
1	M12	110	0.050	0.5250	-	90	0.314	0.100
1	M13	110	0.050	1.0500	-	90	0.157	0.050
1	M21	110	0.075	0.4030	-	90	0.629	0.200
1	M22	110	0.075	0.8060	-	90	0.314	0.100
1	M23	110	0.075	1.6125	-	90	0.157	0.050
1	M31	110	0.100	0.5500	-	90	0.629	0.200
1	M32	110	0.100	1.1000	-	90	0.314	0.100
1	M33	110	0.100	2.2000	-	90	0.157	0.050

* Average
** Not measured

Table 2a : Concrete Mixture Proportions (Per Cubic Yard)

Group	Nominal Strength (psi)	W / C Ratio	Cement (lb)	Water (lb)	Aggregate Fine * (lb)	Aggregate Coarse ** (lb)
1 - 9	6000	0.41	550	225	1564	1588

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

** Crushed Limestone - Fogel's Quarry, Ottawa, KS.
Bulk Specific Gravity (SSD) = 2.58 ; Absorption = 2.7 % ; Max. Size = 3/4 in. ;
Unit Weight = 90.5 lb/cu. ft.

Table 2b : Concrete Properties

Group	Slump (in.)	Concrete Temperature (F)	Air Content (%)	Age at Test (days)	Av. Comp. Strength (psi)
1	2 1/4	57	5.8	7	3890
2	3 1/2	65	6.8	10	4230
3	1	55	3.5	7	5460
4a	2 1/2	75	3.0	10	5360
4b	2 1/2	75	3.0	11	5530
5a	2 1/2	72	3.9	8	4560
5b	2 1/2	72	3.9	9	4610
6a	2 1/2	75	3.9	9	4600
6b	2	72	3.8	9	4720
6c	1 3/4	65	3.2	8	4530
7	2	70	3.2	9	4750
8	2	56	4.1	8	4630
9a	2	49	3.2	19	5990
9b	2	45	3.1	10	5040

Table 3 : Beam - end Tests

Group	Specimen Label *	Ht. of Ribs (in.)	Rib Spacing (in.)	Rel. Rib Area	Cover (in.)	Concrete Strength (psi)	Bond Str. (lb)	Mod. Bond Str. *** (lb)	Stirrups
1	M11-8-4 **	0.05	0.2630	0.200	1 7/8	3890	27930	31670	
	M12-8-4 **	0.05	0.5250	0.100	1 13/16	3890	38270	43390	
	M13-8-4 **	0.05	1.0500	0.050	2	3890	36230	41080	
	M31-8-4 **	0.10	0.5500	0.200	1 15/16	3890	27250	30890	
	M32-8-4 **	0.10	1.1000	0.100	2 1/16	3890	32670	37040	
	M33-8-4 **	0.10	2.2000	0.050	2 1/16	3890	28500	32310	
2	NH8-8-4A **	0.06	0.604	0.078	2	4230	28540	31030	
	NH8-8-4B **	0.06	0.604	0.078	2 1/16	4230	25520	27750	
	Avg.							29390	
	NH8-8-4C	0.06	0.604	0.078	2	4230	37510	40780	
	NH8-10-4A **	0.06	0.604	0.078	1 7/8	4230	36710	39910	
	NH8-10-4B **	0.06	0.604	0.078	1 15/16	4230	41010	44590	
	Avg.							42250	
	NH8-10-4C	0.06	0.604	0.078	2	4230	41600	45220	
	NH8-13.5-.5A **	0.06	0.604	0.078	1 7/8	4230	32500	35330	
	NH8-13.5-.5B **	0.06	0.604	0.078	1 7/8	4230	32110	34910	
	Avg.							35120	
	NH8-13.5-.5C	0.06	0.604	0.078	2	4230	31600	34390	
3	M11-10-4	0.05	0.2630	0.200	1 7/8	5460	35410	33890	
	M12-10-4	0.05	0.5250	0.100	2	5460	38540	36880	
	M13-10-4	0.05	1.0500	0.050	2	5460	40080	38350	
	M31-10-4	0.10	0.5500	0.200	2 1/4	5460	32450	31050	
	M32-10-4	0.10	1.1000	0.100	2	5460	44340	42430	
	M33-10-4	0.10	2.2000	0.050	1 7/8	5460	38440	36790	
	S8H-8-4A	0.05	0.6670	0.070	2	5460	35790	34249	
	S8H-8-4B	0.05	0.6670	0.070	2	5460	37500	35886	
	S8H-8-4C	0.05	0.6670	0.070	1 7/8	5460	31000	29665	
	Avg.							33267	
	S8H-10-4A	0.05	0.6670	0.070	1 7/8	5460	41400	39618	
	S8H-10-4B	0.05	0.6670	0.070	1 7/8	5460	44560	42642	
	S8H-10-4C	0.05	0.6670	0.070	2	5460	40270	38536	
	Avg.							40265	
	S8H-13.5-.5A	0.05	0.6670	0.070	2	5460	31400	30048	
	S8H-13.5-.5B	0.05	0.6670	0.070	2 1/8	5460	27380	26201	

Table 3 : Beam - end Tests (Cont'd)

Group	Specimen Label *	Ht. of Ribs (in.)	Rib Spacing (in.)	Rel. Rib Area	Cover (in.)	Concrete Strength (psi)	Bond Str. (lb)	Mod. Bond Str. *** (lb)	Stirrups
3	S8H-13.5-.5C	0.05	0.6670	0.070	2	5460	28750	27512	
	Avg.							27921	
4	M11-10-4A	0.050	0.2630	0.200	2 1/16	5360	39850	38490	
	M11-10-4B	0.050	0.2630	0.200	2	5530	42590	40500	
	Avg.							39495	
	M12-10-4A	0.050	0.5250	0.100	2 1/8	5360	39660	38300	
	M12-10-4B	0.050	0.5250	0.100	2	5530	39480	37540	
	Avg.							37920	
	M13-10-4A	0.050	1.0500	0.050	2 1/8	5530	42500	40410	
	M13-10-4B	0.050	1.0500	0.050	2 1/16	5360	37890	36600	
	Avg.							38505	
	M21-10-4A	0.075	0.4030	0.200	2 1/16	5360	40500	39120	
	M21-10-4B	0.075	0.4030	0.200	2 1/8	5530	41410	39380	
	Avg.							39250	
	M22-10-4A	0.075	0.8060	0.100	2 1/16	5360	42680	41220	
	M23-10-4A	0.075	1.6125	0.050	2	5360	35000	33800	
	M23-10-4B	0.075	1.6125	0.050	2	5530	40890	38880	
	Avg.							36340	
	M31-10-4A	0.100	0.5500	0.200	2 1/8	5360	36790	35530	
	M31-10-4B	0.100	0.5500	0.200	2 1/8	5530	41390	39360	
	Avg.							37445	
	M32-10-4A	0.100	1.1000	0.100	2	5360	45230	43680	
	M32-10-4B	0.100	1.1000	0.100	2	5360	39320	37980	
	Avg.							40830	
	M33-10-4A	0.100	2.2000	0.050	2 1/8	5360	38420	37110	
5	M11-12-.5A	0.050	0.2630	0.200	2 1/8	4560	29080	30450	
	M11-12-.5B	0.050	0.2630	0.200	2 1/8	4610	29880	31120	
	M11-12-.5C	0.050	0.2630	0.200	2 1/16	4610	28780	29970	
	Avg.							30513	
	M12-12-.5A	0.050	0.5250	0.100	2 1/16	4610	31400	32700	
	M12-12-.5B	0.050	0.5250	0.100	2 1/8	4610	34130	35540	
	M12-12-.5C	0.050	0.5250	0.100	2 1/8	4560	29900	31310	
	Avg.							33183	
	M13-12-.5A	0.050	1.0500	0.050	2 1/8	4610	29720	30950	
	M13-12-.5B	0.050	1.0500	0.050	2 3/16	4610	28050	29210	

Table 3 : Beam - end Tests (Cont'd)

Group	Specimen Label *	Ht. of Ribs (in.)	Rib Spacing (in.)	Rel. Rib Area	Cover (in.)	Concrete Strength (psi)	Bond Str. (lb)	Mod. Bond Str. *** (lb)	Stirrups
5	M13-12-.5C	0.050	1.0500	0.050	2 3/16	4560	31240	32710	
	Avg.							30957	
	M21-12-.5A	0.075	0.4030	0.200	2 3/8	4610	30600	31870	
	M21-12-.5B	0.075	0.4030	0.200	2 1/8	4560	25420	26620	
	M21-12-.5C	0.075	0.4030	0.200	2 1/8	4610	31340	32640	
	Avg.							30377	
	M22-12-.5A	0.075	0.8060	0.100	2	4610	31460	32760	
	M22-12-.5B	0.075	0.8060	0.100	2 1/8	4560	29620	31020	
	M22-12-.5C	0.075	0.8060	0.100	2 1/4	4610	26000	27080	
	Avg.							30287	
	M23-12-.5A	0.075	1.6125	0.050	2	4610	31240	32530	
	M23-12-.5B	0.075	1.6125	0.050	2 1/16	4560	30770	32220	
	M23-12-.5C	0.075	1.6125	0.050	2 1/16	4610	28080	29240	
	Avg.							31330	
	M31-12-.5A	0.100	0.5500	0.200	2 1/16	4560	31130	32600	
	M31-12-.5B	0.100	0.5500	0.200	2 1/16	4610	29990	31230	
	M31-12-.5C	0.100	0.5500	0.200	2 3/16	4560	29030	30400	
	Avg.							31410	
	M32-12-.5A	0.100	1.1000	0.100	1 15/16	4560	29950	31360	
	M32-12-.5B	0.100	1.1000	0.100	1 15/16	4610	30260	31510	
	M32-12-.5C	0.100	1.1000	0.100	2 1/16	4610	30110	31360	
	Avg.							31410	
	M33-12-.5A	0.100	2.2000	0.050	2 1/8	4610	32110	33440	
	M33-12-.5B	0.100	2.2000	0.050	2 3/16	4610	27970	29130	
	M33-12-.5C	0.100	2.2000	0.050	2 1/8	4610	25750	26820	
	Avg.							29797	
	S8V-12-.5A	0.055	0.6670	0.070	2 1/4	4560	30070	31490	
	S8V-12-.5B	0.055	0.6670	0.070	2 3/16	4610	29540	30760	
	S8V-12-.5C	0.055	0.6670	0.070	2	4610	29180	30390	
	Avg.							30880	
	S8H-12-.5A	0.055	0.6670	0.070	2 1/8	4560	27270	28560	
	S8H-12-.5B	0.055	0.6670	0.070	2 1/16	4610	29160	30370	
	S8H-12-.5C	0.055	0.6670	0.070	2 1/16	4610	29950	31190	
	Avg.							30040	
6	M11-12-.5A	0.050	0.2630	0.200	2 1/8	4600	41820	43600	4 - #3
	M11-12-.5B	0.050	0.2630	0.200	2 1/8	4720	46060	47410	4 - #3
	M11-12-.5C	0.050	0.2630	0.200	2 1/16	4530	41850	43970	4 - #3
	Avg.							44993	
	M12-12-.5A	0.050	0.5250	0.100	2 1/8	4600	39840	41540	4 - #3

Table 3 : Beam - end Tests (Cont'd)

Group	Specimen Label *	Ht. of Ribs (in.)	Rib Spacing (in.)	Rel. Rib Area	Cover (in.)	Concrete Strength (psi)	Bond Str. (lb)	Mod. Bond Str. *** (lb)	Stirrups
6	M12-12-.5B	0.050	0.5250	0.100	1 15/16	4720	41560	42770	4 - #3
	M12-12-.5C	0.050	0.5250	0.100	1 15/16	4530	38350	40290	4 - #3
	Avg.							41533	
	M13-12-.5A	0.050	1.0500	0.050	2 1/16	4600	33380	34800	4 - #3
	M13-12-.5B	0.050	1.0500	0.050	2 5/16	4720	37110	38190	4 - #3
	M13-12-.5C	0.050	1.0500	0.050	2 3/16	4530	38890	40860	4 - #3
	Avg.							37950	
	M21-12-.5A	0.075	0.4030	0.200	2 1/4	4720	42560	43800	4 - #3
	M21-12-.5B	0.075	0.4030	0.200	2 3/16	4530	45180	47470	4 - #3
	M21-12-.5C	0.075	0.4030	0.200	2	4600	45140	47060	4 - #3
	Avg.							46110	
	M22-12-.5A	0.075	0.8060	0.100	2 1/8	4720	41730	42950	4 - #3
	M22-12-.5B	0.075	0.8060	0.100	2 3/16	4530	40920	42990	4 - #3
	M22-12-.5C	0.075	0.8060	0.100	2	4600	37920	39530	4 - #3
	Avg.							41823	
	M23-12-.5A	0.075	1.6125	0.050	2 1/16	4720	36560	37630	4 - #3
	M23-12-.5B	0.075	1.6125	0.050	2 1/16	4530	36840	38700	4 - #3
	M23-12-.5C	0.075	1.6125	0.050	2 1/16	4600	36230	37770	4 - #3
	Avg.							38033	
	M31-12-.5A	0.100	0.5500	0.200	2	4530	40840	42910	4 - #3
	M31-12-.5B	0.100	0.5500	0.200	1 15/16	4600	44180	46060	4 - #3
	M31-12-.5C	0.100	0.5500	0.200	2 1/16	4720	45830	47170	4 - #3
	Avg.							45380	
	M32-12-.5A	0.100	1.1000	0.100	2	4530	34980	36750	4 - #3
	M32-12-.5B	0.100	1.1000	0.100	2 1/8	4600	39710	41400	4 - #3
	M32-12-.5C	0.100	1.1000	0.100	2 1/8	4720	44740	46050	4 - #3
	Avg.							41400	
	M33-12-.5A	0.100	2.2000	0.050	1 15/16	4530	34590	36340	4 - #3
	M33-12-.5B	0.100	2.2000	0.050	2	4600	31550	32890	4 - #3
	M33-12-.5C	0.100	2.2000	0.050	2 1/16	4720	27440	28240	4 - #3
	Avg.							32490	
	S8V-12-.5A	0.055	0.6670	0.070	2 1/16	4600	35250	36750	4 - #3
	S8V-12-.5B	0.055	0.6670	0.070	2 3/16	4720	39670	40830	4 - #3
	S8V-12-.5C	0.055	0.6670	0.070	2 1/4	4530	33350	35040	4 - #3
	Avg.							37540	
	S8H-12-.5A	0.055	0.6670	0.070	2 1/8	4600	33450	34870	4 - #3
	S8H-12-.5B	0.055	0.6670	0.070	1 15/16	4720	37210	38300	4 - #3
	S8H-12-.5C	0.055	0.6670	0.070	2 1/16	4530	31960	33580	4 - #3
	Avg.							35583	

Table 3 : Beam - end Tests (Cont'd)

Group	Specimen Label *	Ht. of Ribs (in.)	Rib Spacing (in.)	Rel. Rib Area	Cover (in.)	Concrete Strength (psi)	Bond Str. (lb)	Mod. Bond Str. *** (lb)	Stirrups
7	M11-12-.5	0.050	0.2630	0.200	2 3/16	4750	47670	48910	4 - #3
	M12-12-.5	0.050	0.5250	0.100	2 1/16	4750	44420	45570	4 - #3
	M13-12-.5	0.050	1.0500	0.050	2 1/16	4750	39470	40500	4 - #3
	M21-12-.5	0.075	0.4030	0.200	2 1/8	4750	44180	45330	4 - #3
	M22-12-.5	0.075	0.8060	0.100	2 3/16	4750	46460	47670	4 - #3
	M23-12-.5	0.075	1.6125	0.050	2	4750	39460	40490	4 - #3
	M31-12-.5	0.100	0.5500	0.200	2	4750	45790	46980	4 - #3
	M32-12-.5	0.100	1.1000	0.100	2	4750	46050	47250	4 - #3
	M33-12-.5	0.100	2.2000	0.050	2 3/16	4750	40910	41970	4 - #3
	S8V-12-.5	0.055	0.6670	0.070	2 1/8	4750	38980	39990	4 - #3
	S8H-12-.5	0.055	0.6670	0.070	2 1/16	4750	37090	38050	4 - #3
8	M11-12-.5	0.050	0.2630	0.200	2 1/16	4630	32180	33441	
	M12-12-.5	0.050	0.5250	0.100	2 1/8	4630	31990	33244	
	M13-12-.5	0.050	1.0500	0.050	2 1/4	4630	31940	33192	
	M21-12-.5	0.075	0.4030	0.200	2	4630	32050	33306	
	M22-12-.5	0.075	0.8060	0.100	2 1/8	4630	31440	32672	
	M23-12-.5	0.075	1.6125	0.050	2 1/8	4630	30270	31456	
	M31-12-.5	0.100	0.5500	0.200	2	4630	31820	33067	
	M32-12-.5	0.100	1.1000	0.100	2 3/16	4630	33180	34480	
	M33-12-.5	0.100	2.2000	0.050	2 1/8	4630	31350	32579	
	S8V-12-.5	0.055	0.6670	0.070	2 1/8	4630	29360	30511	
	S8H-12-.5	0.055	0.6670	0.070	2	4630	27520	28598	
9	M11-8.5-4A	0.050	0.2630	0.200	3	5990	55510	50716	
	M11-8.5-4B	0.050	0.2630	0.200	3 1/4	5040	45500	45319	
	Avg.							48017	
	M12-8.5-4A	0.050	0.5250	0.100	3 1/8	5990	54680	49957	
	M12-8.5-4B	0.050	0.5250	0.100	3 1/4	5040	42700	42530	
	Avg.							46244	
	M13-8.5-4A	0.050	1.0500	0.050	3	5990	49270	45015	
	M13-8.5-4B	0.050	1.0500	0.050	3	5040	42500	42331	
	Avg.							43673	
	M21-8.5-4	0.075	0.4030	0.200	3	5990	55040	50286	
	M22-8.5-4	0.075	0.8060	0.100	3	5990	53250	48651	
	M23-8.5-4	0.075	1.6125	0.050	3 1/16	5990	48280	44110	
	M31-8.5-4A	0.100	0.5500	0.200	3	5990	50580	46212	
	M31-8.5-4B	0.100	0.5500	0.200	3 1/16	5040	47400	47212	

Table 3 : Beam - end Tests (Cont'd)

Group	Specimen Label *	Ht. of Ribs (in.)	Rib Spacing (in.)	Rel. Rib Area	Cover (in.)	Concrete Strength (psi)	Bond Str. (lb)	Mod. Bond Str. *** (lb)	Stirrups
9	M31-8.5-4C	0.100	0.5500	0.200	3	5040	49000	48805	
	Avg.							47409	
	M32-8.5-4A	0.100	1.1000	0.100	3 1/8	5990	51840	47363	
	M32-8.5-4B	0.100	1.1000	0.100	3 1/8	5040	45600	45419	
	M32-8.5-4C	0.100	1.1000	0.100	3 1/8	5040	34600	34462	
	Avg. w/o M32-8.5-4C							46391	
	Avg. w/ M32-8.5-4C							42415	
	M33-8.5-4A	0.100	2.2000	0.050	3 1/16	5990	44290	40465	
	M33-8.5-4B	0.100	2.2000	0.050	3 1/16	5040	42300	42132	
	M33-8.5-4C	0.100	2.2000	0.050	3 1/8	5040	35500	35359	
	Avg. w/o M33-8.5-4C							41298	
	Avg. w/ M33-8.5-4C							39318	
	S8V-8.5-4A	0.055	0.6670	0.070	3	5990	44120	40309	
	S8V-8.5-4B	0.055	0.6670	0.070	3	5040	40000	39841	
	Avg.							40075	
	S8H-8.5-4A	0.055	0.6670	0.070	3 1/8	5990	44650	40794	
	S8H-8.5-4B	0.055	0.6670	0.070	3 1/8	5040	39200	39044	
	Avg.							39919	

* Specimen Label

1. Machined Bars (MHX-B-LR) 2. SMI #8 Bars (S8O-B-LR) 3. North Star #8 Bars (N8O-B-LR)

H = Rib height designation : 1 = Low, 0.05 in. ; 2 = Medium, 0.075 in. ; 3 = High, 0.10 in.
X = Rib spacing designation : 1 = Small ; 2 = Medium ; 3 = Large
O = Orientation of longitudinal rib : V = Vertical ; H = Horizontal
B = Bonded length, in.
L = Lead length, in.
R = Replication mark : A , B , C

** Specimen without side stirrups

*** Modified Bond Strength = Bond Strength $(5000/f'c)^{1/2}$

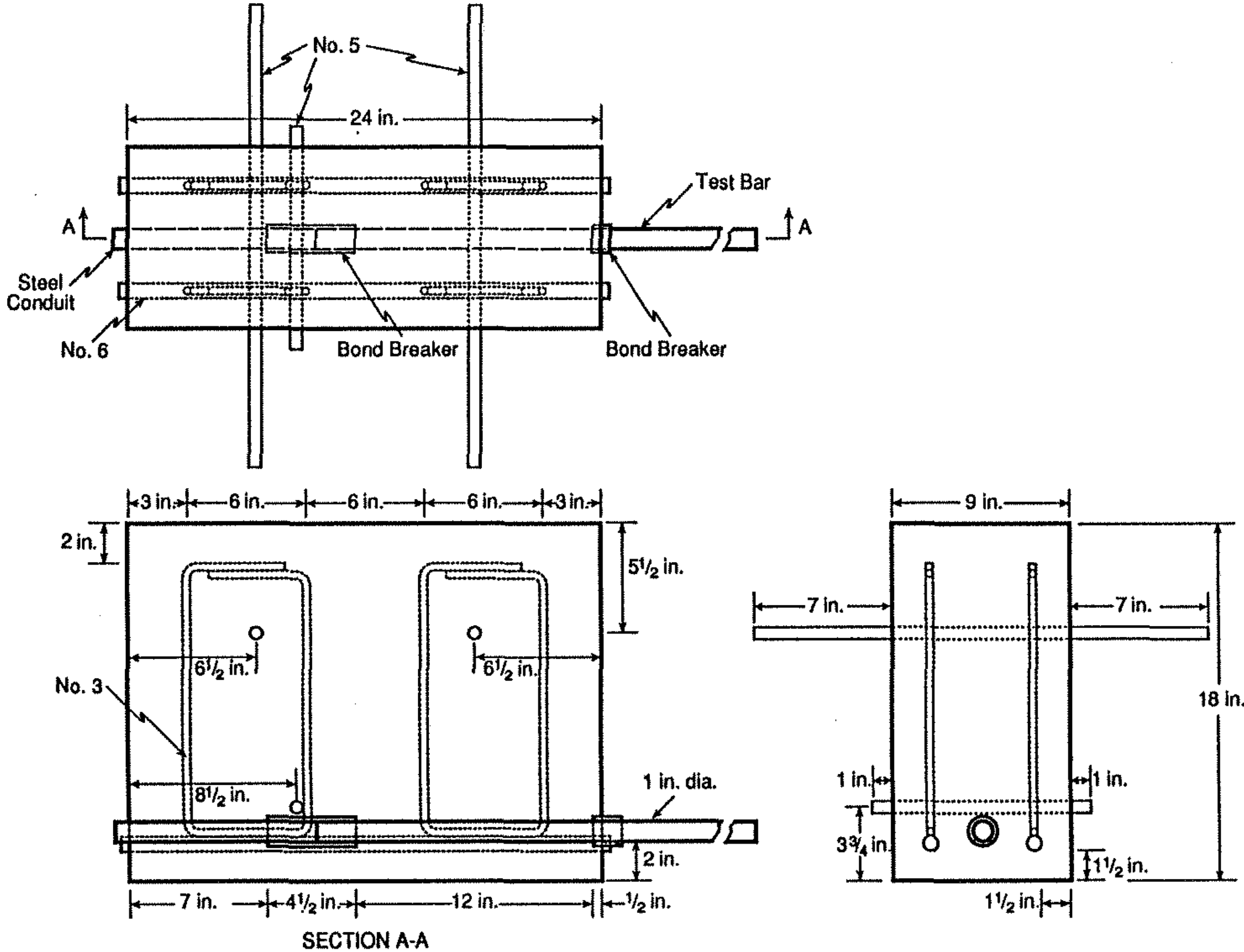

Fig. 1a Beam-end test specimen for evaluating the bond strength of reinforcing bars not confined by transverse reinforcement

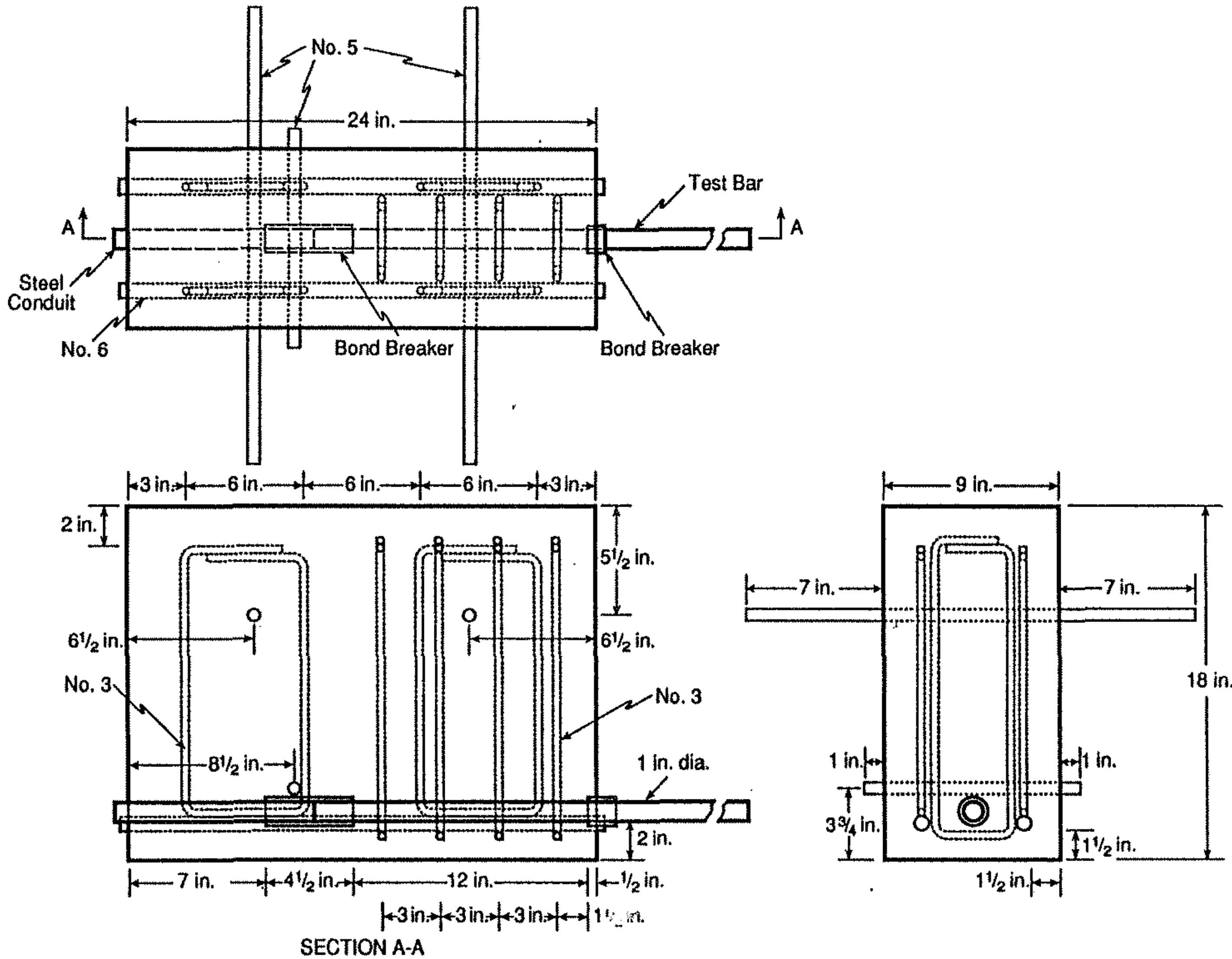

Fig. 1b Beam-end test specimen for evaluating the bond strength of reinforcing bars confined by transverse reinforcement

Deformation Pattern	Relative Rib Area
M 11	0.20
M 12	0.10
M 13	0.05
M 21	0.20
M 22	0.10
M 23	0.05
M 31	0.20
M 32	0.10
M 33	0.05

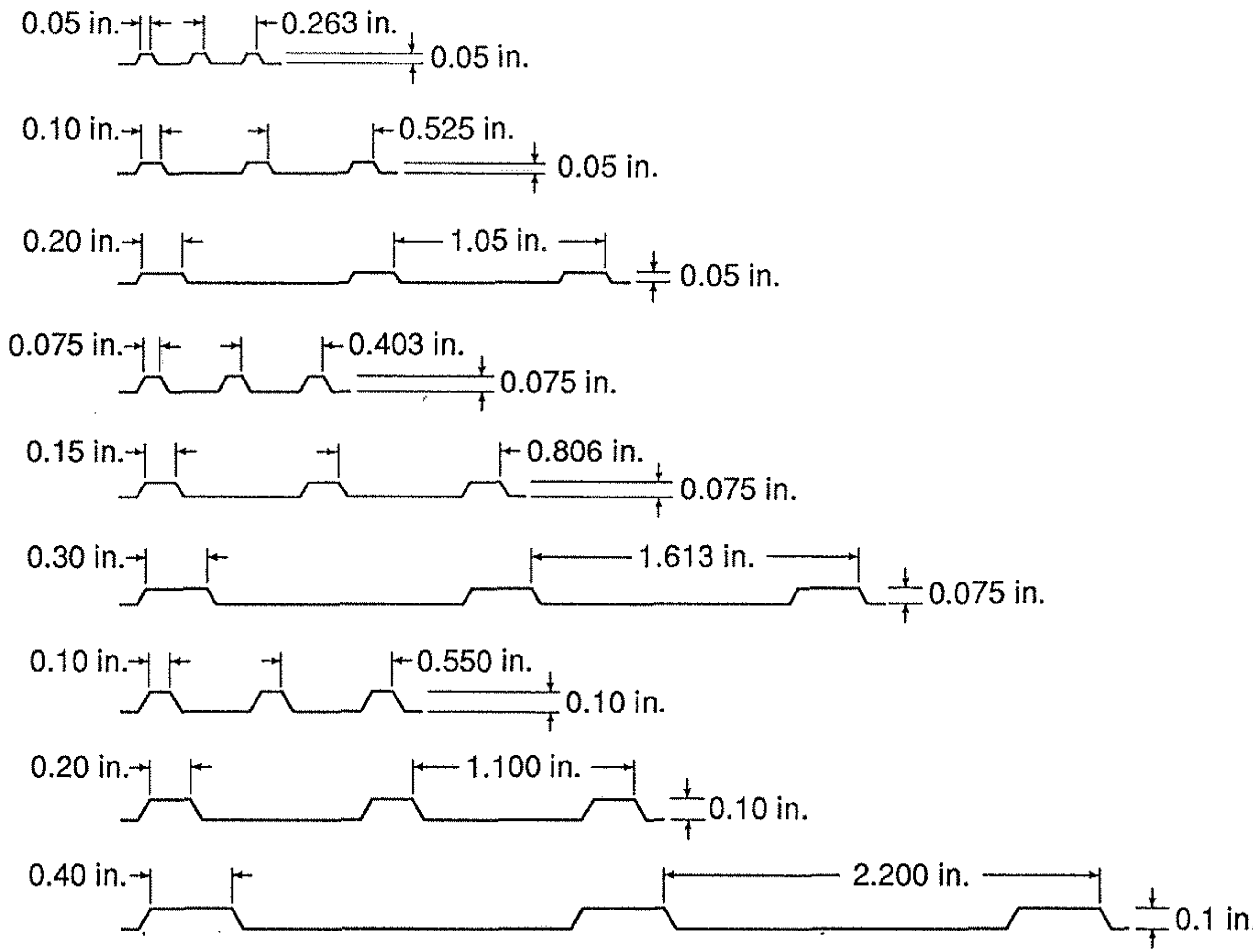

Fig. 2a Machined bar deformation patterns. Face angle = 60° for all bars

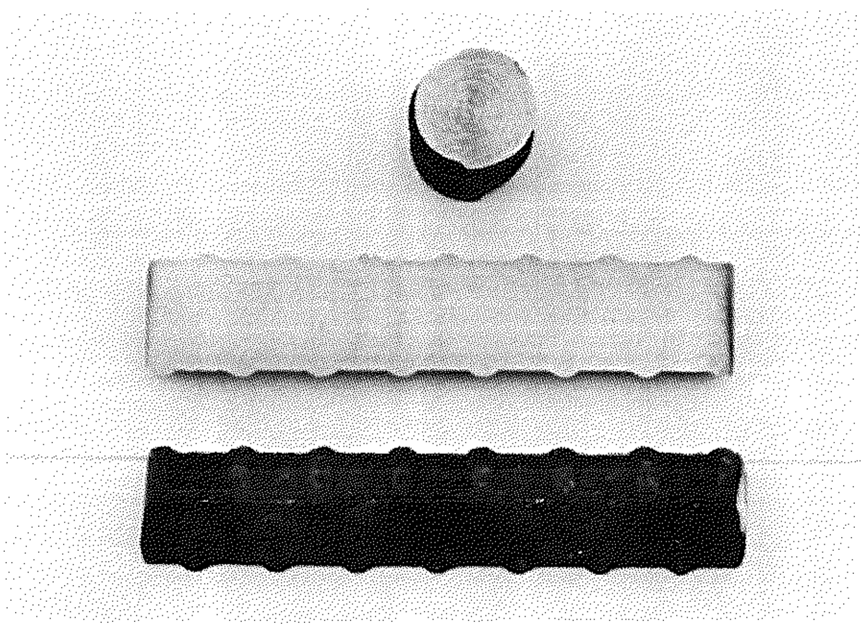

Fig. 2b Conventional reinforcement deformation pattern

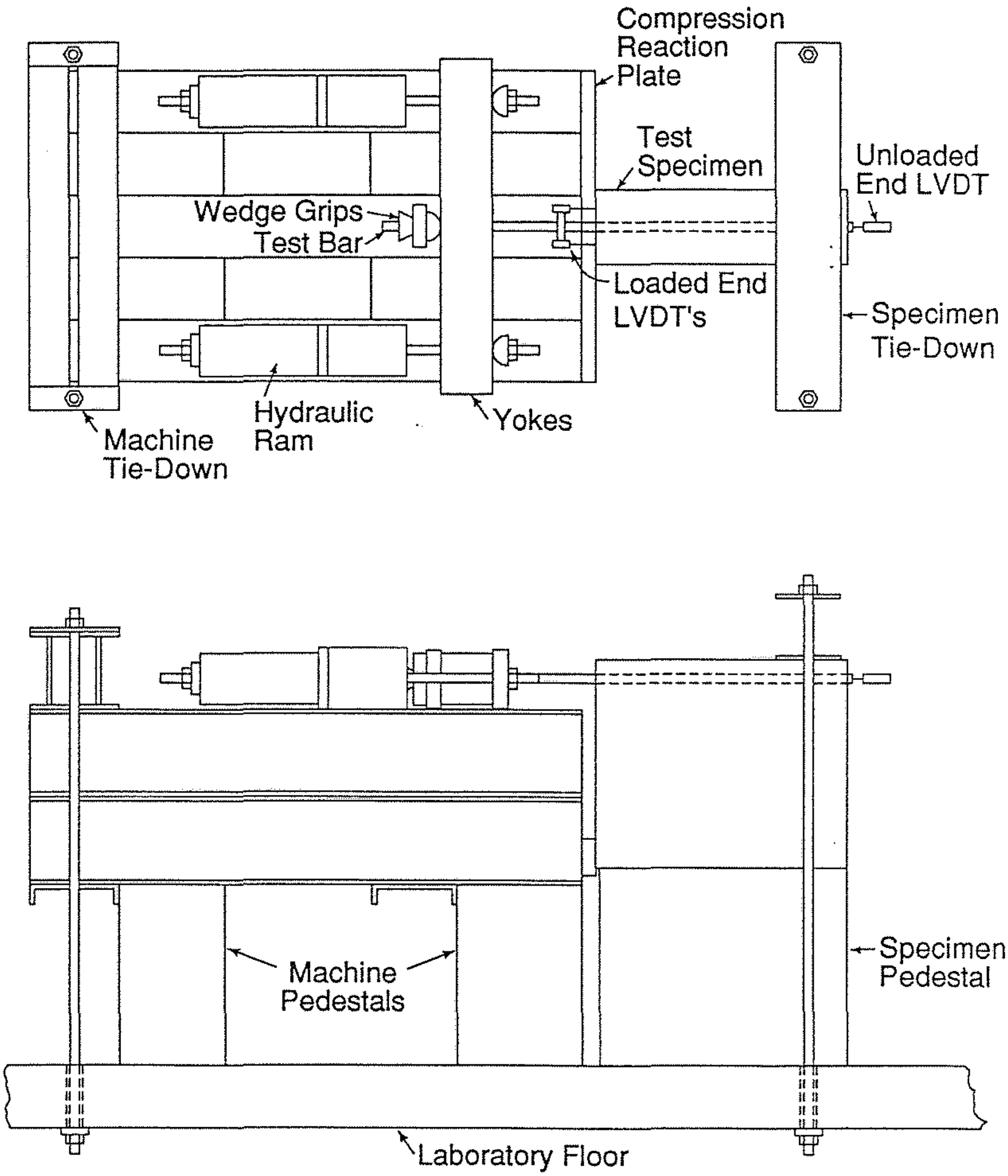

Fig. 3 Schematic of test apparatus

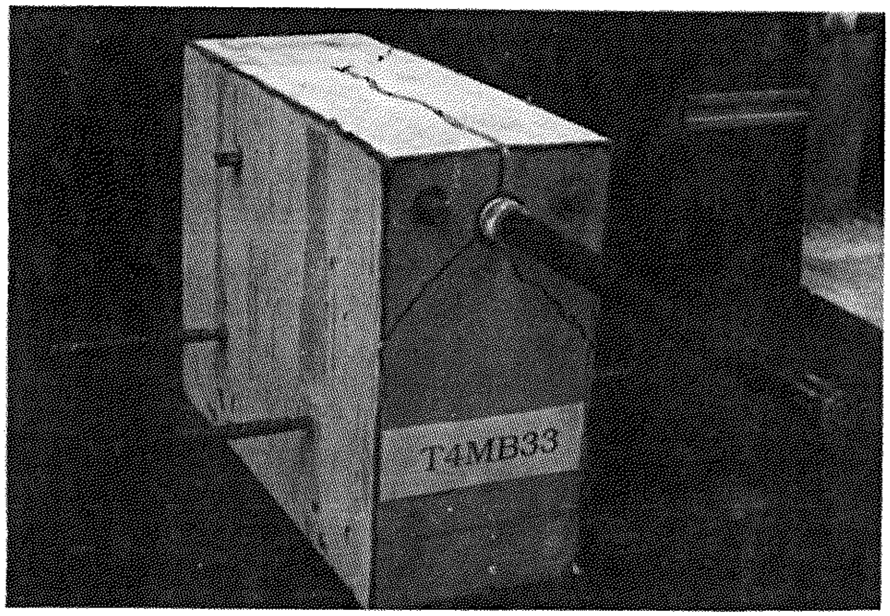

Fig. 4 Beam-end test specimen without transverse stirrups after failure. Cracks on the front face of specimen form an inverted Y centered on the test bar

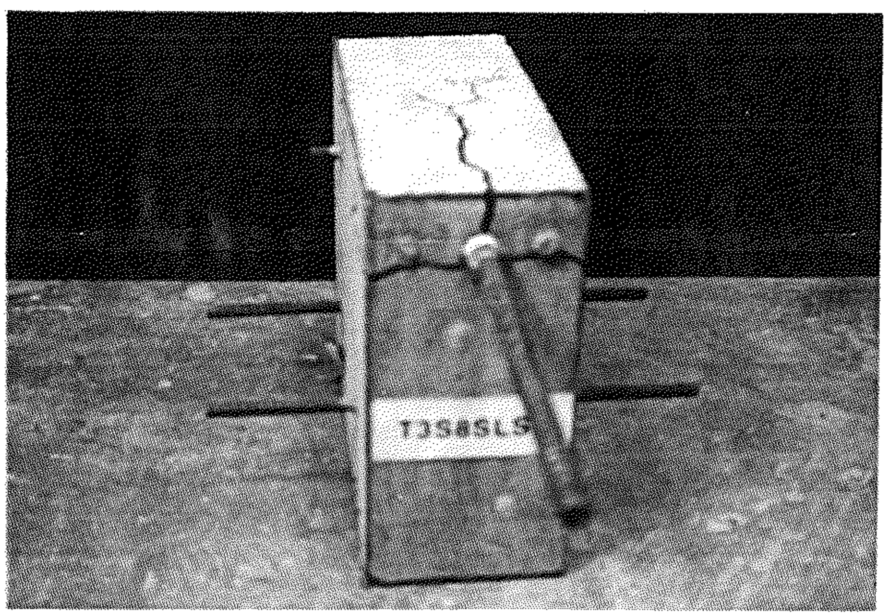

Fig. 5 Beam-end test specimen without transverse stirrups after failure. Cracks on the front face of specimen form an inverted T centered on the test bar

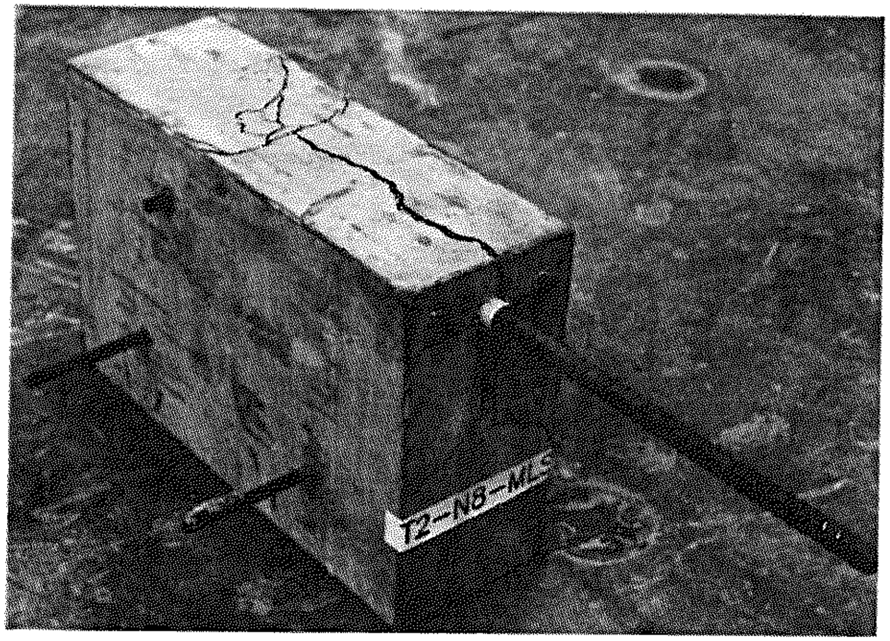

Fig. 6 Beam-end test specimen without transverse stirrups after failure. Cracks on the front face of specimen form an inverted Y with vertical crack passing through the location of the test bar

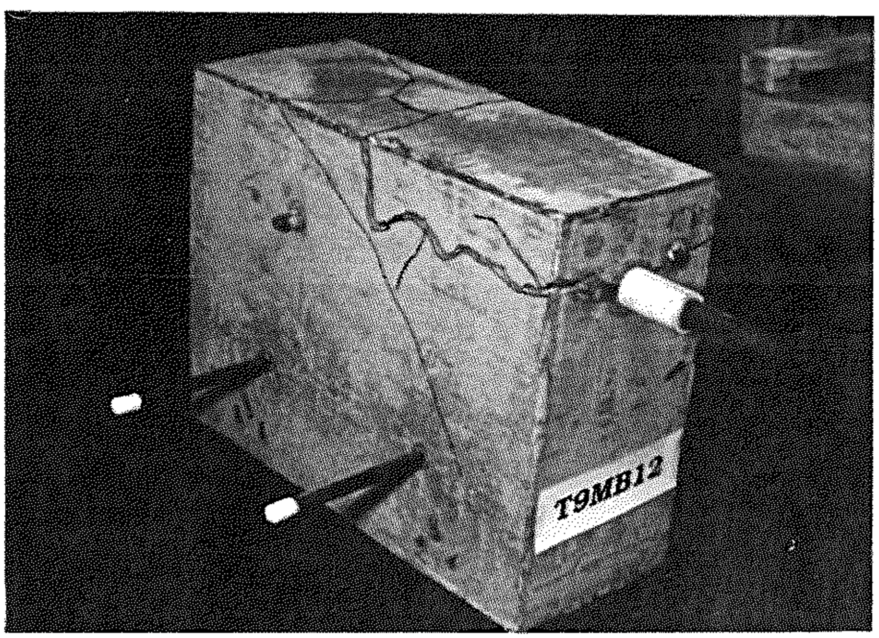

Fig. 7 Beam-end test specimen with 3 in. cover, without transverse reinforcement, after failure

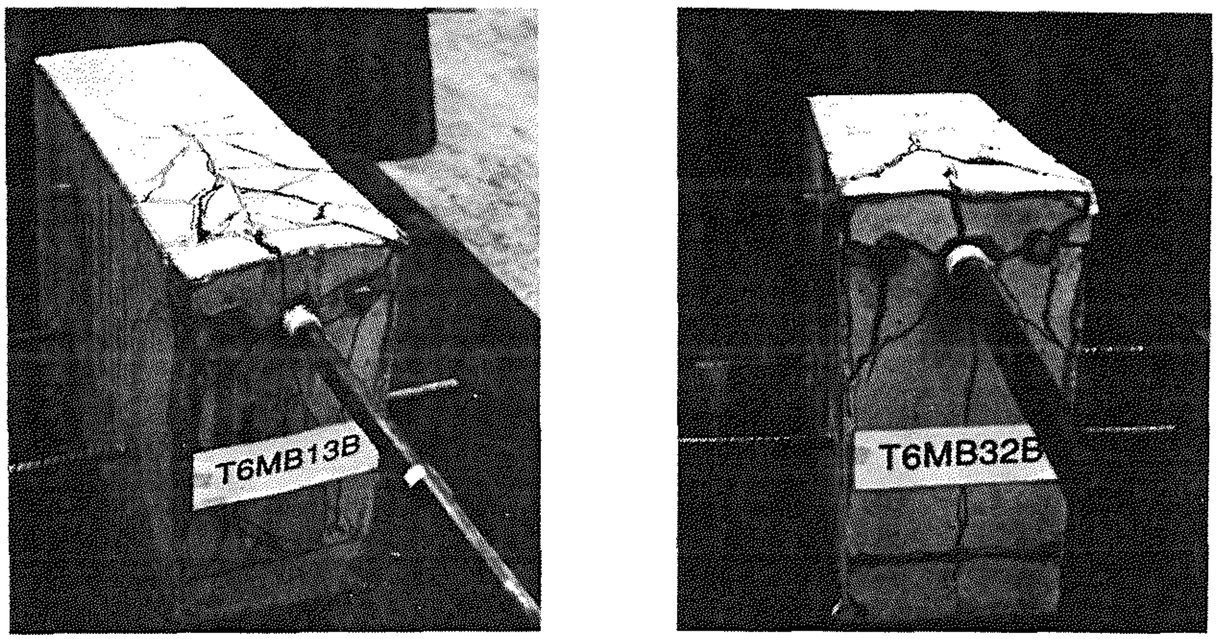

Fig. 8 Beam-end test specimens with transverse reinforcement after failure

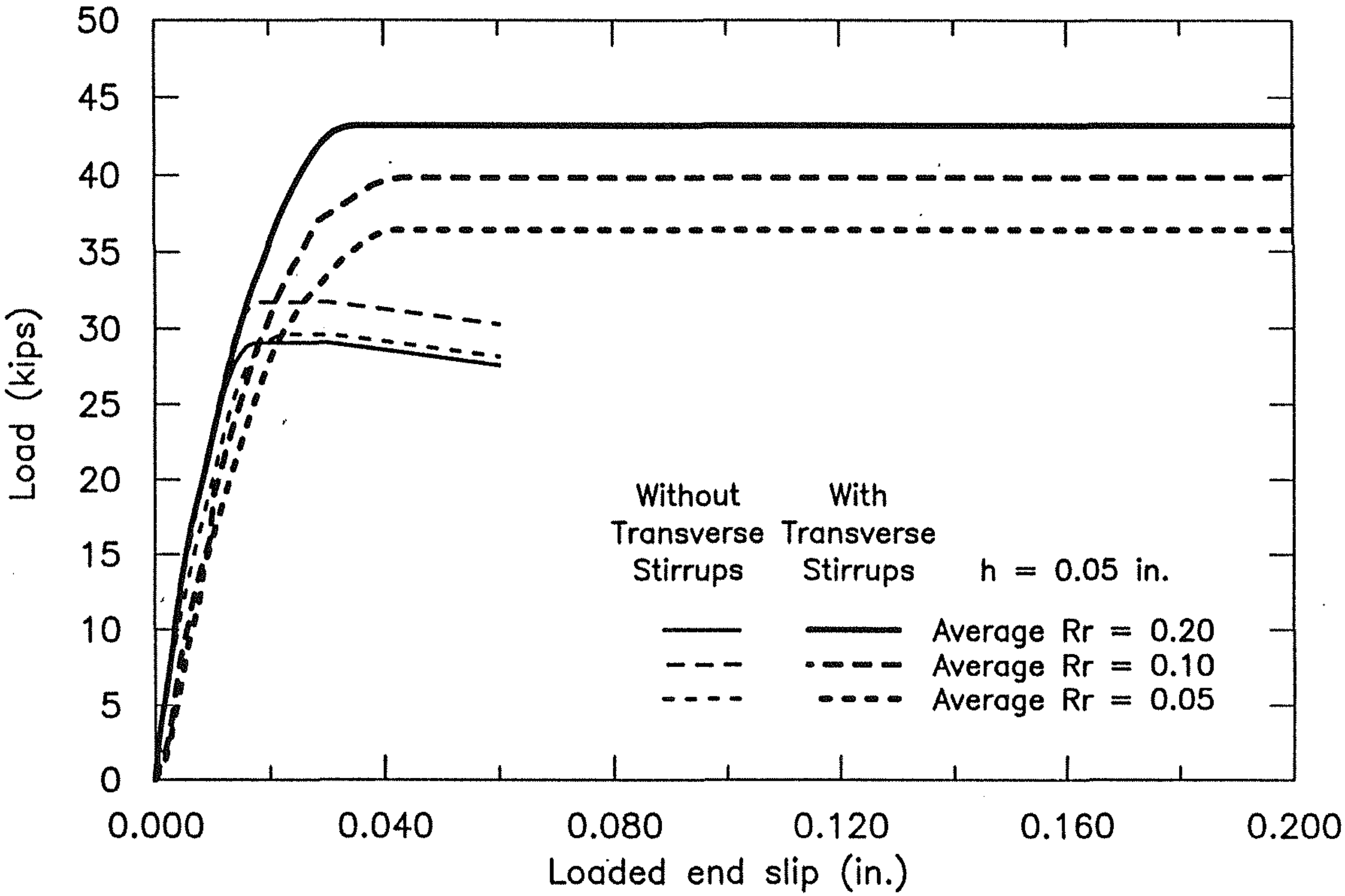

Fig. 9 Average load-loaded end slip curves for test bars with rib height h = 0.05 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 2 in., lead length = 1/2 in., bonded length = 12 in.)

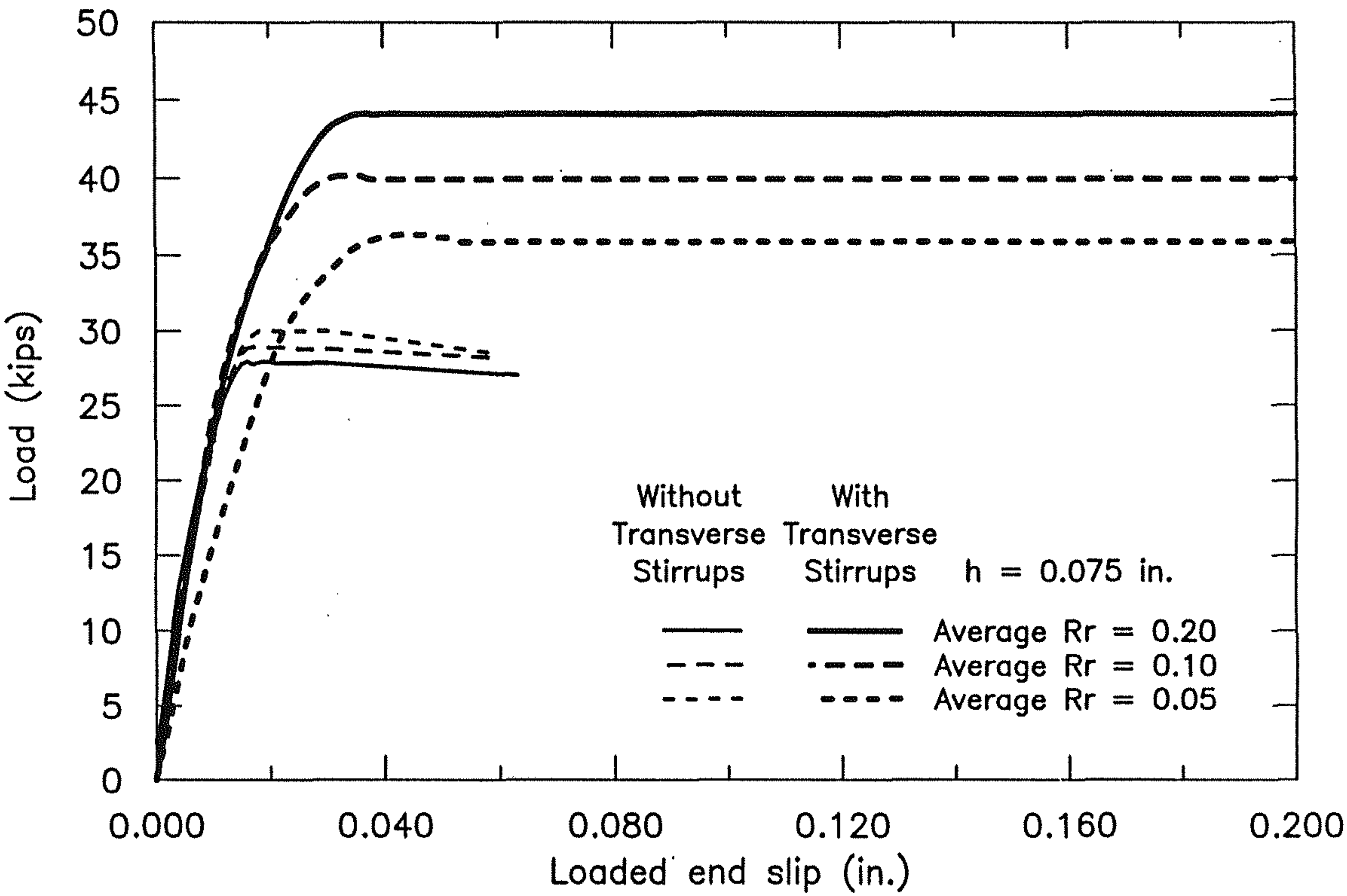

Fig. 10 Average load-loaded end slip curves for test bars with rib height h = 0.075 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 2 in., lead length = 1/2 in., bonded length = 12 in.)

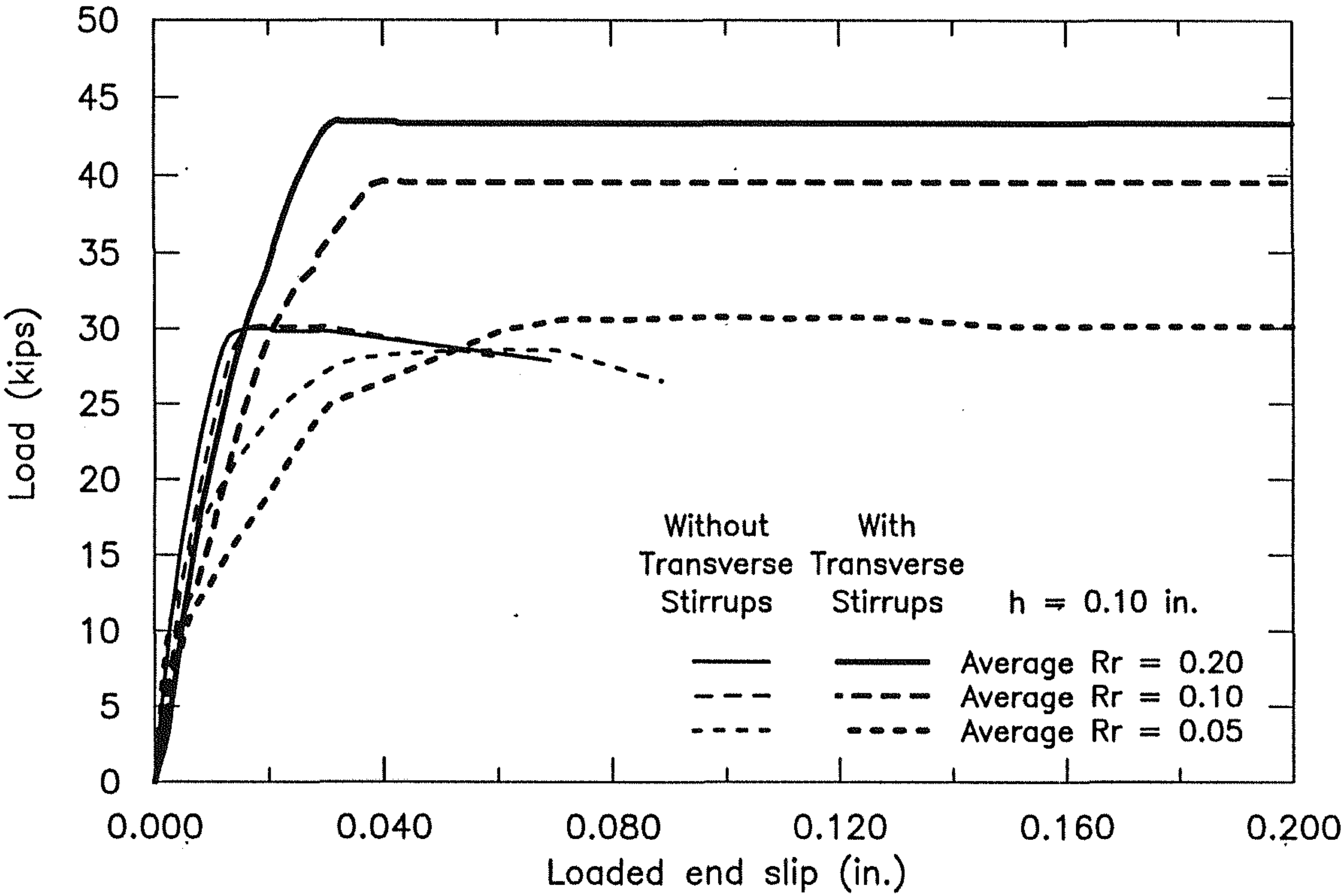

Fig. 11 Average load-loaded end slip curves for test bars with rib height h = 0.10 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 2 in., lead length = $^{1}/_{2}$ in., bonded length = 12 in.)

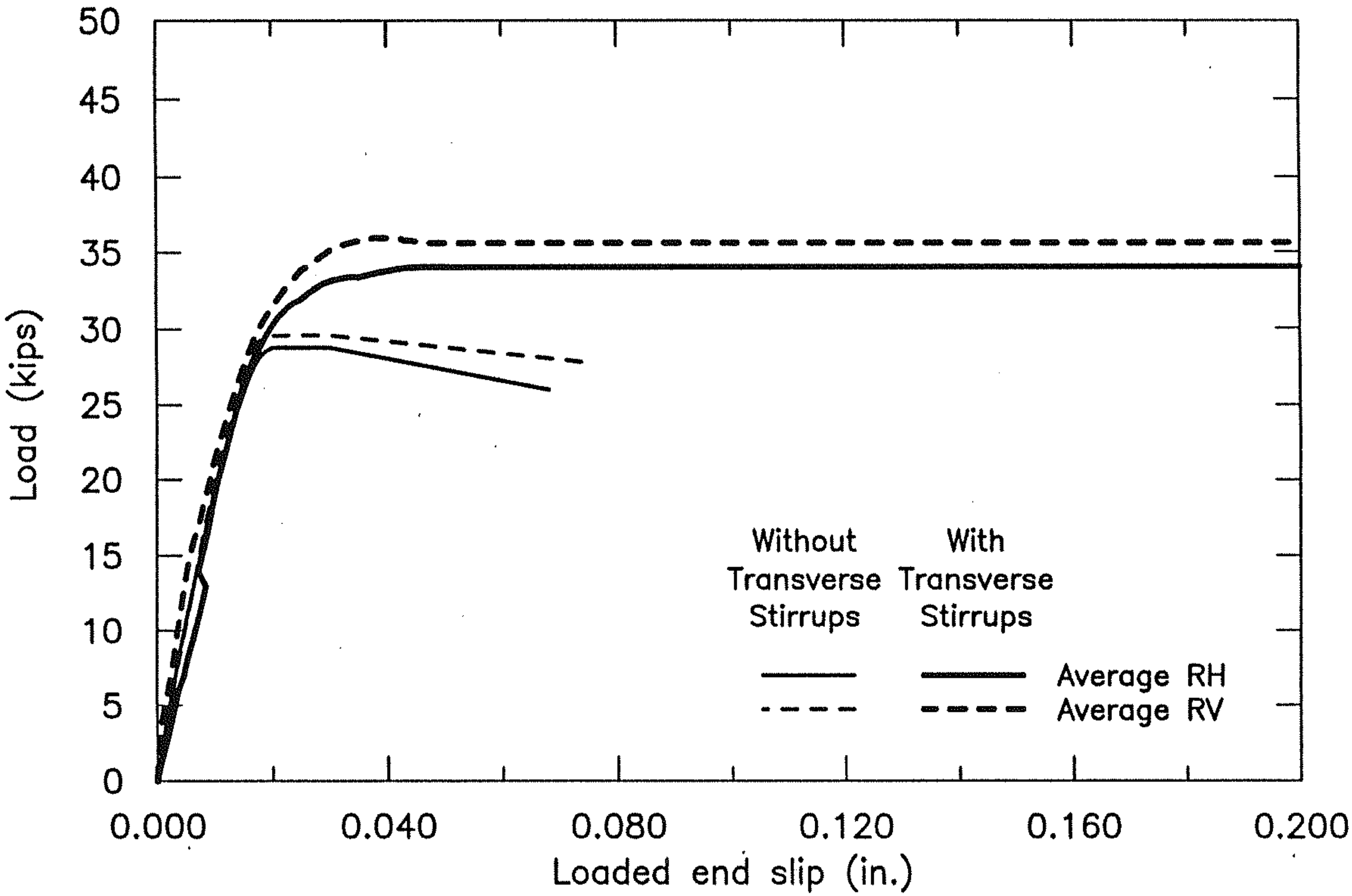

Fig. 12 Average load-loaded end slip curves for ASTM A 615 reinforcing bars with relative rib area = 0.07 (cover = 2 in., lead length = $1/2$ in., bonded length = 12 in.)

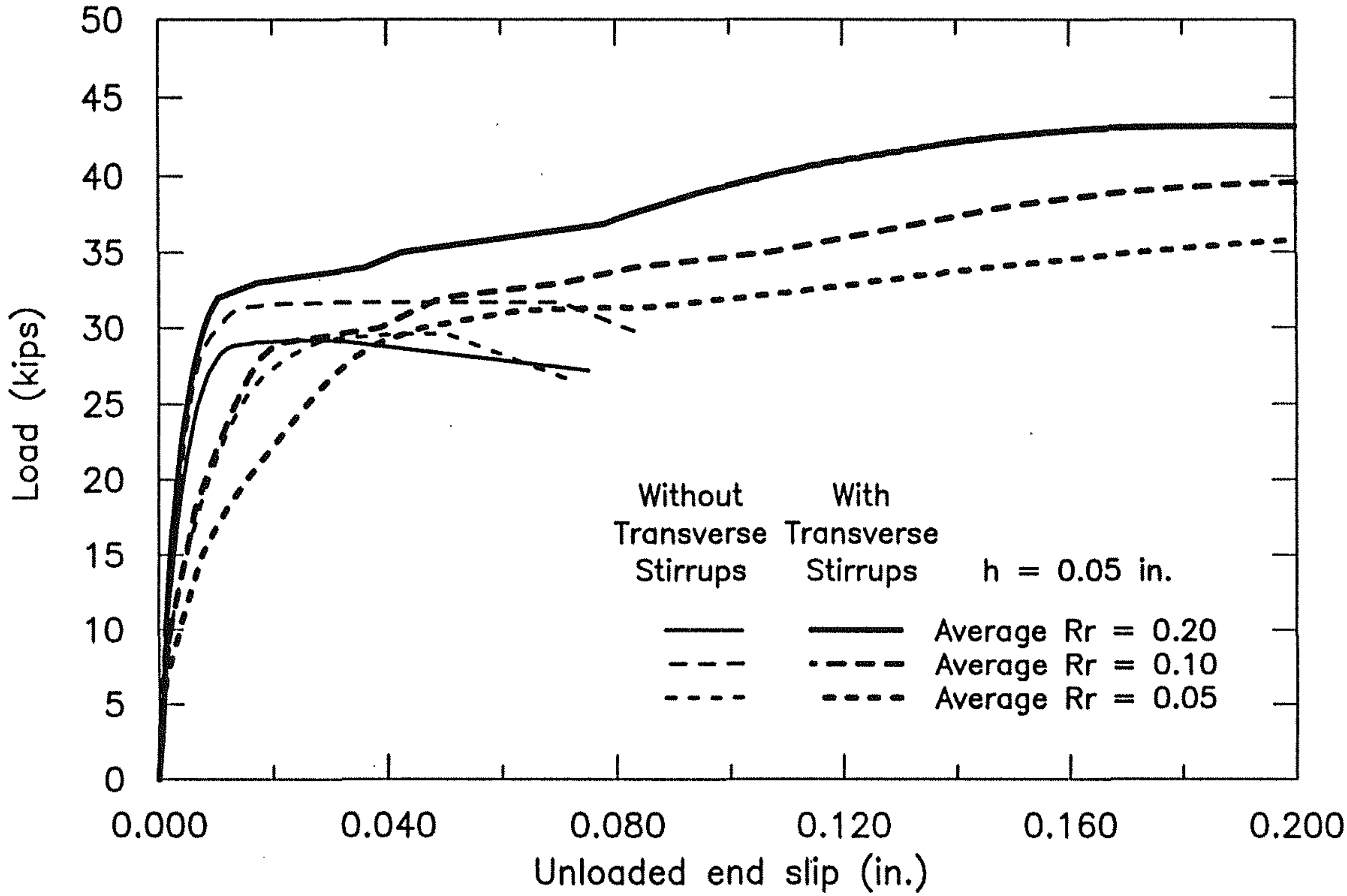

Fig. 13 Average load-unloaded end slip curves for test bars with rib height h = 0.05 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 2 in., lead length = 1/2 in., bonded length = 12 in.)

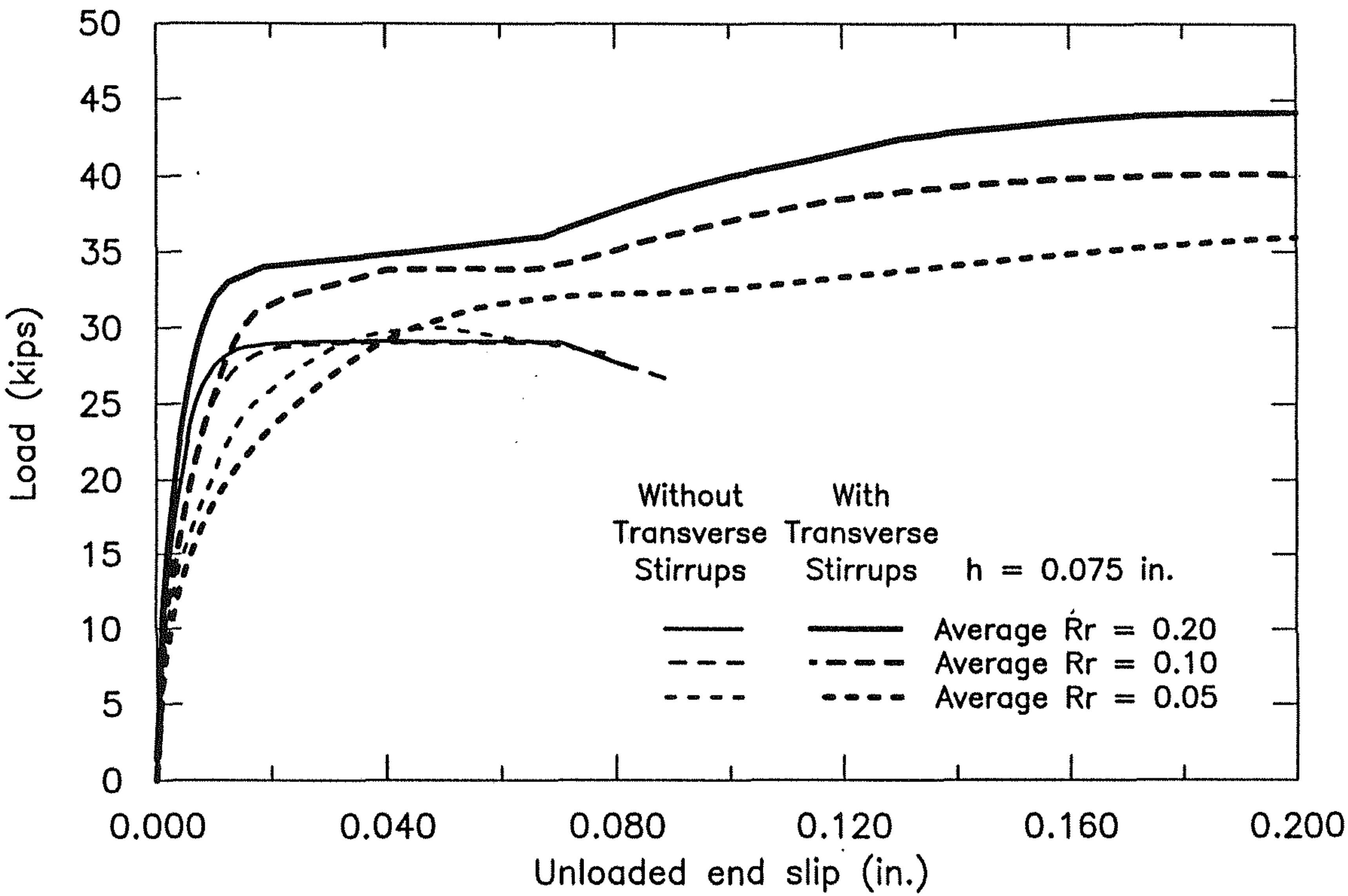

Fig. 14 Average load-unloaded end slip curves for test bars with rib height h = 0.075 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 2 in., lead length = 1/2 in., bonded length = 12 in.)

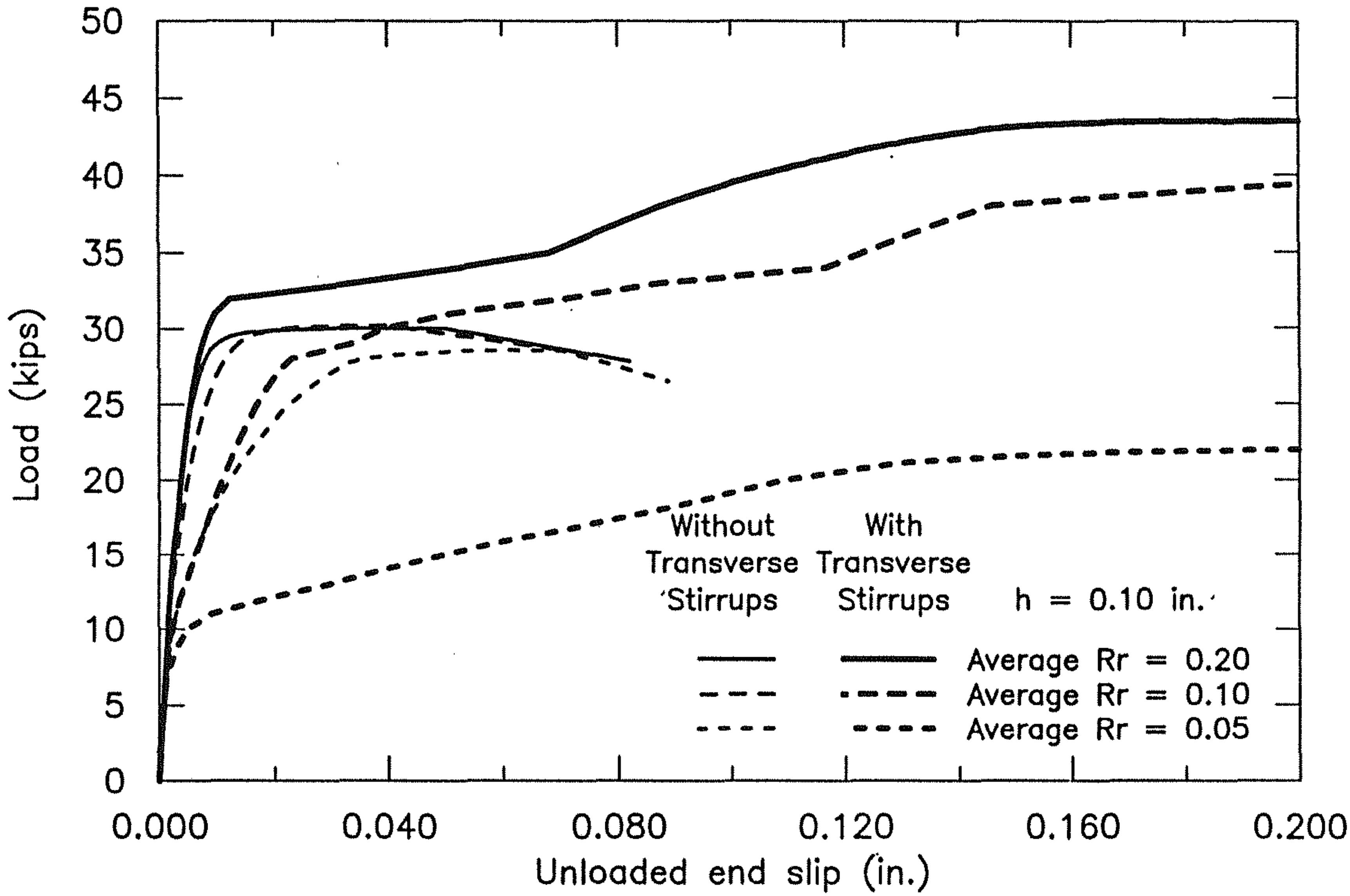

Fig. 15 Average load-unloaded end slip curves for test bars with rib height h = 0.10 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 2 in., lead length = 1/2 in., bonded length = 12 in.)

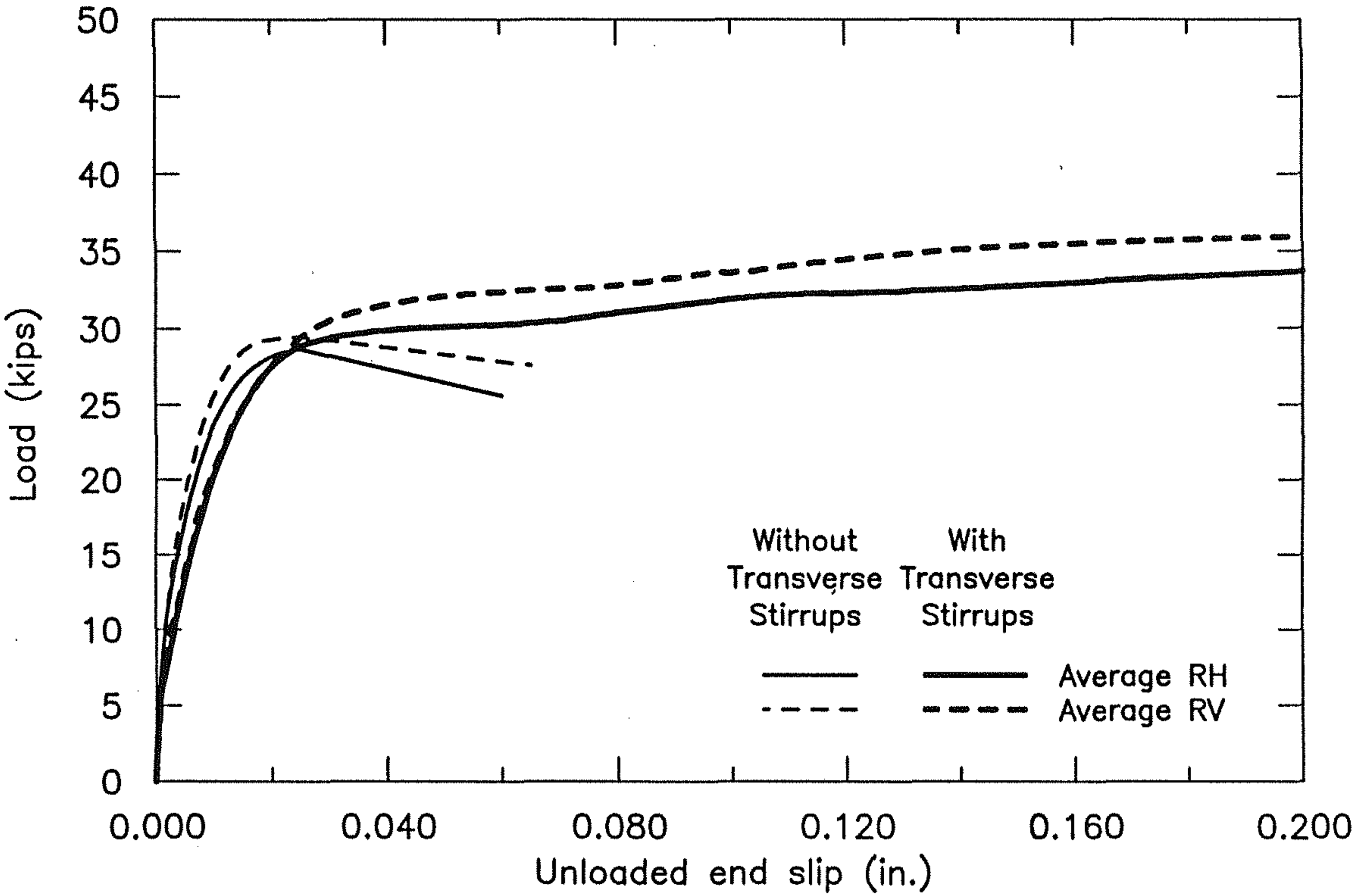

Fig. 16 Average load-unloaded end slip curves for ASTM A 615 reinforcing bars with relative rib area = 0.07 (cover = 2 in., lead length = 1/2 in., bonded length = 12 in.)

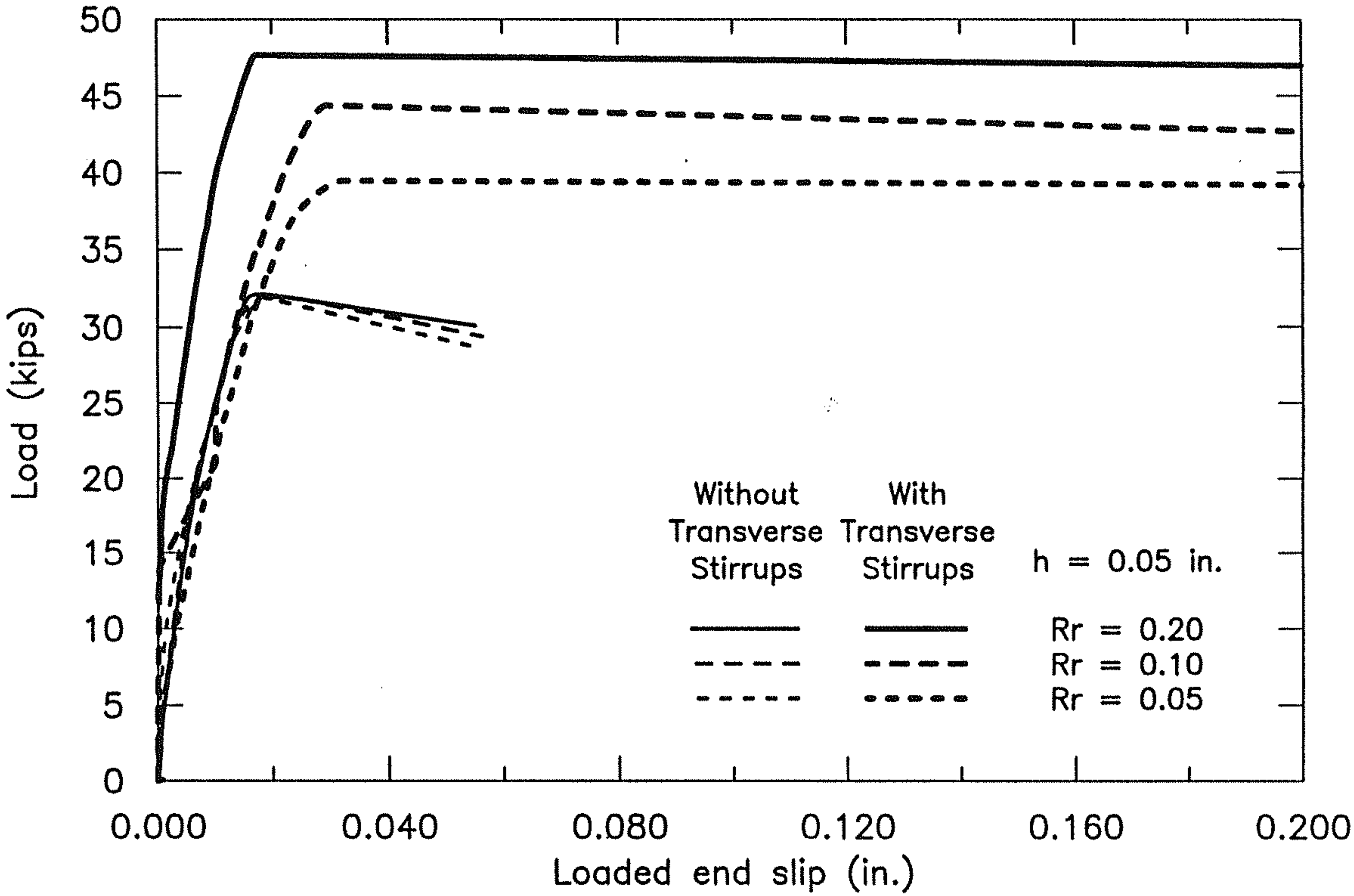

Fig. 17 Load-loaded end slip curves for test bars with rib height h = 0.05 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 2 in., lead length = 1/2 in., bonded length = 12 in.) hooked auxiliary reinforcement

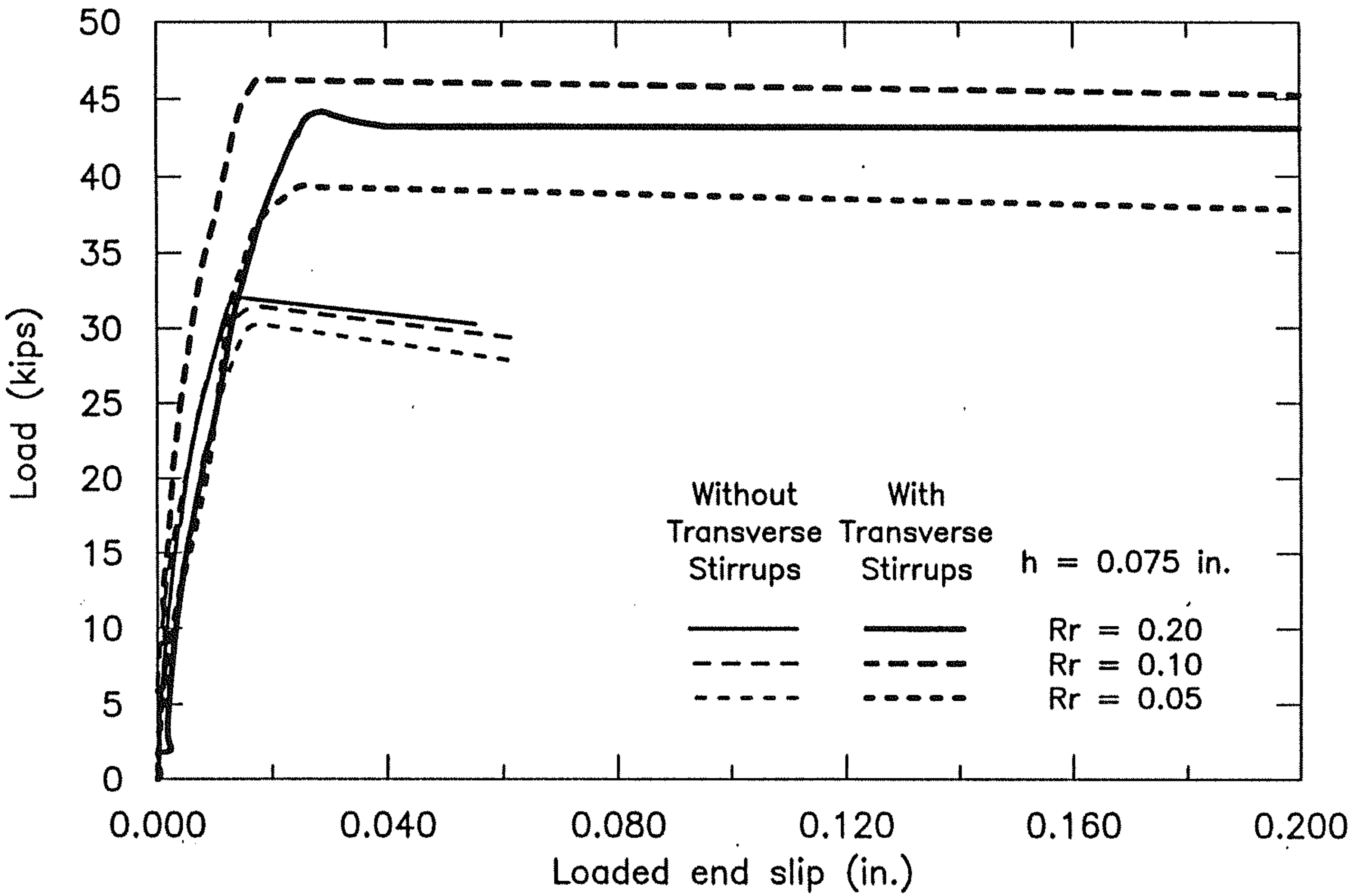

Fig. 18 Load-loaded end slip curves for test bars with rib height h = 0.075 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 2 in., lead length = 1/2 in., bonded length = 12 in.) hooked auxiliary reinforcement

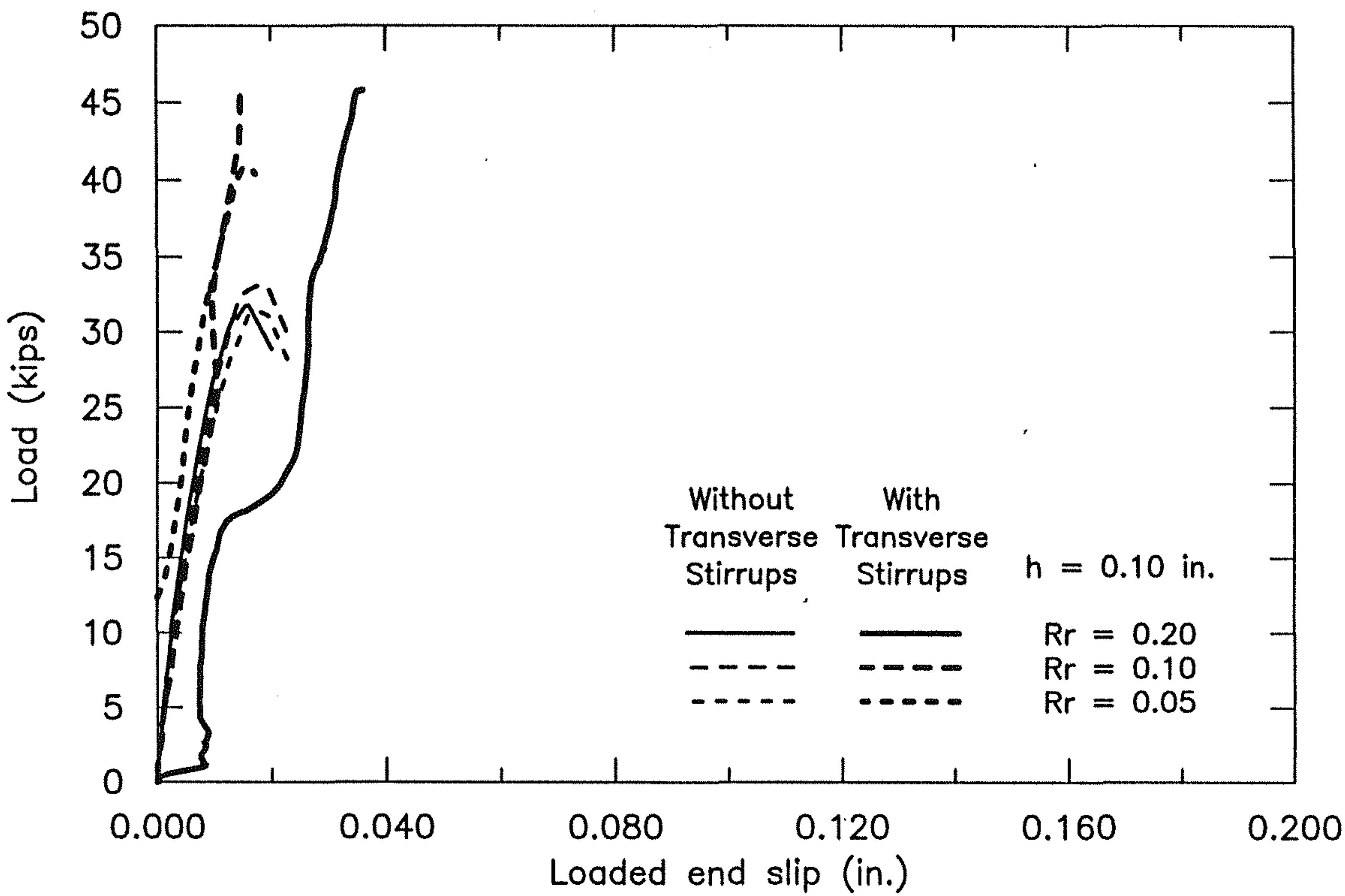

Fig. 19 Load-loaded end slip curves for test bars with rib height h = 0.10 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 2 in., lead length = 1/2 in., bonded length = 12 in.) hooked auxiliary reinforcement

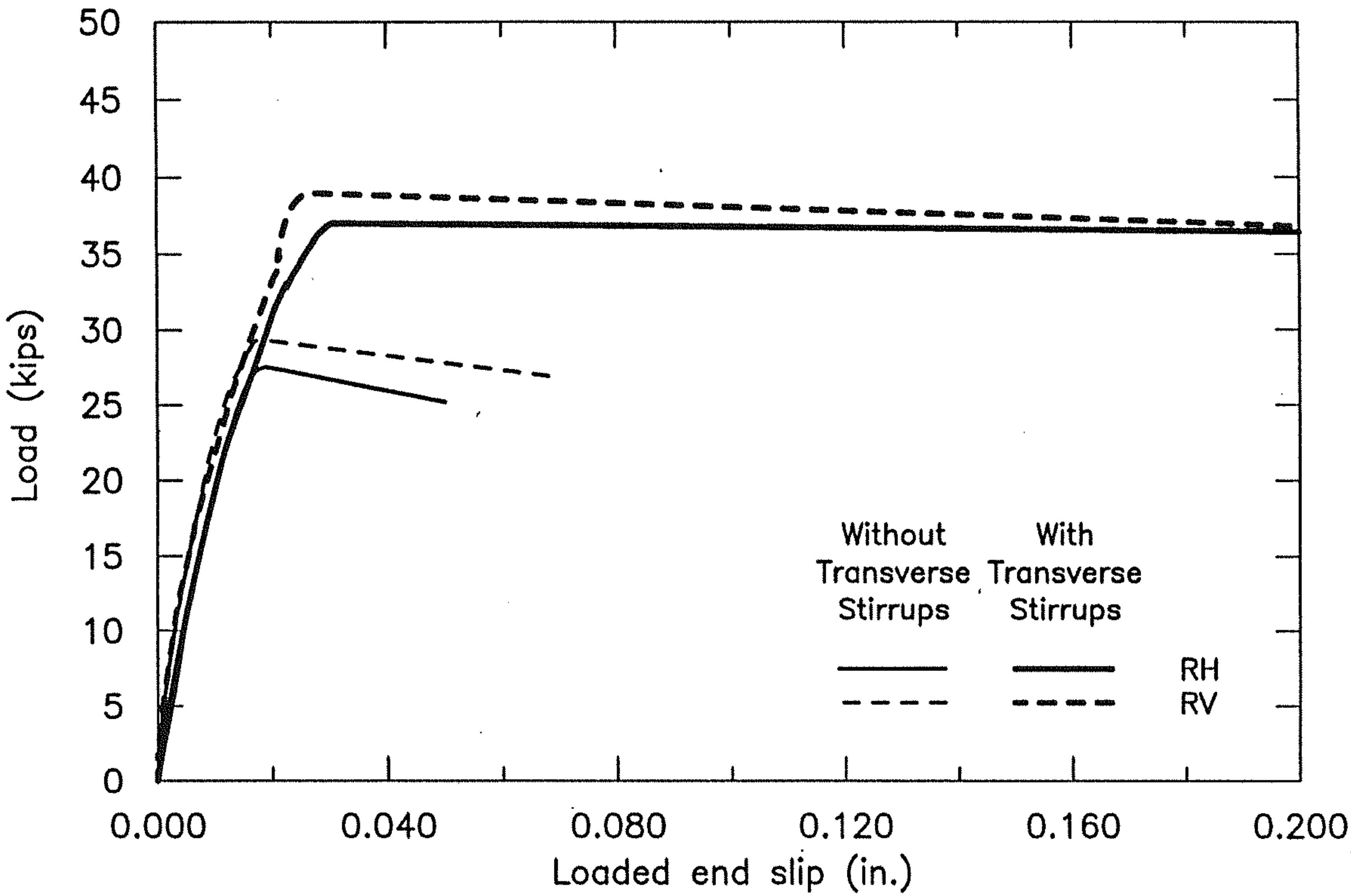

Fig. 20 Load-loaded end slip curves for ASTM A 615 reinforcing bars with relative rib area = 0.07 (cover = 2 in., lead length = 1/2 in., bonded length = 12 in.) hooked auxiliary reinforcement

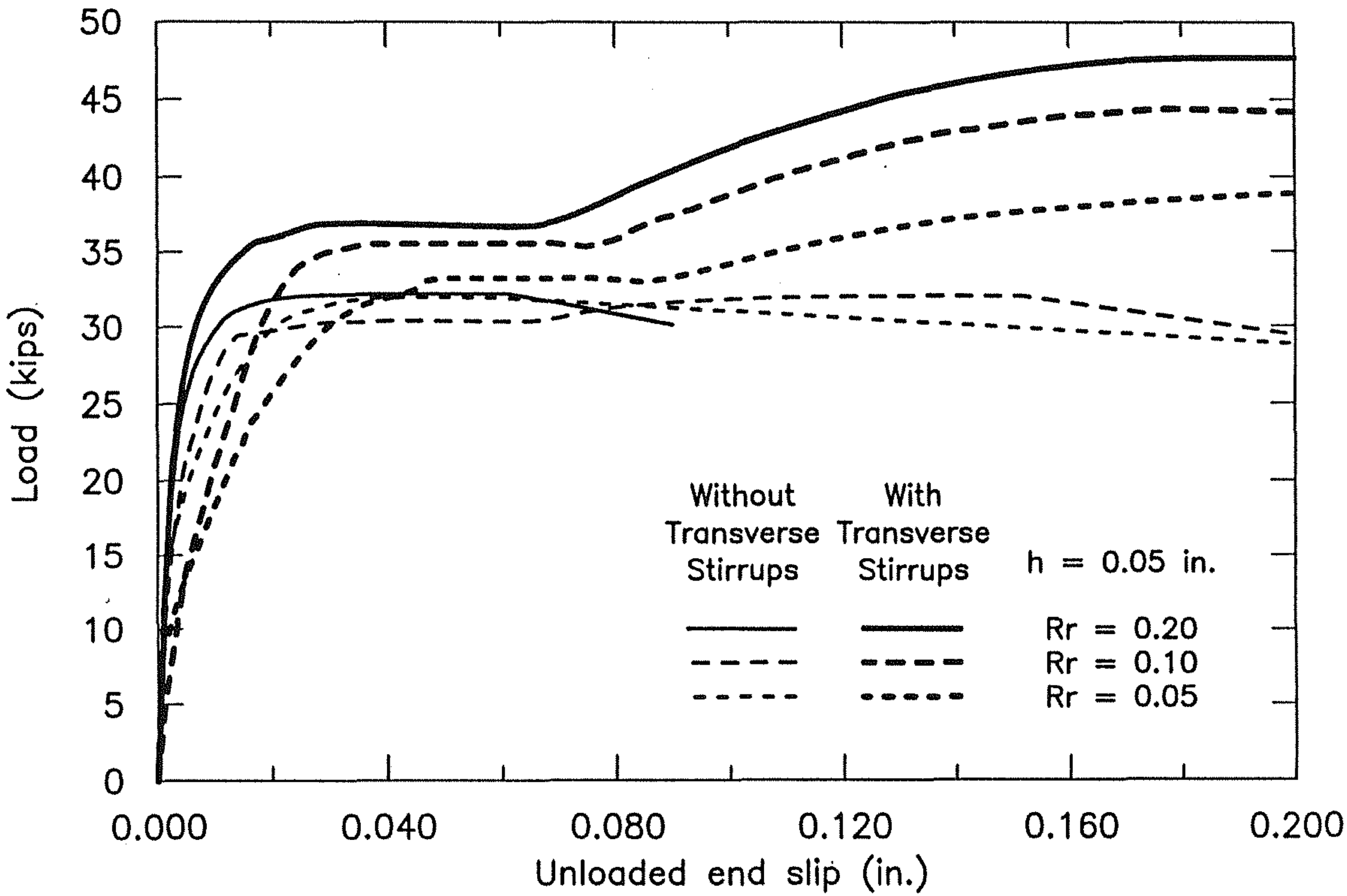

Fig. 21 Load-unloaded end slip curves for test bars with rib height h = 0.05 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 2 in., lead length = 1/2 in., bonded length = 12 in.) hooked auxiliary reinforcement

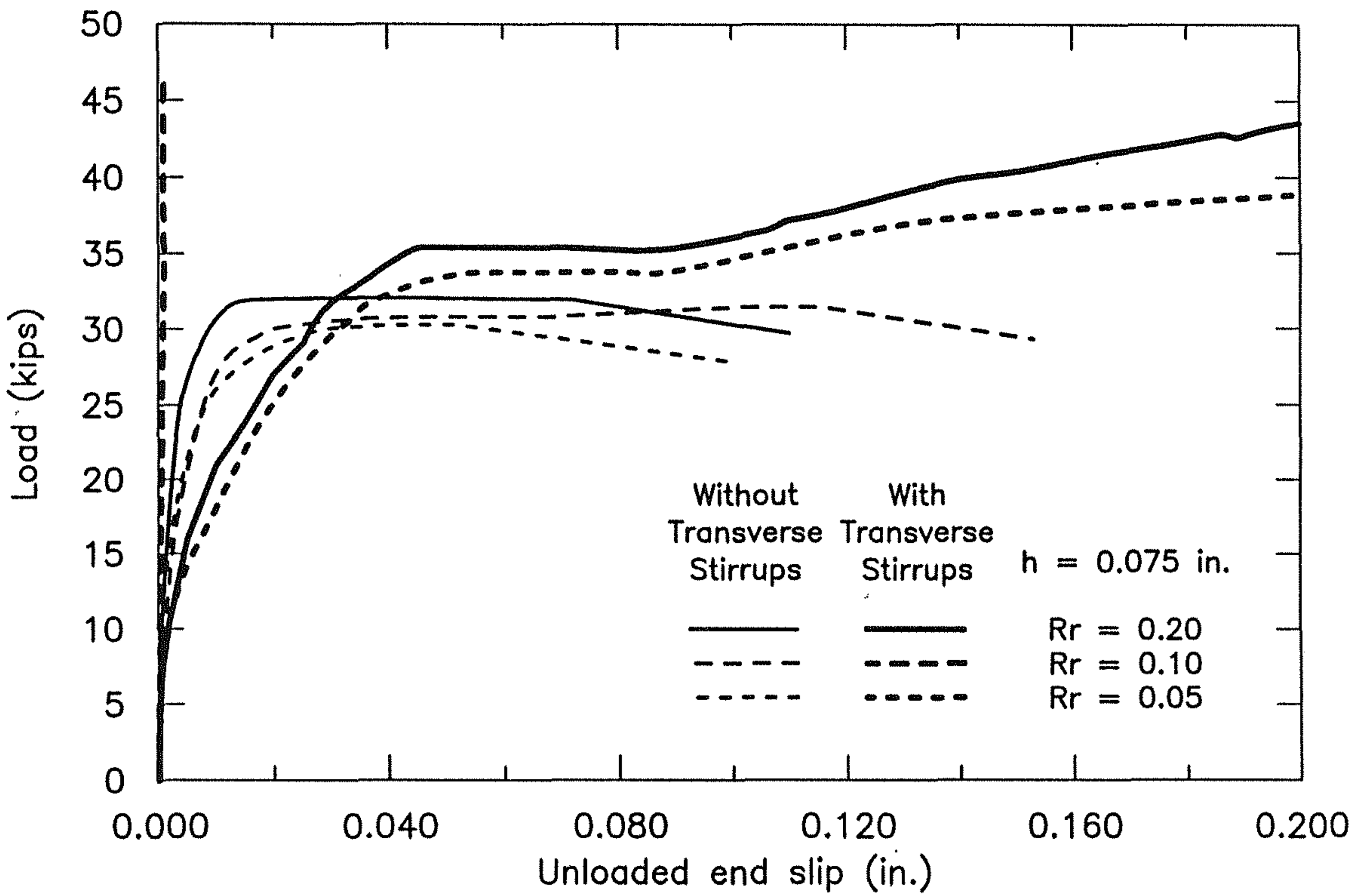

Fig. 22 Load-unloaded end slip curves for test bars with rib height h = 0.075 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 2 in., lead length = 1/2 in., bonded length = 12 in.) hooked auxiliary reinforcement

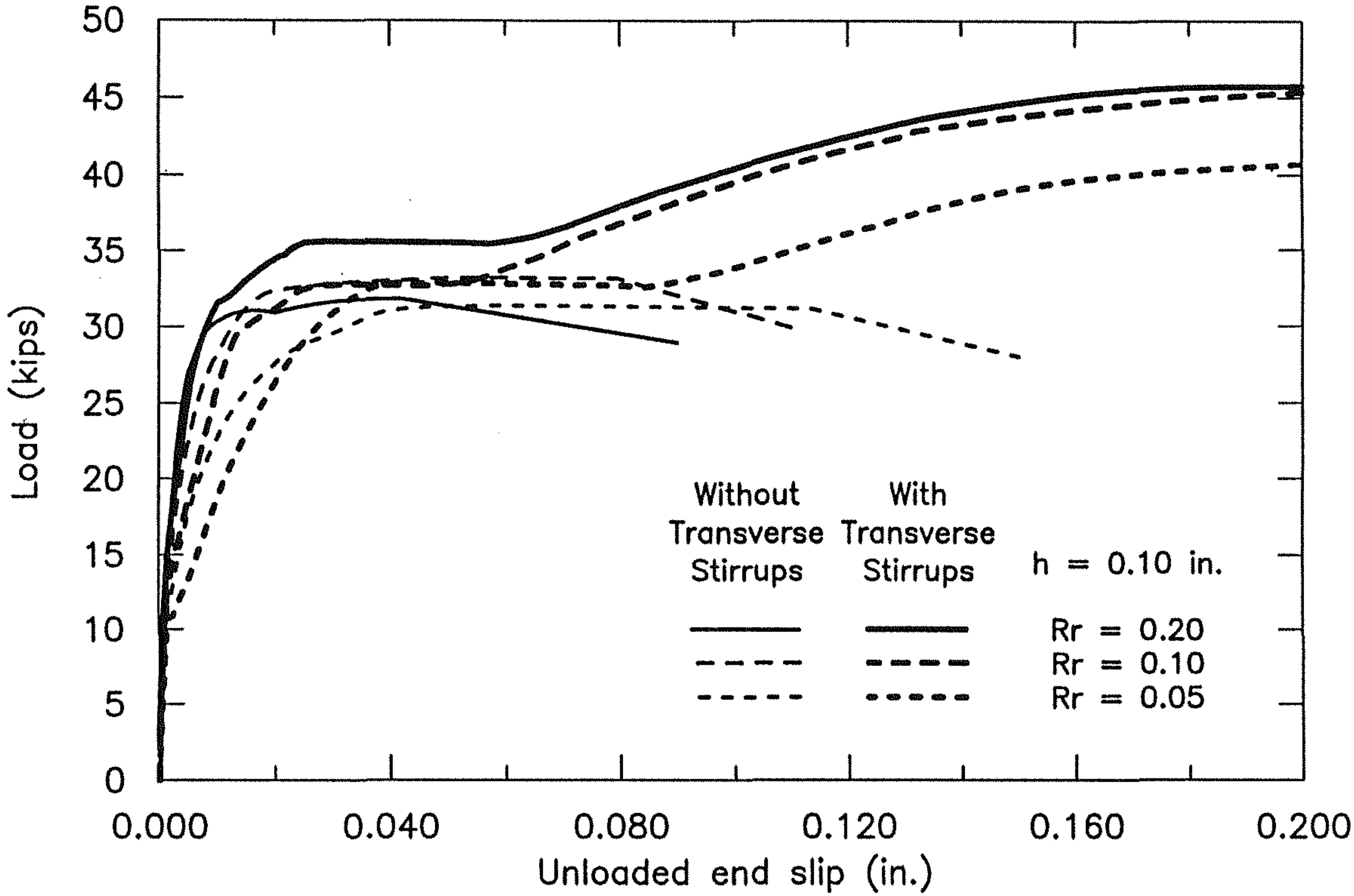

Fig. 23 Load-unloaded end slip curves for test bars with rib height h = 0.10 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 2 in., lead length = 1/2 in., bonded length = 12 in.) hooked auxiliary reinforcement

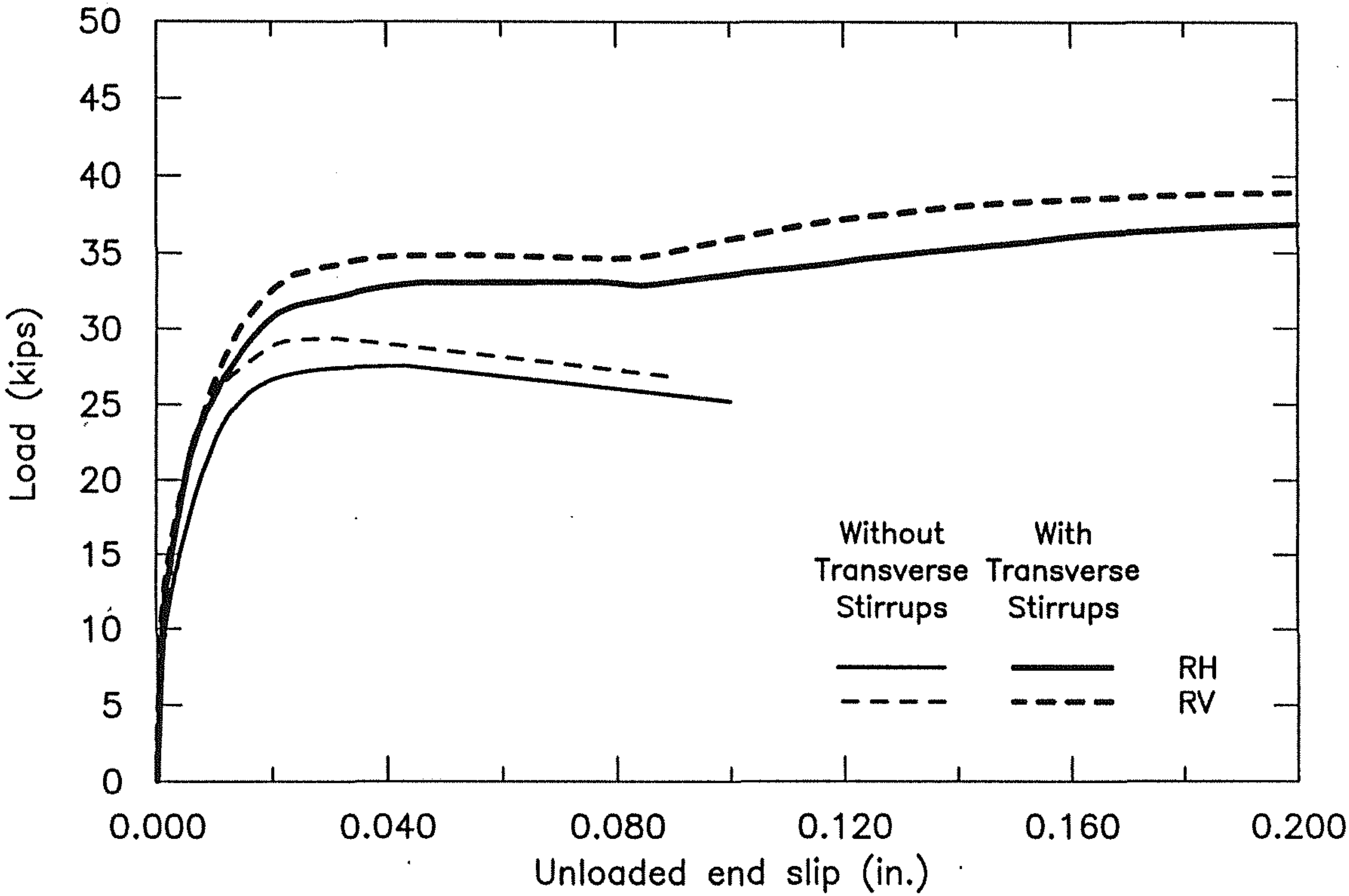

Fig. 24 Load-unloaded end slip curves for ASTM A 615 reinforcing bars with relative rib area = 0.07 (cover = 2 in., lead length = $1/2$ in., bonded length = 12 in.) hooked auxiliary reinforcement

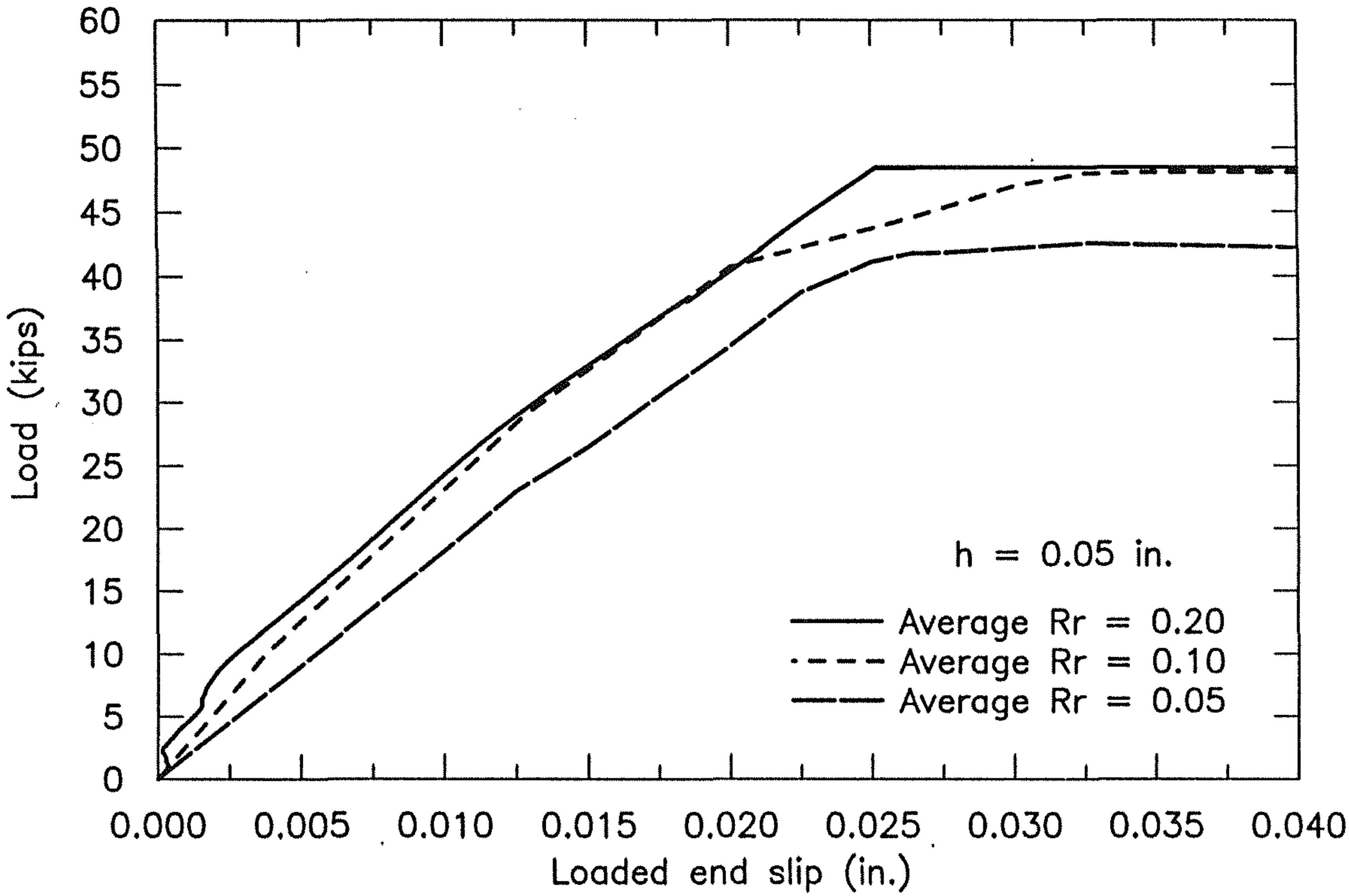

Fig. 25 Average load-loaded end slip curves for test bars not confined by transverse reinforcement with rib height h = 0.05 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 3 in., lead length = 4 in., bonded length = $8^{1}/_{2}$ in.)

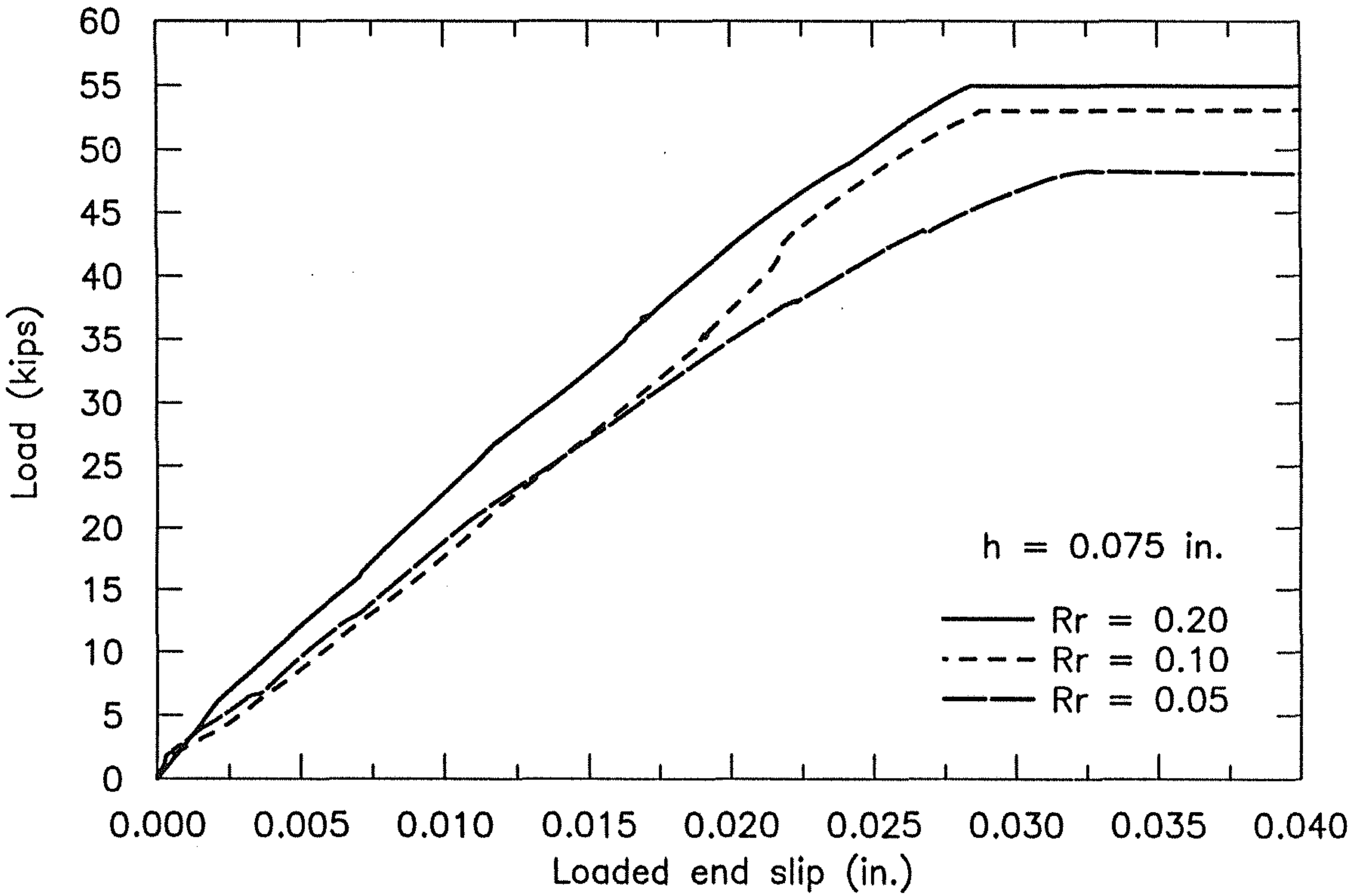

Fig. 26 Average load-loaded end slip curves for test bars not confined by transverse reinforcement with rib height h = 0.075 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 3 in., lead length = 4 in., bonded length = $8^1/_2$ in.)

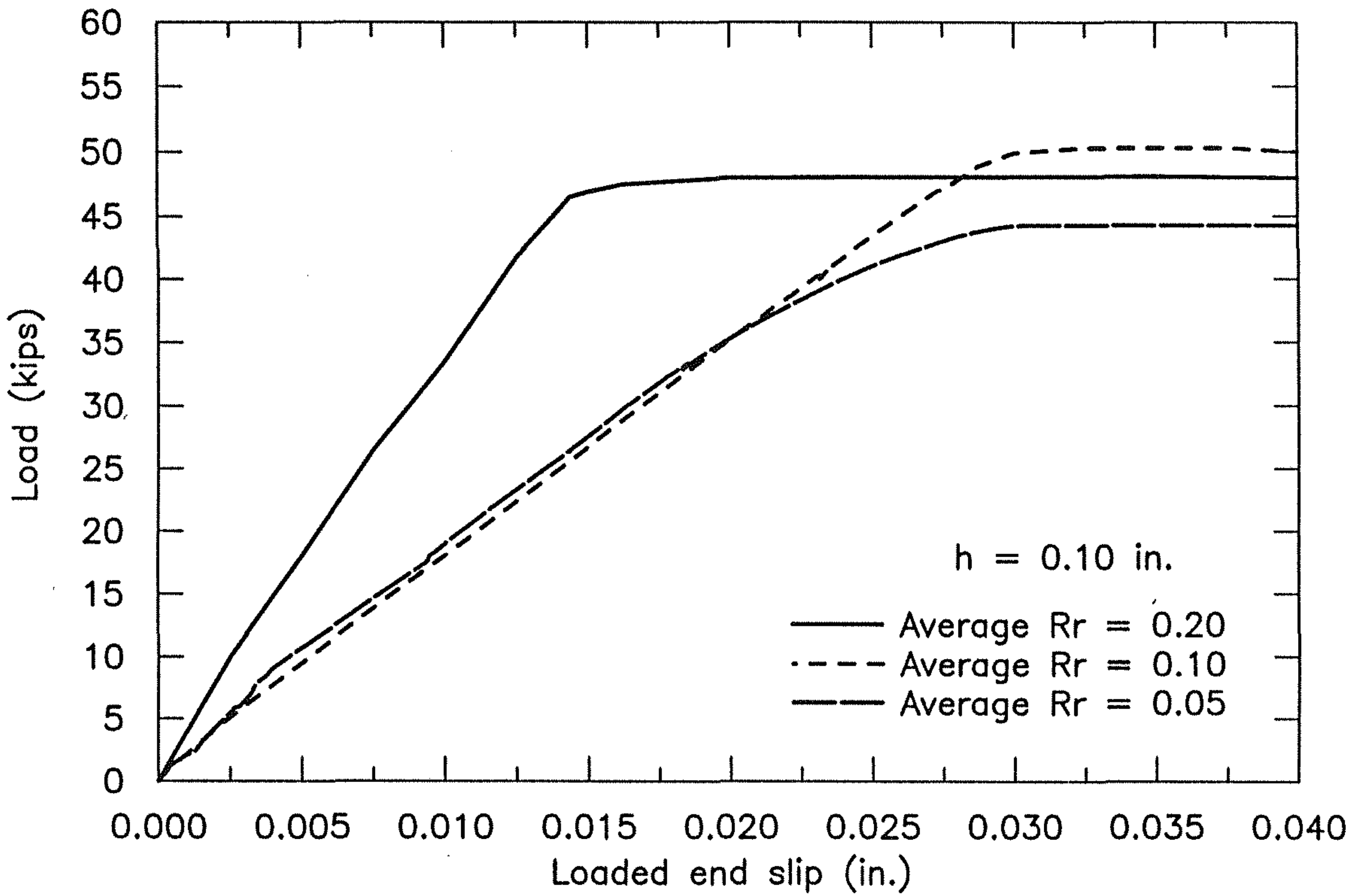

Fig. 27 Average load-loaded end slip curves for test bars not confined by transverse reinforcement with rib height h = 0.10 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 3 in., lead length = 4 in., bonded length = $8^1/_2$ in.)

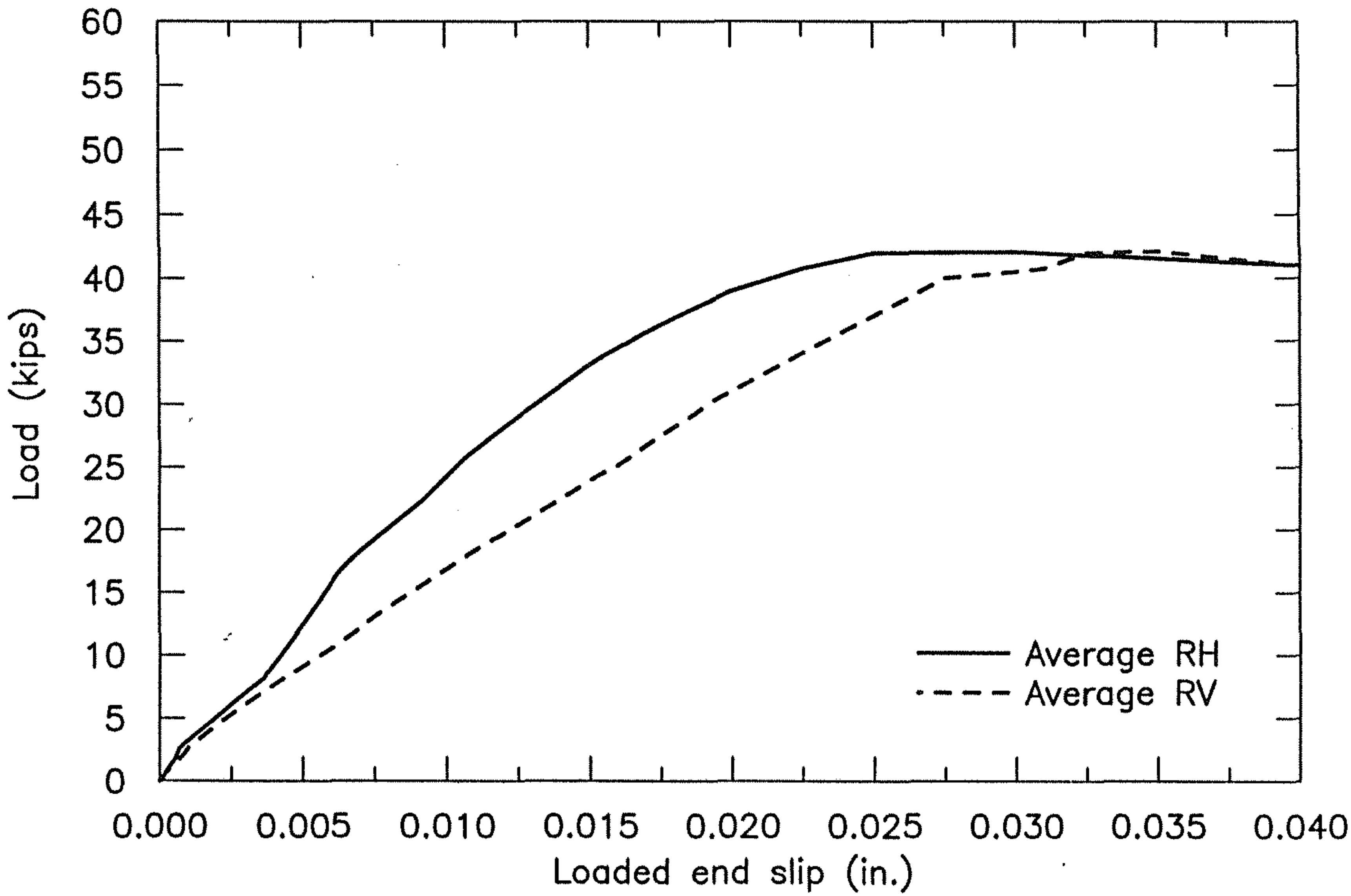

Fig. 28 Average load-loaded end slip curves for ASTM A 615 reinforcing bars not confined by transverse reinforcement with relative rib area = 0.07 (cover = 3 in., lead length = 4 in., bonded length = $8^1/_2$ in.)

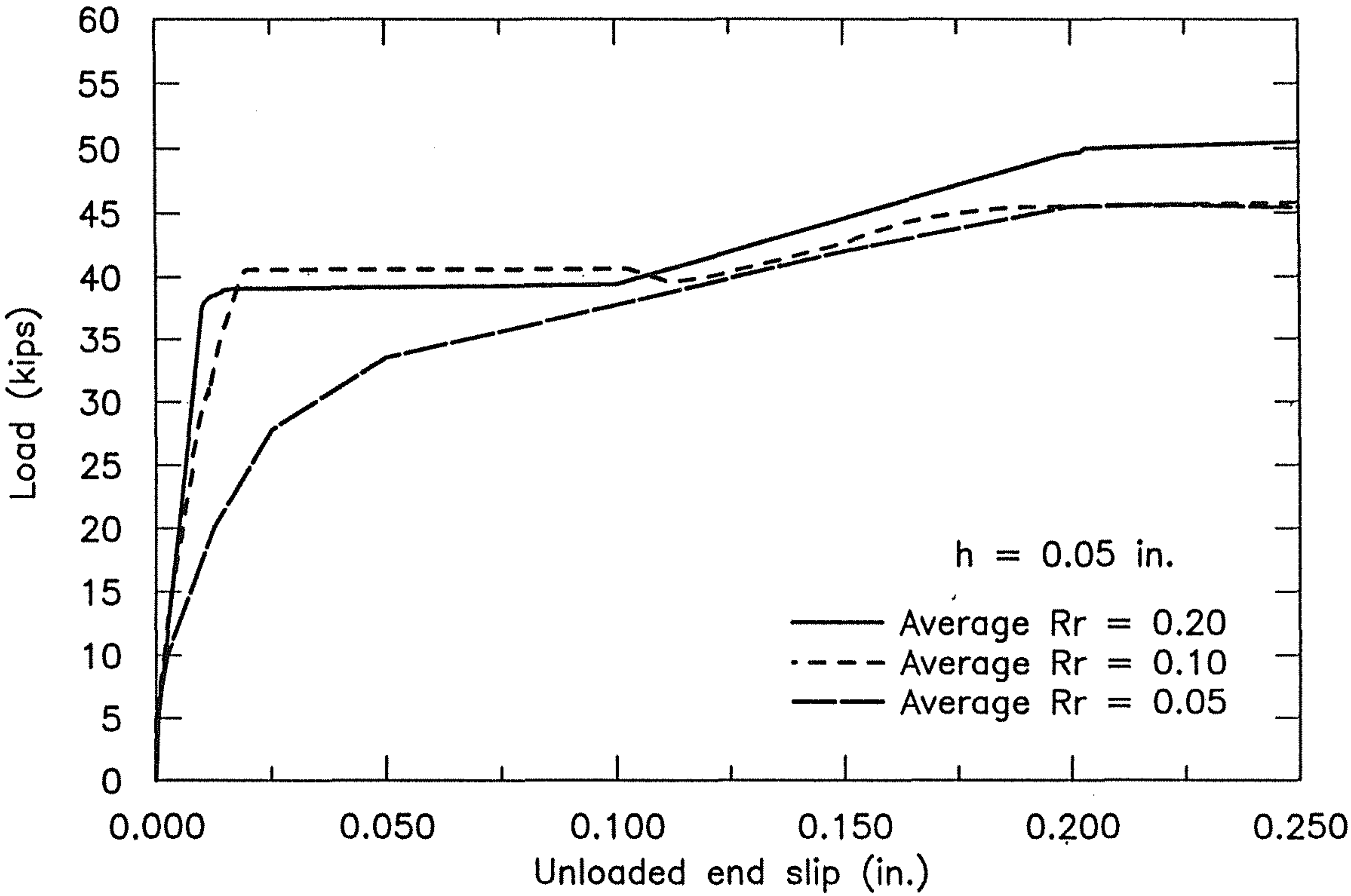

Fig. 29 Average load-unloaded end slip curves for test bars not confined by transverse reinforcement with rib height h = 0.05 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 3 in., lead length = 4 in., bonded length = 8 1/2 in.)

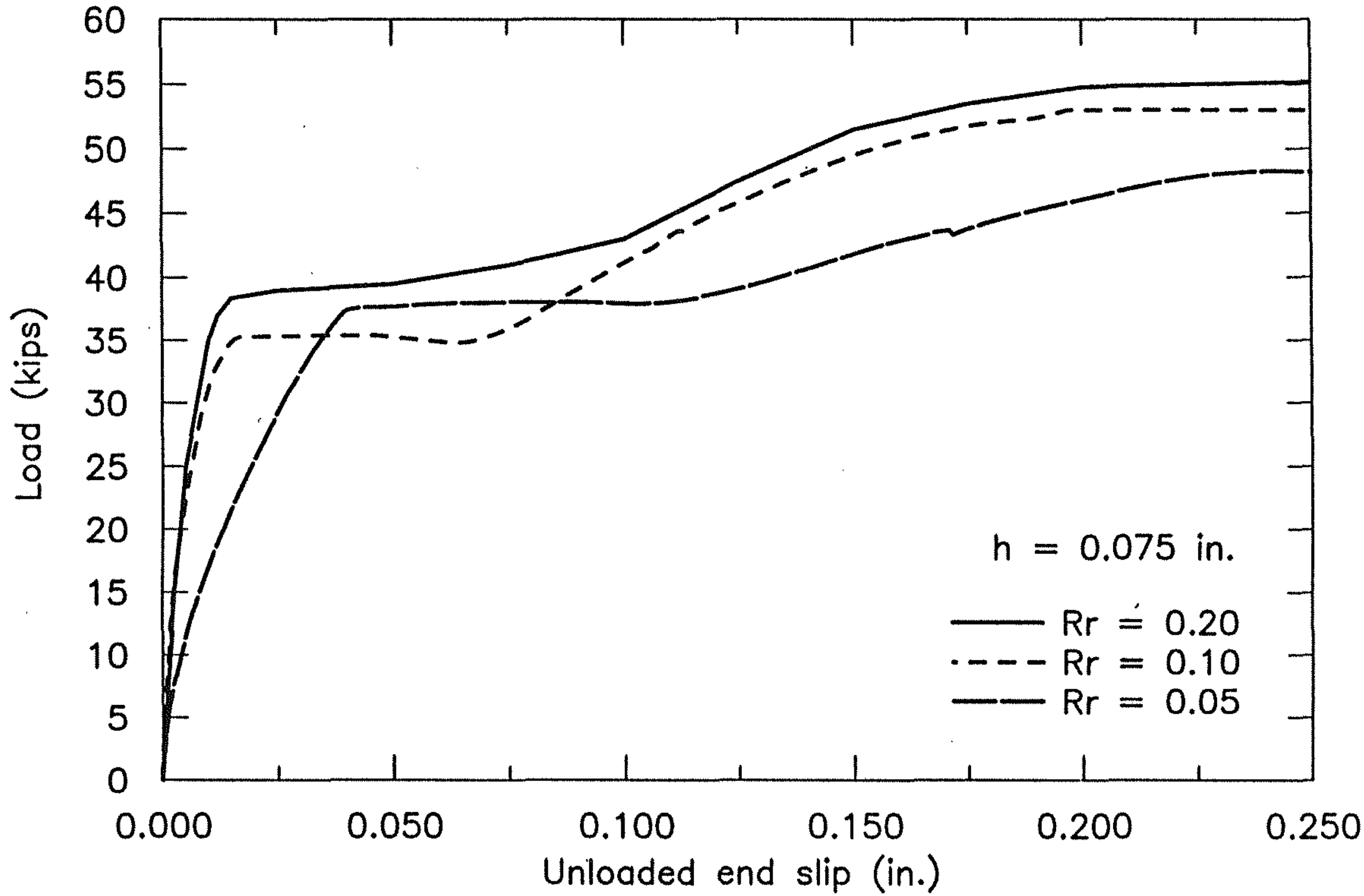

Fig. 30 Average load-unloaded end slip curves for test bars not confined by transverse reinforcement with rib height h = 0.075 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 3 in., lead length = 4 in., bonded length = $8^1/_2$ in.)

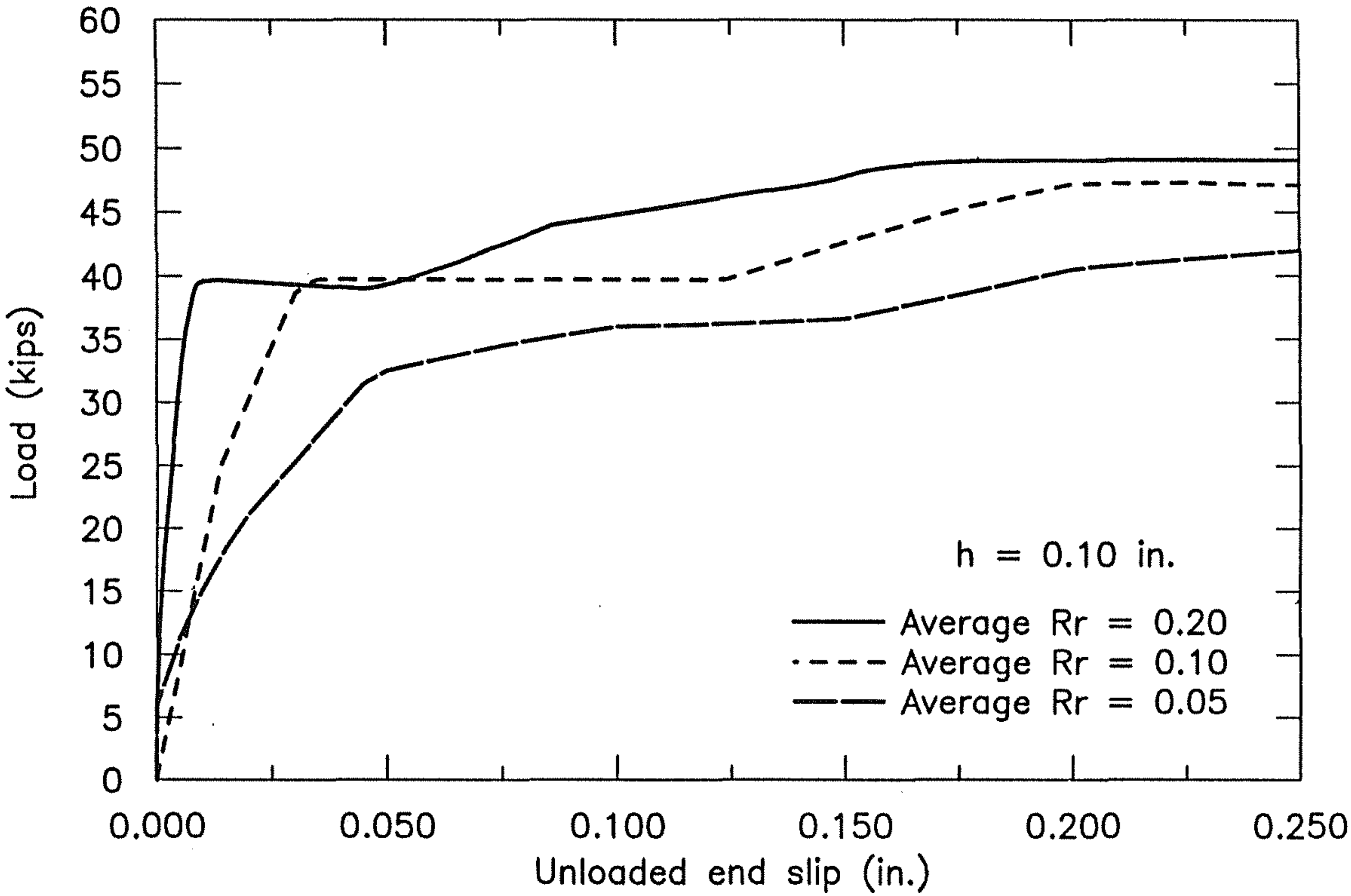

Fig. 31 Average load-unloaded end slip curves for test bars not confined by transverse reinforcement with rib height h = 0.10 in. and relative rib areas = 0.20, 0.10, and 0.05 (cover = 3 in., lead length = 4 in., bonded length = $8^1/_2$ in.)

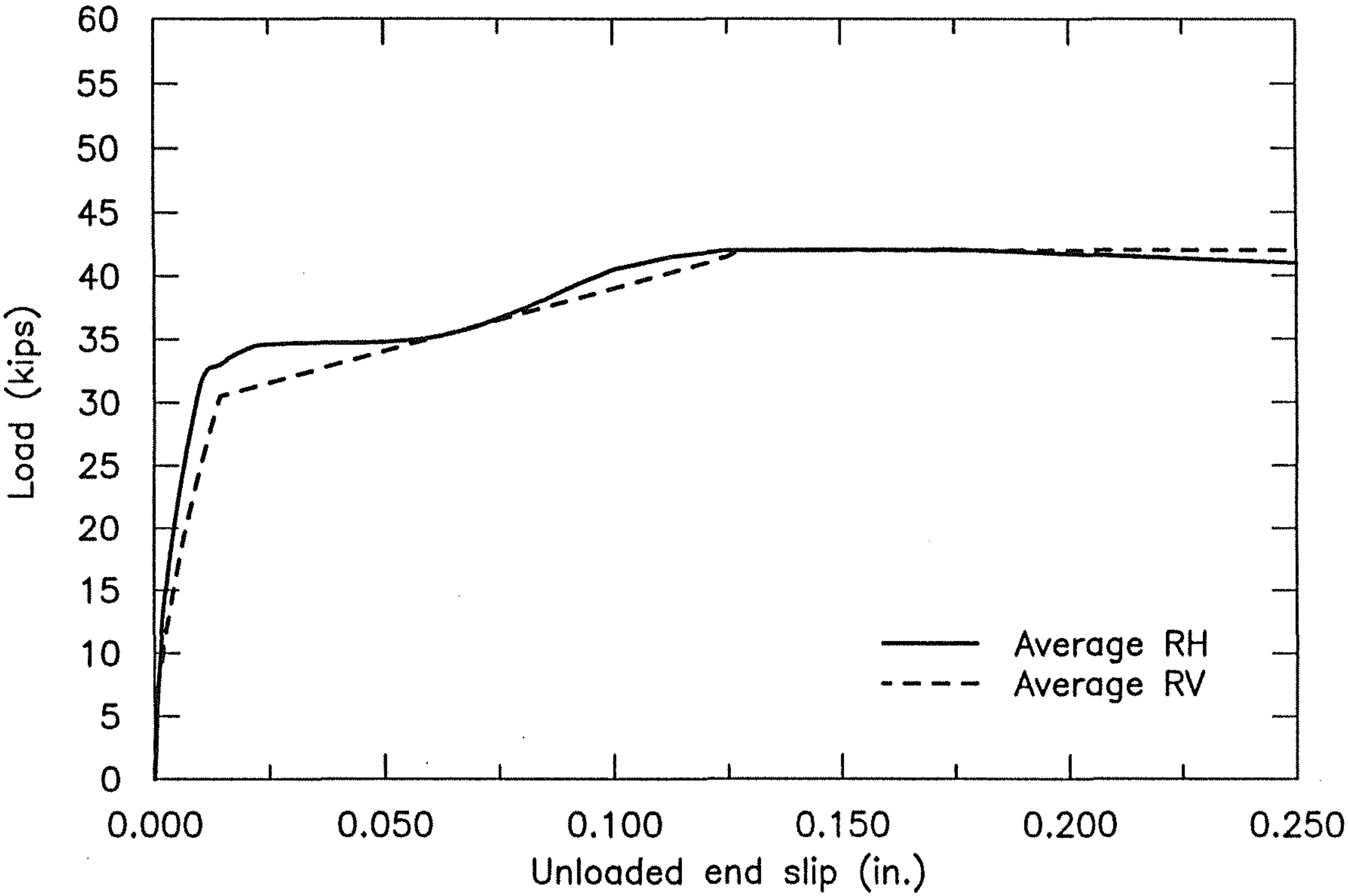

Fig. 32 Average load-unloaded end slip curves for ASTM A 615 reinforcing bars not confined by transverse reinforcement with relative rib area = 0.07 (cover = 3 in., lead length = 4 in., bonded length = $8^1/_2$ in.)

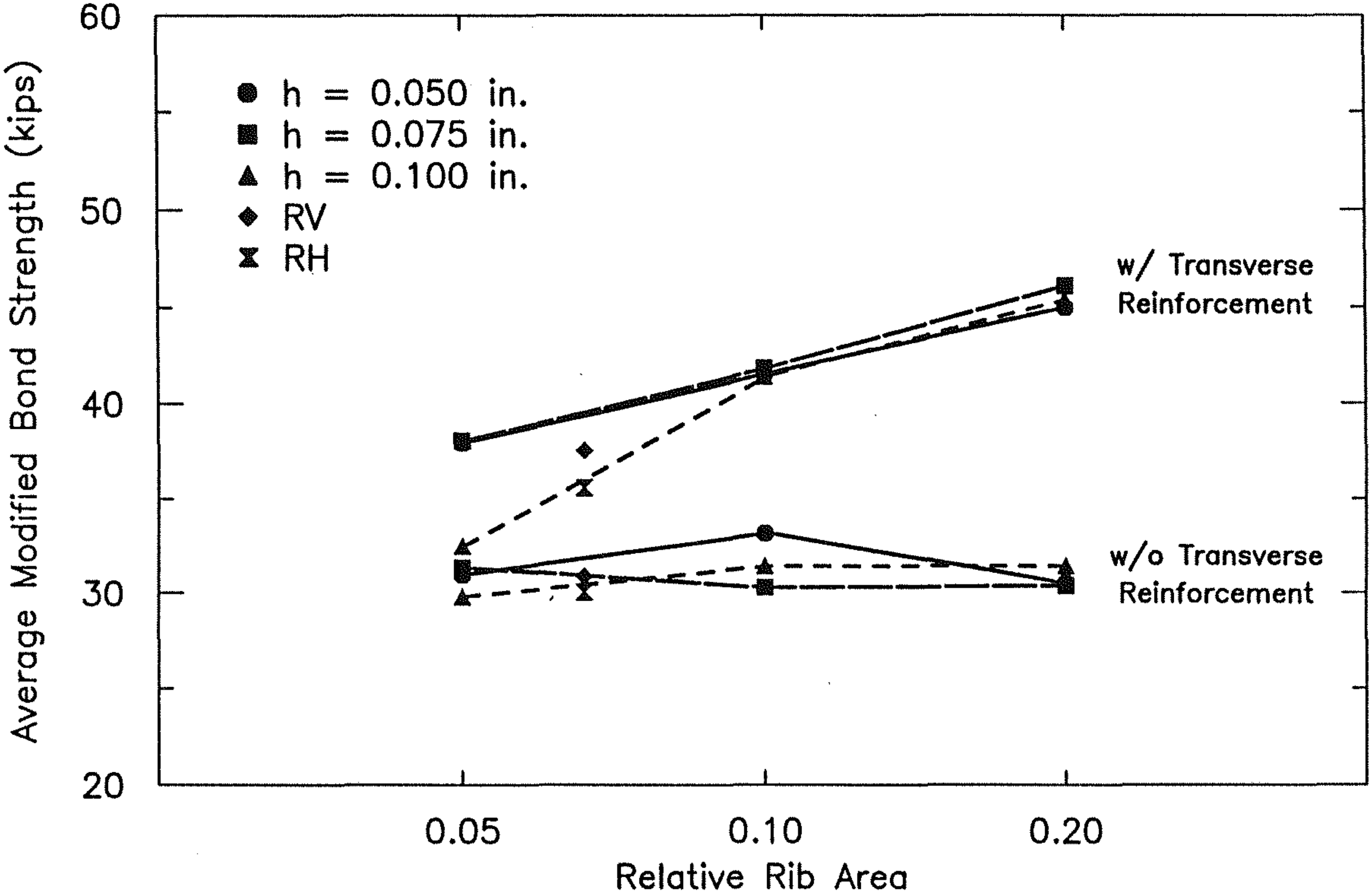

Fig. 33 Average modified bond strength versus relative rib area comparing the effects of confinement provided by transverse reinforcement (cover = 2 in., lead length = 1/2 in., bonded length = 12 in.)

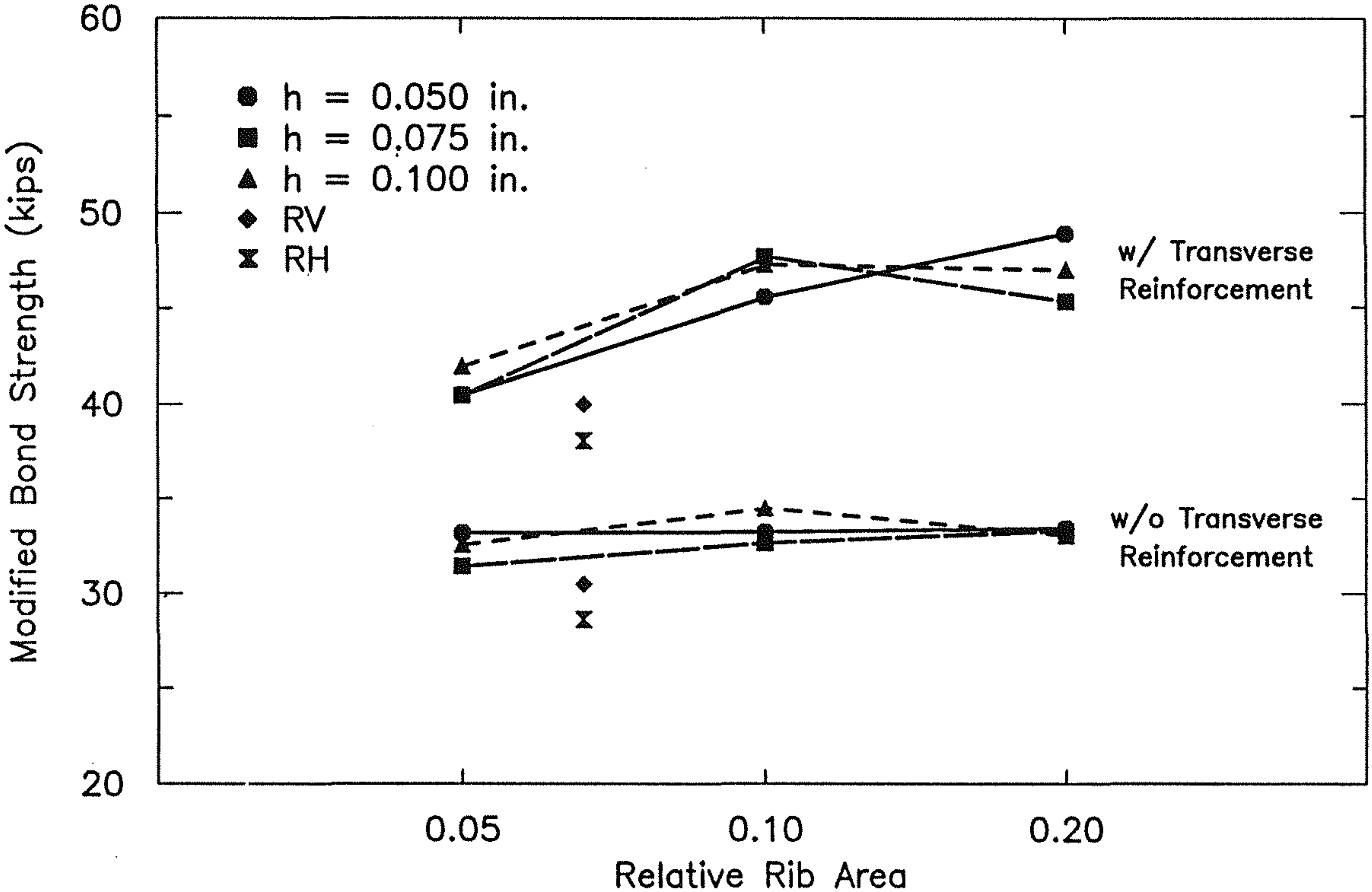

Fig. 34 Modified bond strength versus relative rib area comparing the effects of confinement provided by transverse reinforcement. Beam-end test specimens modified to include hooked auxiliary reinforcement (cover = 2 in., lead length = 1/2 in., bonded length = 12 in.)

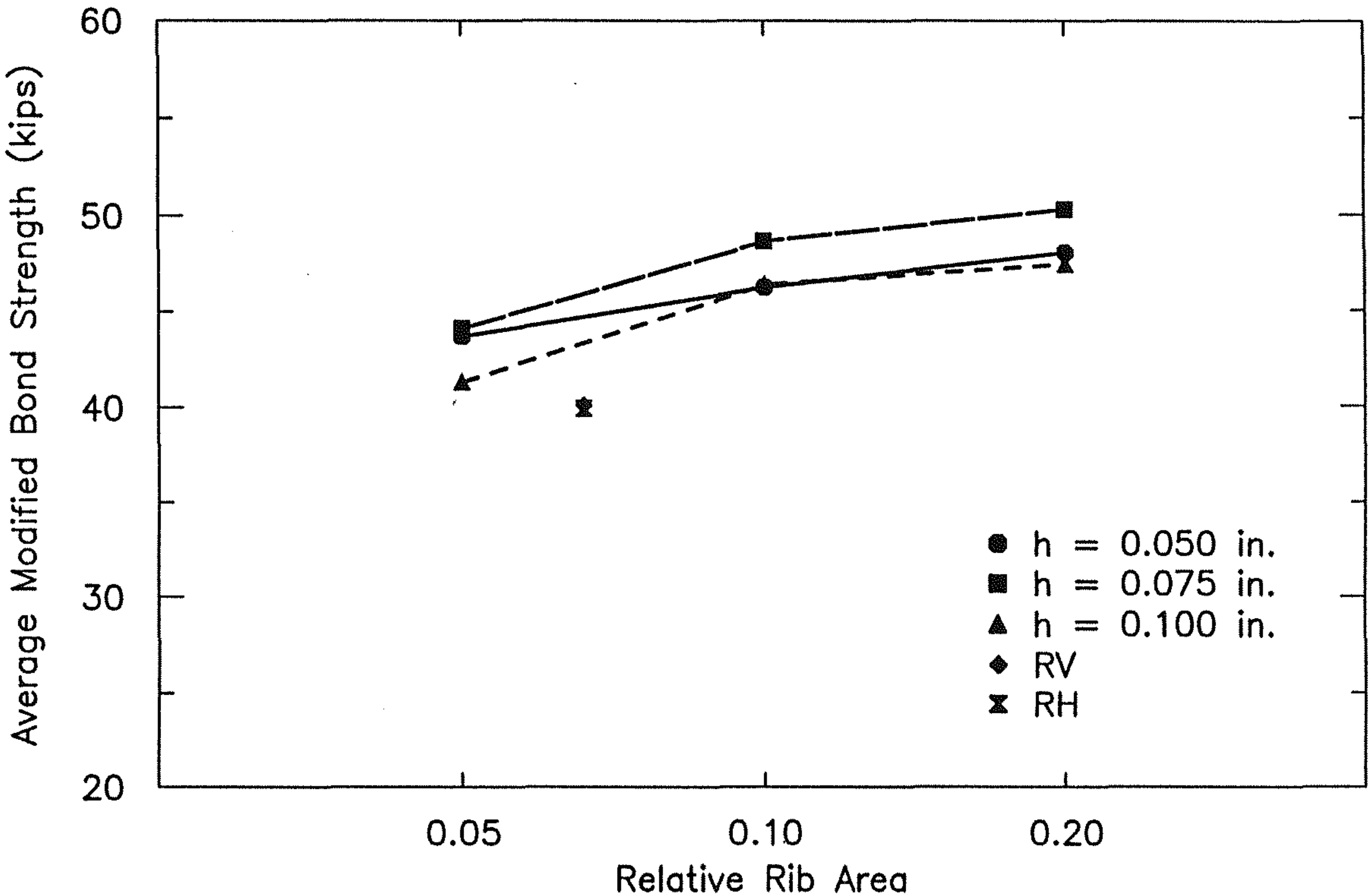

Fig. 35 Average modified bond strength versus relative rib area for reinforing bars with added concrete confinement (cover = 3 in., lead length = 4 in., bonded length = 8 1/2 in.). Low strength specimens not considered

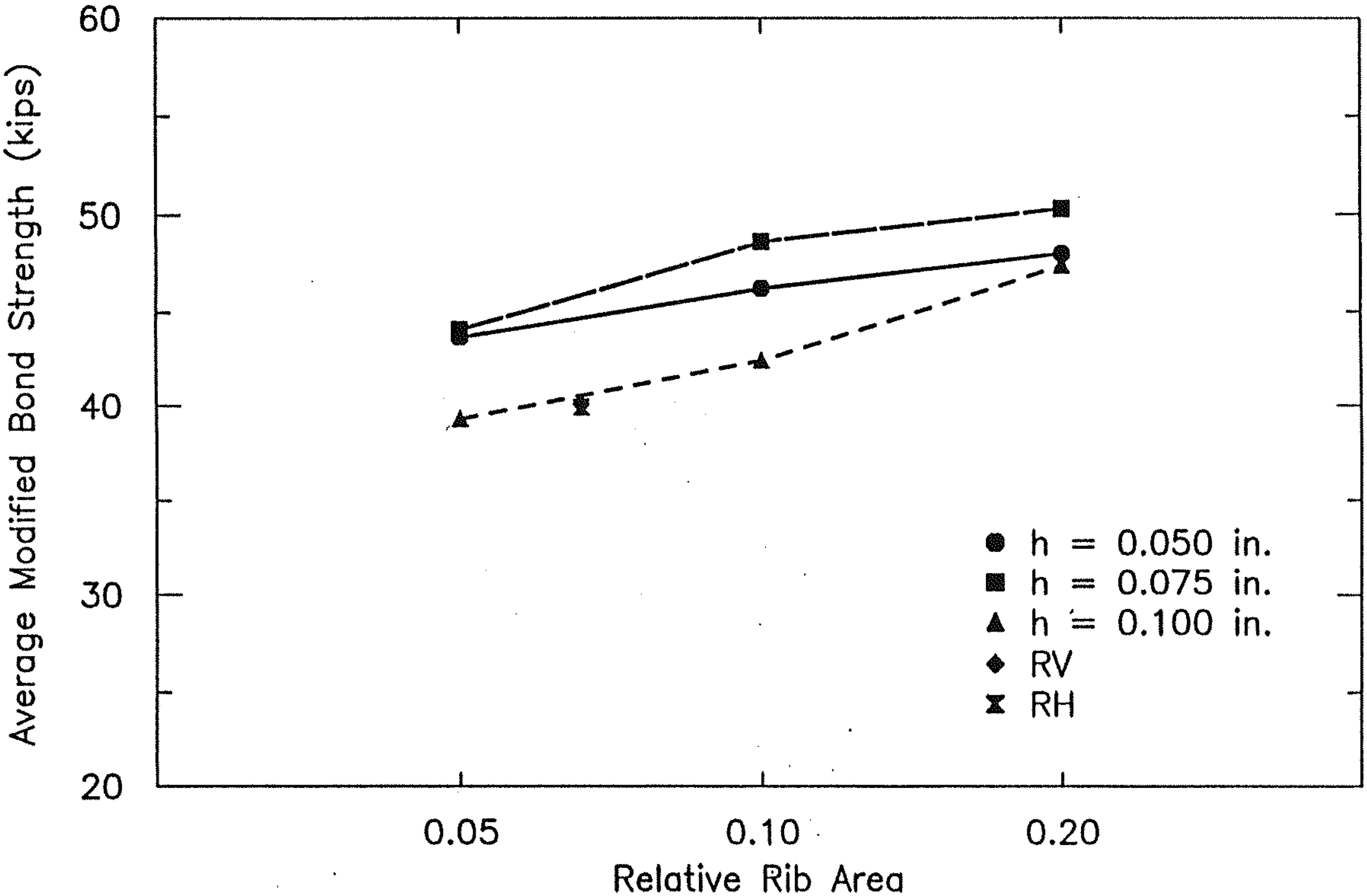

Fig. 36 Average modified bond strength versus relative rib area for reinforing bars with added concrete confinement (cover = 3 in., lead length = 4 in., bonded length = 8½ in.). All specimens considered