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Structural Engineering and Engineering Materials

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January 1998

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.

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

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ABSTRACT

ASTM **A** 944 beam-end specimens are used to evaluate the relative bond strength of epoxy-coated No. 19 [No. 6] reinforcing bars with coating thicknesses ranging from 160 to 510 µm (6.4 to 19.9 mils). Three deformation patterns are evaluated using epoxy meeting the requirements of ASTM **A** 775. The reduction in bond strength caused by epoxy coatings between 160 and 420 µm (6.4 and 16.5 mils) is largely independent of coating thickness, The reduction increases for coatings thicker than 420 µm (16.5 mils).

Keywords: bond (concrete to reinforcement); deformed reinforcement; development; epoxy coating; reinforcing steels; relative rib **area;** structural engineering.

ACKNOWLEDGEMENTS

Support for this research was provided by the National Science Foundation through NSF Grant No. CMS-9402563 under the Research Experiences for Undergraduates Program, ABC Coating, Inc., Akzo Nobel, Birmingham Steel Corporation, Chaparral Steel Company, Lane Enterprises, and Richmond Screw Anchor Company.

INTRODUCTION

Epoxy-coated steel reinforcing bars. are widely used in concrete construction to improve corrosion resistance. Current standards (ASTM A 775) allow coating thicknesses between 175 and 300 μm (7 and 12 mils) to be used. The coating, however, causes a reduction in bond strength between reinforcing bars and concrete. As a result, the ACI Building Code (ACI 318-95) and the AASHTO Bridge Specifications (1996) require the use of a development length modification factor of 1.5 for most applications.

Choi et al. (1990, 1991) evaluated the effect of coating thickness on the bond strength of epoxy-coated bars. Their work shows that coating thickness has no significant effect on bond strength as the coating thickness increases from 76 to 300 μm (3 to 12 mils) for No. 19 [No. 6] bars and from 76 to 400 μm (3 to 16 mils) for No. 25 [No. 8] bars. For No. 16 [No. 5] bars, the study shows a decrease in bond strength as coating thickness increases. It would be desirable in many cases to increase the maximum allowable coating thickness.

While it has been shown that coating thickness plays little role in the bond strength of No. 25 [No. 8] bars and larger, and plays a large role in the bond strength of No. 16 [No. 5] bars and smaller, no studies to date have evaluated the bond strength of epoxy-coated No. 19 [No. 6] bars with coating thicknesses significantly greater than 300 μm (12 mils).

This study addresses the bond strength of No. 19 [No. 6] reinforcing bars coated with epoxy meeting the requirements of ASTM A 775. Bars with average coating thicknesses from 160 to 510 μm (6.4 to 19.9 mils) are tested to determine whether thicknesses greater than 300 μm (12 mils) can be used on these bars without causing a significant reduction in bond strength.

EXPERIMENTAL PROGRAM

The experimental program consisted of 72 beam-end specimens. No. 19 [No. 6] test bars were obtained from three companies: Birmingham Steel Corporation, Chaparral Steel Company, and Structural Metals Inc. (SMI). The three deformation patterns are designated B, C, and S, respectively. For each deformation pattern, tests were run on 12 uncoated bars and 12 coated bars, three each with approximate coating thicknesses of 175, 300, 380,-and 460 μm (7, 12, 15, and 18 mils). Actual coating thicknesses ranged from 160 to 510 μm (6.4 to 19.9 mils).

Test Specimens

The test specimens were fabricated according to ASTM A 944 (Fig. 1) with a nominal cover of 38 mm (1.5 in.). Test bars were oriented with the longitudinal ribs in the vertical plane. Auxiliary reinforcement consisted of two No. 16 [No. 5] bars parallel to the test bar for flexural reinforcement and four No. 10 [No. 3] closed stirrups. Uncoated bars were used as stirrups in the front of the specimens and epoxy-coated bars were used as stirrups in the back of the specimens [The use of epoxy-coated stirrups was for convenience only and had no effect on the tests]. No. 16 [No. 5] transverse bars were used in accordance with ASTM A 944. Prior to testing, cover was measured by placing a straight edge on top of the test specimen and measuring the distance from the straight edge to the top of the test bar to the nearest 1 mm ($^1/_{16}$ in.) using a ruler. Nominal embedment length, lead length, and cover were constant for all specimens at 267 mm (10.5 in.), 12.7 mm (0.5 in.) and 38.1 mm (1.5 in.), respectively.

Materials

Reinforcing Steel–The test bars were ASTM A 615 grade 420 [60] No. 19 [No. 6] bars with three different deformation patterns (Fig. **2).** The Birmingham steel, B, bars had diagonal ribs oriented 70 degrees to the longitudinal axis. The Chaparral steel, C, bars had diagonal ribs oriented 60 degrees to the longitudinal axis. The SMI, S, bars had ribs that were perpendicular to the longitudinal axis. The test bars for each deformation pattern came from the same heat of steel. Bar properties are listed in Table 1.

The epoxy coating was applied by ABC Coating Company Inc. at approximate thicknesses of 175, 300, 380, and 460 μm (7, 12, 15, and 18 mils) using Akzo Nobel Resicoat 500607 epoxy powder. With the exception of coating thickness, the epoxy was applied in accordance with ASTM A 775. Average coating thicknesses were measured using a pull-off type gauge (ASTM A 775). Coating measurements were taken at five points along the bonded length on each side of the test bars. The average of these measurements was used to analyze the effects of. coating thickness on bond strength.

Concrete–Air-entrained concrete was supplied by a local ready mix plant. The concrete contained Type I portland cement, 19 mm ($^3/_4$ in.) nominal maximum size crushed limestone, and Kansas River sand. The concrete was cast with water-cement ratios between 0.44 and 0.49, providing a nominal strength of about 34 MPa (5000 psi). Mix proportions and concrete properties are listed in Table 2.

Placement Procedure

Concrete was placed in two lifts of nearly equal volume. Each specimen received its first lift before any specimen received a second lift. After each lift was placed, the specimens were vibrated at four points, starting at the end closest to the bonded length. Standard test cylinders were cast according to ASTM C 192 and cured side by side with the test specimens. Forms were stripped after the concrete had reached a minimum compressive strength of 19 MPa (2700 psi).

The test specimens were cast in three batches, each covering the full range of deformation patterns and coating thicknesses. Each batch was placed with the specimens arranged in a different order so as not to create systematic differences in bond strength due to differences in concrete properties from different portions of the discharge of the ready-mix truck. Forms were grouped by deformation pattern because differences in bond strength between deformation patterns are not a consideration in this study. To limit bias due to differences in concrete properties, forms with coated and uncoated bars were alternated. Coated bars were placed in a different order (based on coating thickness) in each batch, so that no three bars had either an ascending or descending coating thickness order.

Test Procedure

Specimens were tested in accordance with ASTM A 944 using the testing apparatus shown in Fig. 3. Each group of specimens was tested over a 48 hour period at concrete strengths between 32 and 35 MPa (4700 and 5000 psi). Load was applied at a rate of about 15 kN [3.5 kips] per minute using two steel rods with diameters of 25 mm (1 in.), which were, in turn, loaded by hollow-core, 500 kN (60 ton) hydraulic jacks, powered by an Amsler hydraulic testing machine.

Displacement of the test bar at both the loaded and unloaded ends was measured using spring-loaded linear variable differential transformers (LVDTs). Two loaded end slip LVDTs were mounted on a yoke attached to the test bar 127 mm (5 in.) from the front face of the specimen. Results in this report for loaded end slip include elastic lengthening of the test bar between the yoke and the face of the test specimen. Unloaded end slip was measured by one LVDT placed against the end of the test bar, through the steel conduit at the rear of the specimen.

RESULTS AND DISCUSSION

Load-Slip Curve and Cracking Patterns

Typical load-slip curves for the test specimens (in this case from Test Group B) are shown in Figs. A.1-A.6. The load-loaded end-slip curves exhibit significant scatter, with the uncoated bars exhibiting generally, but not universally, greater stiffness than the coated bars. In contrast, the load-unloaded end-slip curves for the coated bars are nearly always stiffer than the matching curves for the coated bars, since the unloaded slip is sensitive to the bond properties along the full embedded length of the bar.

Cracking patterns were similar for all specimens. As observed in earlier studies (Choi et al. 1990, Darwin and Graham 1993), a small thin longitudinal crack began at the front of the top of the specimen just before failure, and with failure, widened, lengthened and ended in an inverted T at the middle of the top face. On the front face of the specimen, cracking occurred in an inverted Y, splitting around the test bar. Specimens with epoxy-coated test bars failed with a bang, but specimens with uncoated test bars failed more quietly.

When concrete was chipped away after testing, the epoxy-coated bars showed no sign of having bonded with the concrete. Coated bars were clean, and the concrete that had been in contact with them was smooth. For the uncoated test bars, some concrete remained stuck to the bars, and concrete powder was visible on the front side of the ribs. The concrete that had been in contact with the uncoated test bars was rougher than the concrete that had been in contact with the epoxy-coated bars.

Bond Strength

Bond strengths are given in Table 3, along with coating thicknesses, covers and concrete strengths. Modified bond strengths are calculated to account for differences in concrete strength and deviations in cover from the nominal value of 38.1 mm (1.5 in.). To do this, test strengths are normalized to a concrete strength of 34 MPa (5000 psi), using the assumption that bond strength is proportional to the $^1/_4$ power of the compressive strength (Darwin et al. 1995, 1996), and to a cover of 38.1 mm (1.5 in.) using the assumption that bond strength is directly proportional to the cover to the center of the bar (Darwin et al. 1995, 1996). Thus, bond strengths are multiplied by $(34/f'_c)^{1/4}$ $47.6/(9.5+C_b)$ $[(5000/f'_c)^{1/4}$ $1.875/(0.375+C_b)]$, where f'_c and C_b are the measured compressive strength and cover, respectively. The effect of the epoxy coating is evaluated by averaging the modified bond strengths of the uncoated bars tested from each group for each deformation pattern. The modified bond strength of each epoxy-coated bar is then divided by the average strength of uncoated bars from the same group with the same deformation pattern to obtain the ratio of the bond strength of the epoxy-coated bar to the bond strength of the uncoated bars, or C/U ratio.

The effect of coating thickness on the C/U ratio is analyzed using the technique of dummy variables (Draper and Smith 1981). Application of this technique is based on the assumption that the effect of epoxy coating on bond strength may be different for different deformation patterns, but that the effect of coating thickness on bond strength is the same for all patterns. Best-fit lines for C/U ratio versus coating thickness established using this technique are shown in Fig. 4. The general trend of the best-fit lines is a reduction in the C/U ratio with an increase in coating thickness for the full range of coating thicknesses evaluated. The test results show significant scatter, as expected for bond tests.

Three of the data points for Chaparral Steel may be considered to be unrepresentative. Specimen C7A, with a coating thickness of 187 µm (7.35 mils) and a C/U ratio of 0.856, was cast in the first batch with the first concrete discharged from the ready mix truck. Its strength is low for C-pattern bars with a nominal thickness of 175 μm (7 mils). The test results for specimen C-12b, with a coating thickness of 353 μm (13.89 mils), is significantly higher than any of the data and the bond strength for specimen C15C, with a coating thickness of 394 μm (15.50 mils) and a C/U ratio of 0.762, is significantly weaker than any of the other test specimens. These three specimens are removed from the data base to limit their effect on the analysis. As shown in Fig. 5, however, removal of the three data points has little effect on the observed trend, which is an overall decrease in bond strength of coated bars as the coating thickness increases from 160 to 510 μm (6.4 to 19.9 mils).

In contrast to the results shown in Figs. 4 and 5, a detailed evaluation of the data indicates that there is a significant range of coating thickness over which the relative bond strength of coated reinforcement is not affected. This point is illustrated in Fig. 6, where the data for bars with coatings in excess of 430 μm (17 mils) are removed. In this case, the overall trend of the data is a slight increase in C/U as the coating thickness increases from 160 μm (7 mils) to a maximum value of 423 μm (16.65 mils), the upper limit for bars with coating thicknesses less than 430 μm (17 mils). Since the actual data is based on bars with an upper coating thickness very close to 420 μm (16.5 mils), this can be considered a safe upper bound for bars with coatings meeting the requirements of ASTM A 775. For No. 19 [No. 6] bars, coating thicknesses in excess of 430 μm (17 mils) result in a noticeable decrease in bond strength.

Prior research (Choi et al. 1990, 1991) demonstrated that the bond strength of epoxy-coated No. 25 [No. 8] bars is not sensitive to coating thickness for coatings with thicknesses up to about 410 μm (16 mils), the upper limit on the data. (It should be noted that most of the data on the No. 25 [No. 8] bars in the earlier study were for coatings with thicknesses of 350 μm [14 mils] or less.) As observed earlier, the work by Choi et al. also demonstrated that bond strength drops significantly with increasing coating thickness for No. 16 [No. 5] bars and smaller.

Overall, the current study indicates that it is realistic to allow an increase in the maximum coating thickness to 420 μm (16.5 mils) for No. 19 [No. 6] and larger bars meeting the requirements of ASTM A 775. The maximum coating thickness for smaller bars should remain 300 μm (12 mils).

CONCLUSIONS

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

1. ASTM A 775 epoxy coatings with thicknesses in the range of 160 to 510 ym (6.4 to 19.9 mils) significantly reduce the bond strength of deformed No. 19 [No. 6] reinforcing bars to concrete.
2. For ASTM A 775 epoxy coatings with a thickness between 160 and 420 ym (6.4 and 16.5 mils), differences in coating thickness have little effect on the amount of bond strength reduction for No. 19 [No. 6] bars. Coatings thicker than 420 μm (16.5 mils) cause an additional drop in bond strength relative to the bond strength obtained with thinner coatings.

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Table l a Average Test Bar Data (S. I. Units)

Nominal Bar Dia.	Rib Pattern+	Yield Strength	Rib Height		Rib Spacing	Rib Gap*	Def. Angle	Rib Face Angle ***	Rib Bearing Area per mm**	Relative Rib Area
			Avg.++	ASTM						
(mm)		(MPa)	(mm)	(mm)	(mm)	(mm)	(deg.)	(deg.)		
19	B	437	1.07	1.15	10.4	2.92	70	42	0.0606	0.08929
19	C	479	0.93	1.11	10.9	4.93	60	44	0.0616	0.07108
19	S	431	1.00	1.10	10.9	3.43	90	22	0.0609	0.08093

Table l b Average Test Bar Data (Customary Units)

Nominal Bar Dia.	Rib Pattern+	Yield Strength	Rib Height		Rib Spacing	Rib Gap*	Rib Angle	Rib Face Angle ***	Rib Bearing Area per in**	Relative Rib Area
			Avg.++	ASTM						
(in.)		(ksi)	(in.)	(in.)	(in.)	(in.)	(deg.)	(deg.)		
0.75	B	63.4	0.042	0.045	0.409	0.115	70	42	0.251	0.08929
0.75	C	69.4	0.036	0.044	0.429	0.194	60	44	0.231	0.07108
0.75	S	62.5	0.039	0.043	0.429	0.135	90	22	0.240	0.08093

\+ B, Birmingham Steel Corporation
C, Chaparral Steel Company
S, Structural Metals Inc.

++ The average height of deformations, h_r, is determined from measurements made on not less than two typical deformations on each side of the bar. Determinations are based on five measurements per deformation, one at the center of the overall length, two at the ends of the overall length, and two located halfway between the center and the ends. The measurements at the ends of the overall length are averaged to obtain a single value and that value is combined with the other three measurements to obtain the average rib height, h_r.

* Thickness of the longitudinal rib.

** Bearing area of the deformations divided by the spacing of the deformations.

*** Average of the face angles measured for the 4 different faces.
B: 30,42,45,50
C: 42,44,45,44
S: 22,23,22,21

Table 2a Concrete Mixture Proportions and Properties (Cubic Meter Batch)

Group	W/C ratio	Cement (kg)	Water (kg)	Aggregate Fine+ (kg)	Aggregate Coarse++ (kg)	Slump (mm)	Concrete Temperature °C	Age at Test (days)	Average Compressive Strength (MPa)
1	0.49	299	146	914	971	36	22	13	34.4
								14	
2	0.48	300	144	917	974	96	23	21	32.5
								22	32.8
3	0.45	303	135	927	984	66	26	25	32.6
								26	32.8

Table 2b Concrete Mixture Proportions and Properties (Cubic Yard Batch)

Group	W/C ratio	Cement (lb)	Water (lb)	Aggregate Fine+ (lb)	Aggregate Coarse++ (lb)	Slump (in.)	Concrete Temperature °F	Age at Test (days)	Average Compressive Strength (psi)
1	0.49	504	246	1541	1637	1 1/2	71	13	4990
								14	
2	0.48	505	242	1546	1642	3 3/4	73	21	4710
								22	4750
3	0.44	510	227	1562	1659	2 1/2	78	25	4720
								26	4760

+ Kansas River Sand – Holiday Sand and Gravel Company, Desoto, KS, bulk specific gravity = 2.62, absorption = 0.5%, fineness modulus = 3.0.

++ Crushed limestone – Fogle Quarry Company, Inc., Ottawa, KS, bulk specific gravity = 2.58, absorption = 2.7%, maximum size = 19mm (¾ in.), unit weight = 1450 kg/m^3 (90.5 lb/ft^3)

Table 3a Beam End Tests (S.I. units)

Test Group	Specimen Label	Coating Thickness (μm)	Cover (mm)	Concrete Strength (MPa)	Bond Strength (kN)	Modified Bond Strength (kN)	C/U Ratio
A	BA1	0	38.10	34.4	70.3	70.3	
A	BA2	0	39.69	34.4	86.1	83.3	
A	BA3	0	42.86	34.4	102.8	93.5	
A	BA4	0	39.69	34.4	103.3	100.0	
A	B7A	199	38.10	34.4	80.3	80.3	0.925
A	B12A	314	39.69	34.4	93.0	90.0	0.981
A	B15A	380	38.10	34.4	82.3	82.3	0.948
A	B18A	504	41.28	34.4	80.2	75.2	0.866
A	CA1	0	38.10	34.4	87.9	88.0	
A	CA2	0	39.91	34.4	89.4	86.2	
A	CA3	0	38.10	34.4	89.8	89.8	
A	CA4	0	39.69	34.4	84.8	82.1	
A	C7A	187	39.69	34.4	76.6	74.2	0.856
A	C12A	342	38.10	34.4	79.6	79.6	0.919
A	C15A	414	36.51	34.4	77.7	80.4	0.929
A	C18A	506	39.69	34.4	73.6	71.3	0.823
A	SA1	0	39.69	34.4	81.0	78.4	
A	SA2	0	38.10	34.4	73.6	73.7	
A	SA3	0	38.10	34.4	84.7	84.7	
A	SA4	0	42.86	34.4	82.6	75.2	
A	S7A	204	42.86	34.4	73.7	67.0	0.859
A	S12A	375	39.69	34.4	83.8	81.2	1.021
A	S15A	420	39.69	34.4	75.8	73.3	0.940
A	S18A	493	41.28	34.4	76.4	71.7	0.919
B	BB1	0	39.69	32.5	94.7	93.0	
B	BB2	0	38.10	32.5	95.3	96.7	
B	BB3	0	38.10	32.8	79.0	80.0	
B	BB4	0	50.80	32.8	96.4	77.1	
B	B7B	175	38.10	32.5	86.6	87.9	1.014
B	B12B	342	36.51	32.8	82.1	86.0	0.992
B	B15B	392	38.10	32.8	79.9	80.9	0.933
B	B18B	465	39.69	32.5	81.6	80.1	0.924
B	CB2	0	38.10	32.5	91.8	93.2	
B	CB3	0	38.10	32.8	79.2	80.2	
B	CB4	0	38.10	32.8	83.5	84.6	
B	C7A-B	176	39.91	32.5	87.8	85.8	0.998
B	C7B	184	42.86	32.5	92.6	85.4	0.994
B	C12B	353	31.75	32.8	83.2	97.3	1.131
B	C15B	423	33.34	32.5	74.6	84.1	0.978
B	C18B	488	39.69	32.8	74.0	72.5	0.843

Table 3a Beam End Tests (S.I. units) (cont'd)

Test Group	Specimen Label	Coating Thickness (μm)	Cover (mm)	Concrete Strength (MPa)	Bond Strength (kN)	Modified Bond Strength (kN)	C/U Ratio
B	SB1	0	36.69	32.5	90.6	94.5	
B	SB2	0	39.69	32.5	87.7	86.2	
B	SB3	0	42.86	32.5	89.5	82.6	
B	SB4	0	44.45	32.5	90.3	80.9	
B	S7B	164	41.28	32.8	78.0	74.1	0.861
B	S12B	371	42.86	32.5	80.7	74.5	0.866
B	S15B	418	44.45	32.8	86.9	77.7	0.903
B	S18B	461	41.28	32.8	77.6	73.7	0.857
C	BC1	0	39.69	32.8	79.5	77.9	
C	BC2	0	42.86	32.8	105.9	97.5	
C	BC3	0	34.93	32.8	101.3	109.9	
C	BC4	0	36.51	32.8	83.3	87.3	
C	B7C	181	38.10	32.8	82.6	83.6	0.897
C	B12C	333	39.69	32.8	95.6	93.6	1.005
C	B15C	410	38.10	32.8	84.9	85.9	0.923
C	B18C	437	41.28	32.8	82.6	78.4	0.841
C	CC1	0	42.86	32.6	99.9	92.2	
C	CC2	0	39.69	32.6	94.8	93.1	
C	CC3	0	41.28	32.8	88.1	83.6	
C	CC4	0	42.86	32.6	90.2	83.2	
C	C7C	162	38.10	32.6	85.1	86.3	0.981
C	C12C	308	36.51	32.8	87.4	91.6	1.040
C	C15C	394	41.28	32.8	70.7	67.1	0.762
C	C18C	466	38.10	32.6	81.3	82.5	0.937
C	SC1	0	41.28	32.8	92.8	88.1	
C	SC2	0	36.51	32.6	76.3	80.1	
C	SC3	0	41.28	32.6	79.1	75.2	
C	SC4	0	39.69	32.6	79.1	77.7	
C	S7C	187	39.69	32.6	76.2	74.8	0.932
C	S12C	338	38.10	32.6	79.7	80.9	1.008
C	S15C	412	39.69	32.6	88.7	87.1	1.085
C	S18C	486	36.51	32.6	73.5	77.2	0.961

*Modified Bond Force = Test Force [34 MPa / concrete strength]^(1/4) [47.625 mm /(cover+ 9.525 mm)]

Table 3b Beam End Tests(U.S. units)

Test Group	Specimen Label	Coating Thickness (mils)	Cover (in.)	Concrete Strength (psi)	Bond Strength (kips)	Modified Bond Strength (kips)	C/U Ratio
A	BA1	0.00	1 1/2	4990	15.80	15.81	
A	BA2	0.00	1 9/16	4990	19.35	18.73	
A	BA3	0.00	1 11/16	4990	23.12	21.03	
A	BA4	0.00	1 9/16	4990	23.23	22.49	
A	B7A	7.85	1 1/2	4990	18.05	18.05	0.925
A	B12A	12.35	1 9/16	4990	20.90	20.24	0.981
A	B15A	14.95	1 1/2	4990	18.50	18.50	0.948
A	B18A	19.85	1 5/8	4990	18.03	16.91	0.866
A	CA1	0.00	1 1/2	4990	19.77	19.78	
A	CA2	0.00	1 9/16	4990	20.10	19.38	
A	CA3	0.00	1 1/2	4990	20.18	20.19	
A	CA4	0.00	1 9/16	4990	19.07	18.46	
A	C7A	7.35	1 9/16	4990	17.22	16.67	0.856
A	C12A	13.46	1 1/2	4990	17.89	17.90	0.919
A	C15A	16.30	1 7/16	4990	17.47	18.08	0.929
A	C18A	19.92	1 9/16	4990	16.55	16.03	0.823
A	SA1	0.00	1 9/16	4990	18.20	17.62	
A	SA2	0.00	1 1/2	4990	16.56	16.57	
A	SA3	0.00	1 1/2	4990	19.04	19.05	
A	SA4	0.00	1 11/16	4990	18.58	16.90	
A	S7A	8.05	1 11/16	4990	16.56	15.06	0.859
A	S12A	14.75	1 9/16	4990	18.85	18.25	1.021
A	S15A	16.53	1 9/16	4990	17.03	16.49	0.940
A	S18A	19.41	1 5/8	4990	17.18	16.11	0.919
B	BB1	0.00	1 9/16	4710	21.29	20.91	
B	BB2	0.00	1 1/2	4710	21.42	21.75	
B	BB3	0.00	1 1/2	4750	17.75	17.98	
B	BB4	0.00	2	4750	21.67	17.33	
B	B7B	6.90	1 1/2	4710	19.48	19.77	1.014
B	B12B	13.48	1 7/16	4750	18.46	19.34	0.992
B	B15B	15.44	1 1/2	4750	17.95	18.18	0.933
B	B18B	18.32	1 9/16	4710	18.34	18.02	0.924
B	CB2	0.00	1 1/2	4710	20.64	20.95	
B	CB3	0.00	1 1/2	4750	17.80	18.03	
B	CB4	0.00	1 1/2	4750	18.77	19.01	
B	C7A-B	6.92	1 9/16	4710	19.73	19.29	0.998
B	C7B	7.25	1 11/16	4710	20.82	19.21	0.994
B	C12B	13.89	1 1/4	4750	18.71	21.87	1.131
B	C15B	16.65	1 5/16	4710	16.77	18.91	0.978
B	C18B	19.21	1 9/16	4750	16.63	16.30	0.843

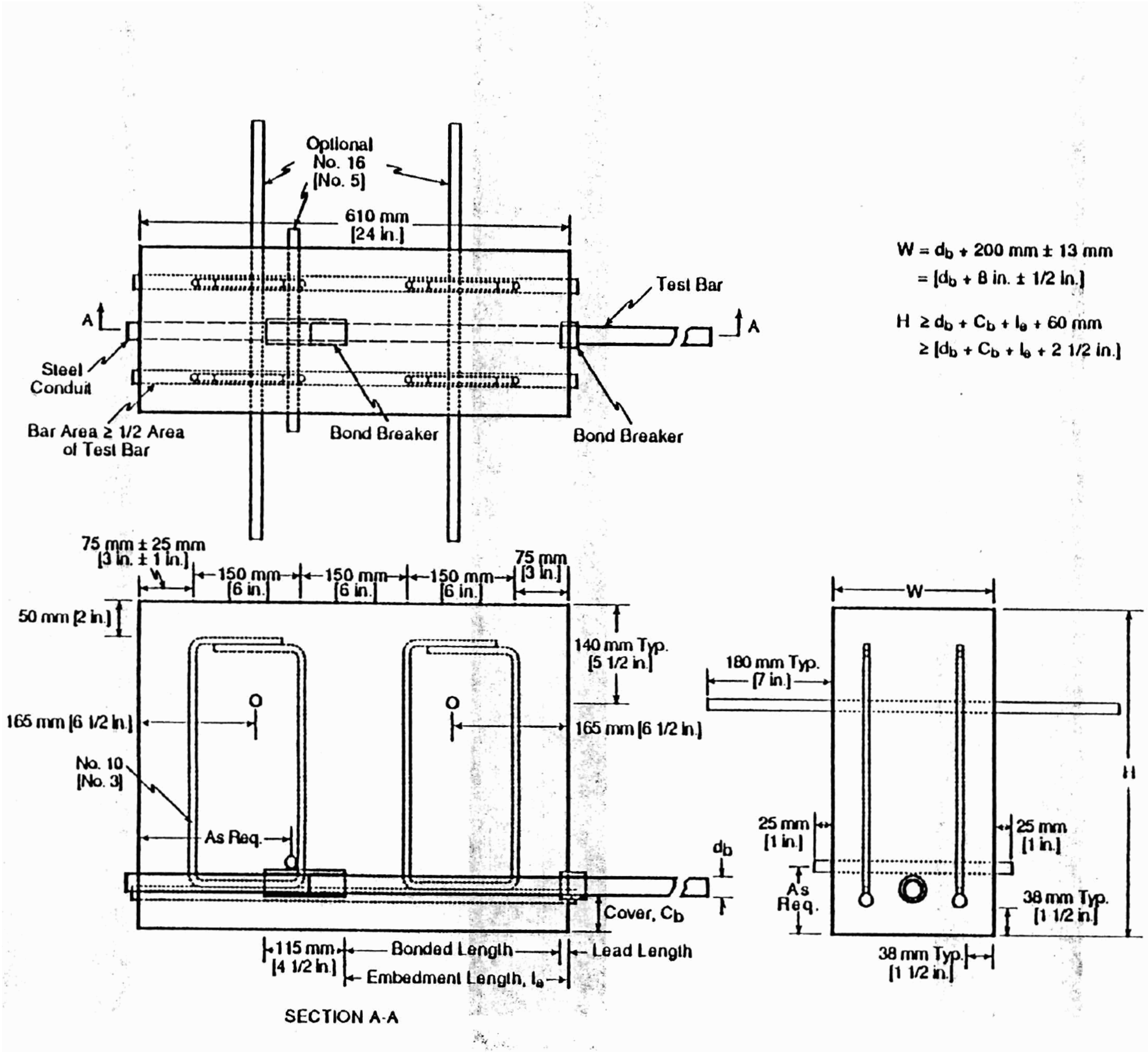

Fig. 1 Beam-end test specimen (ASTM A 944)

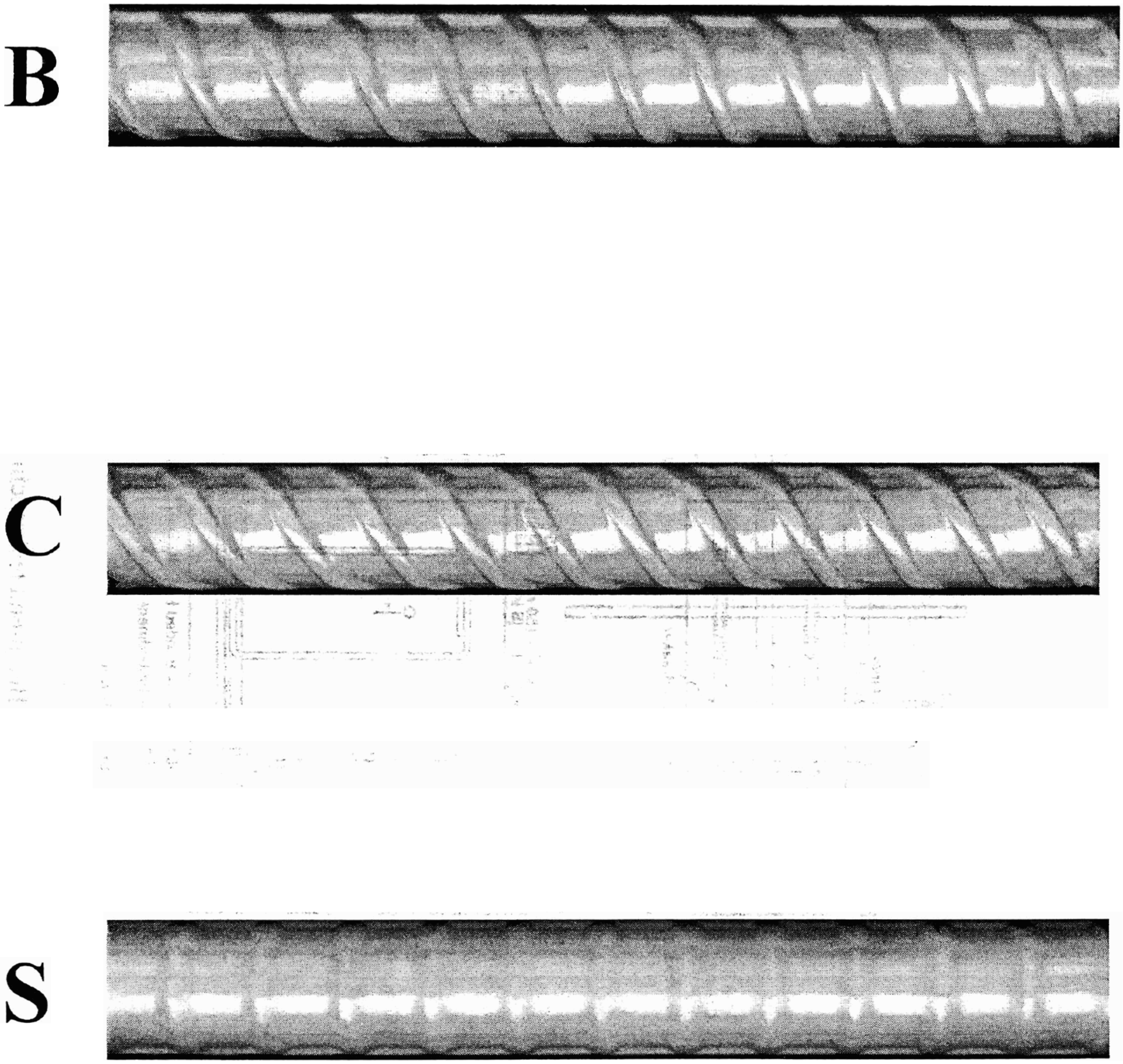

Fig. 2 Reinforcing bar deformation patterns

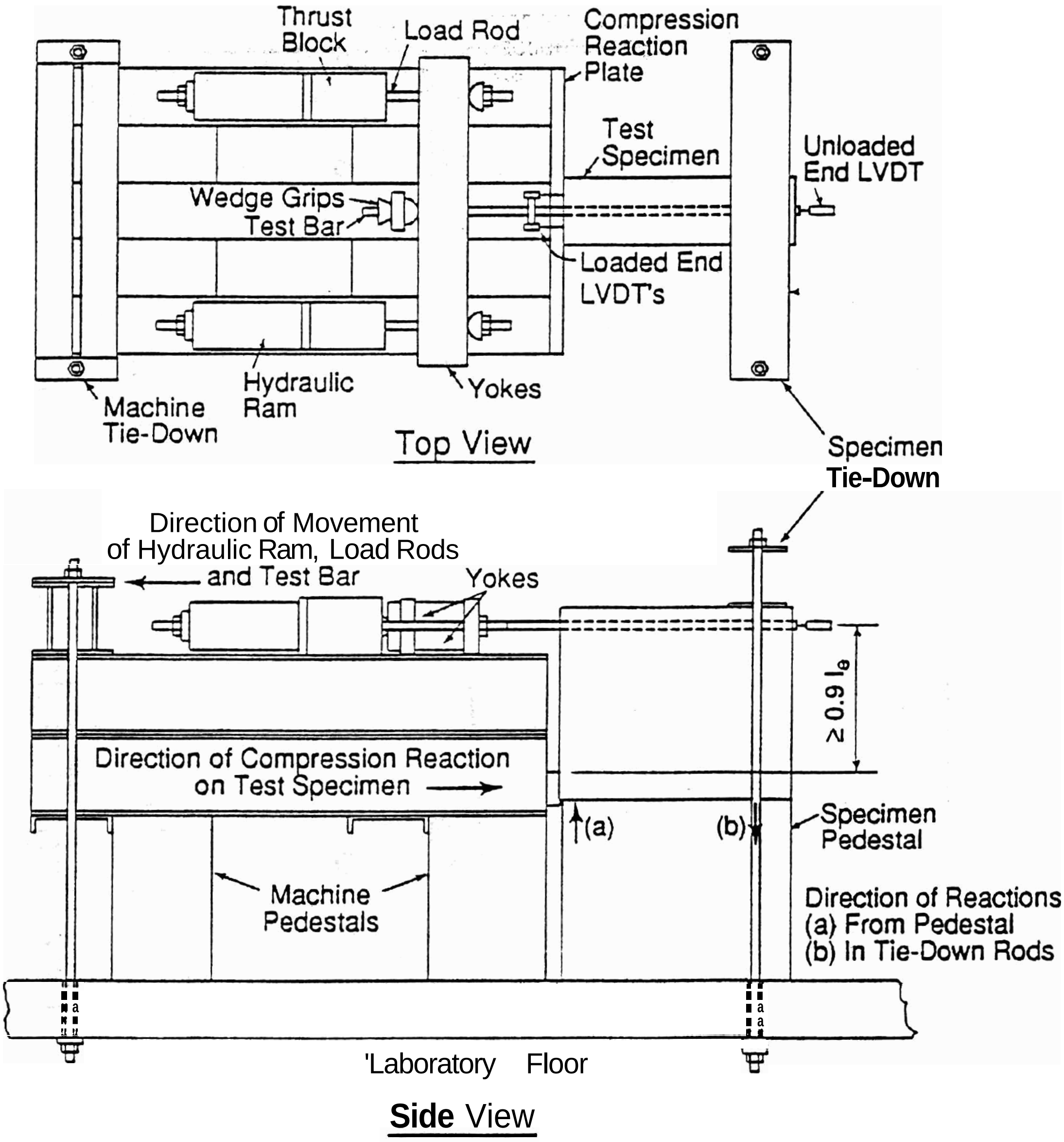

Fig. 3 Testing apparatus (Darwin and Graham 1993)

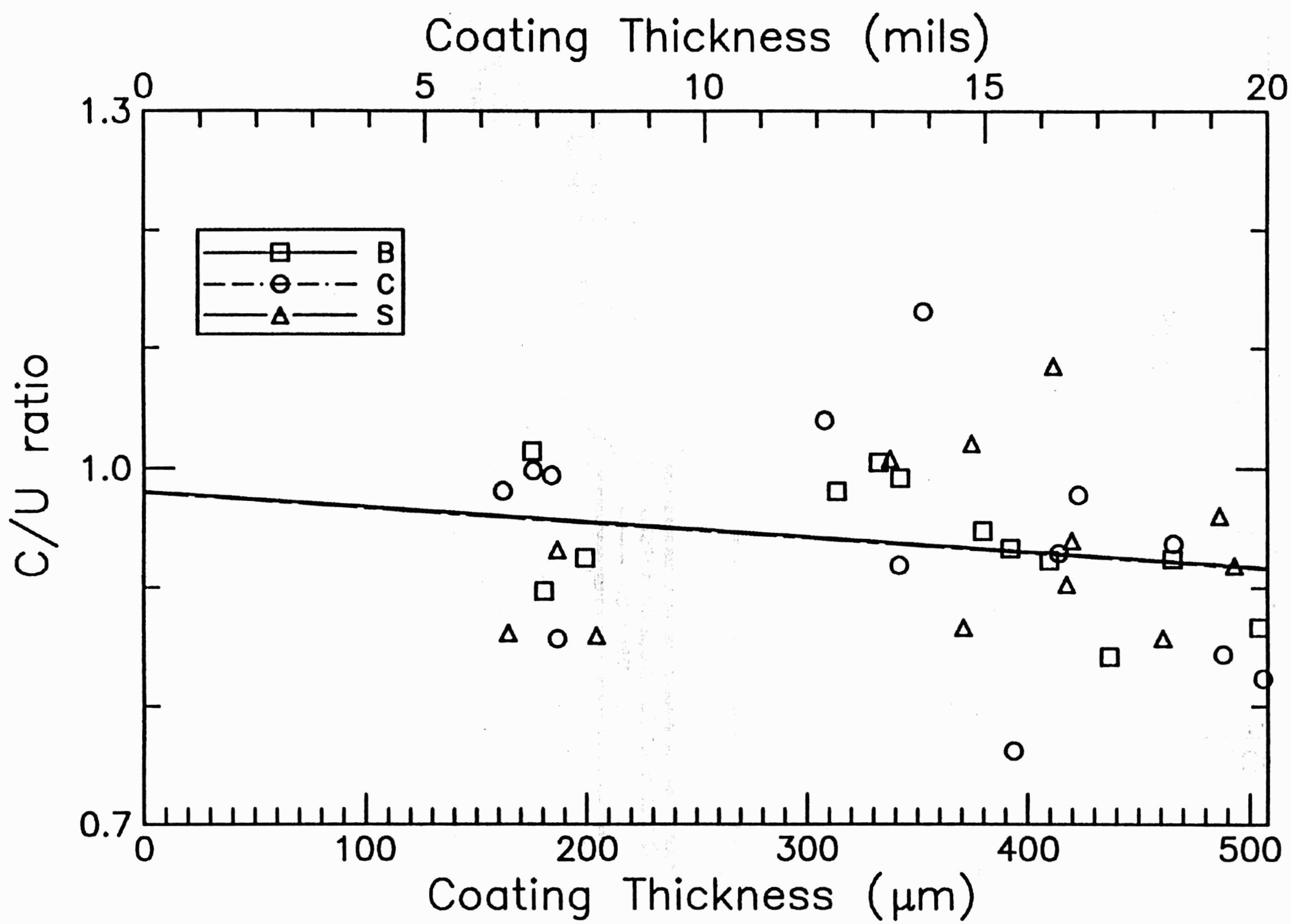

Fig. 4 C/U ratio versus coating thickness for coatings between 160 and 510 µm (6.4 to 19.9 mils)

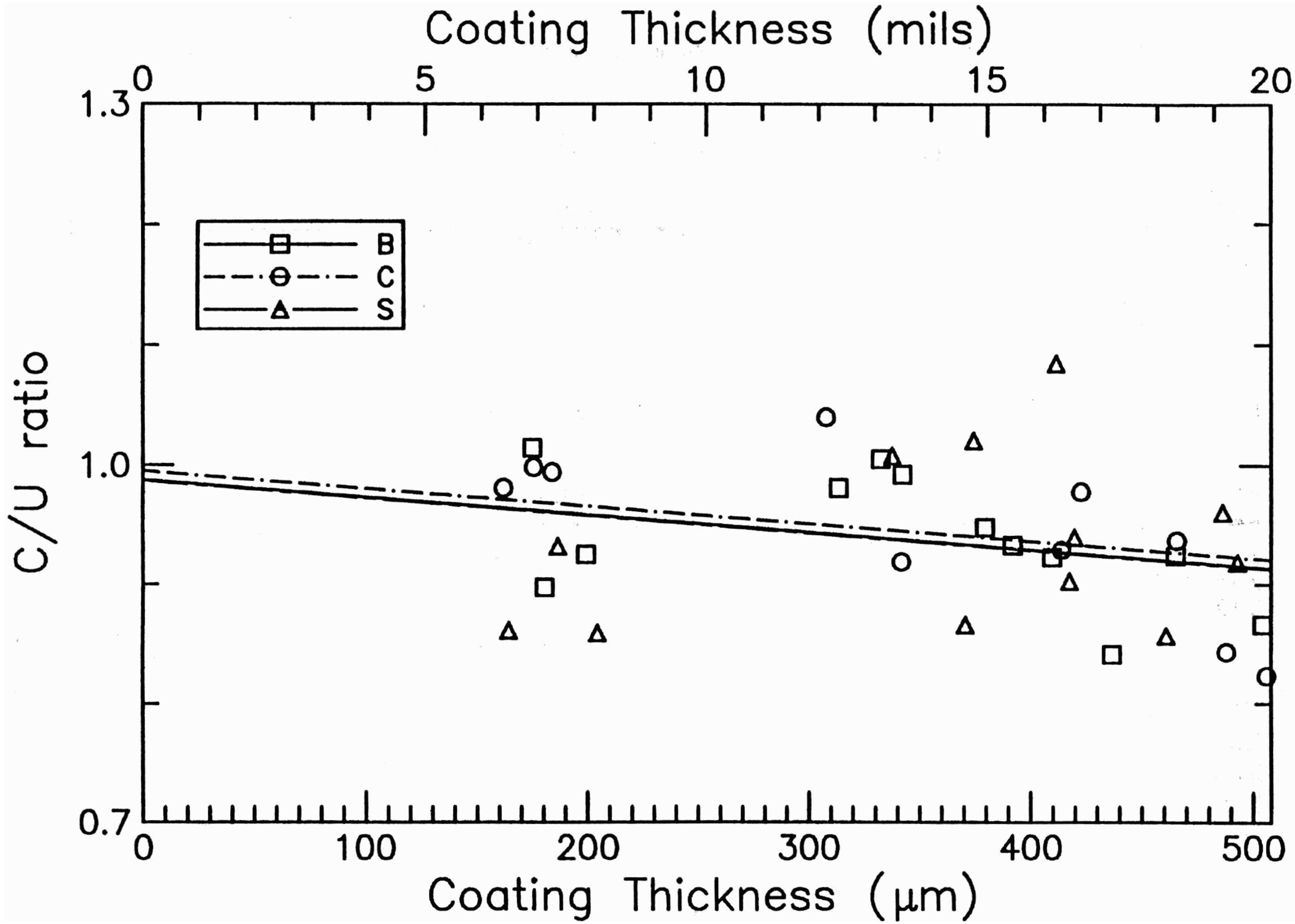

Fig. 5 C/U ratio versus coating thickness for coatings between 160 and 510 μm (6.4 to 19.9 mils), with unrepresentative test results removed

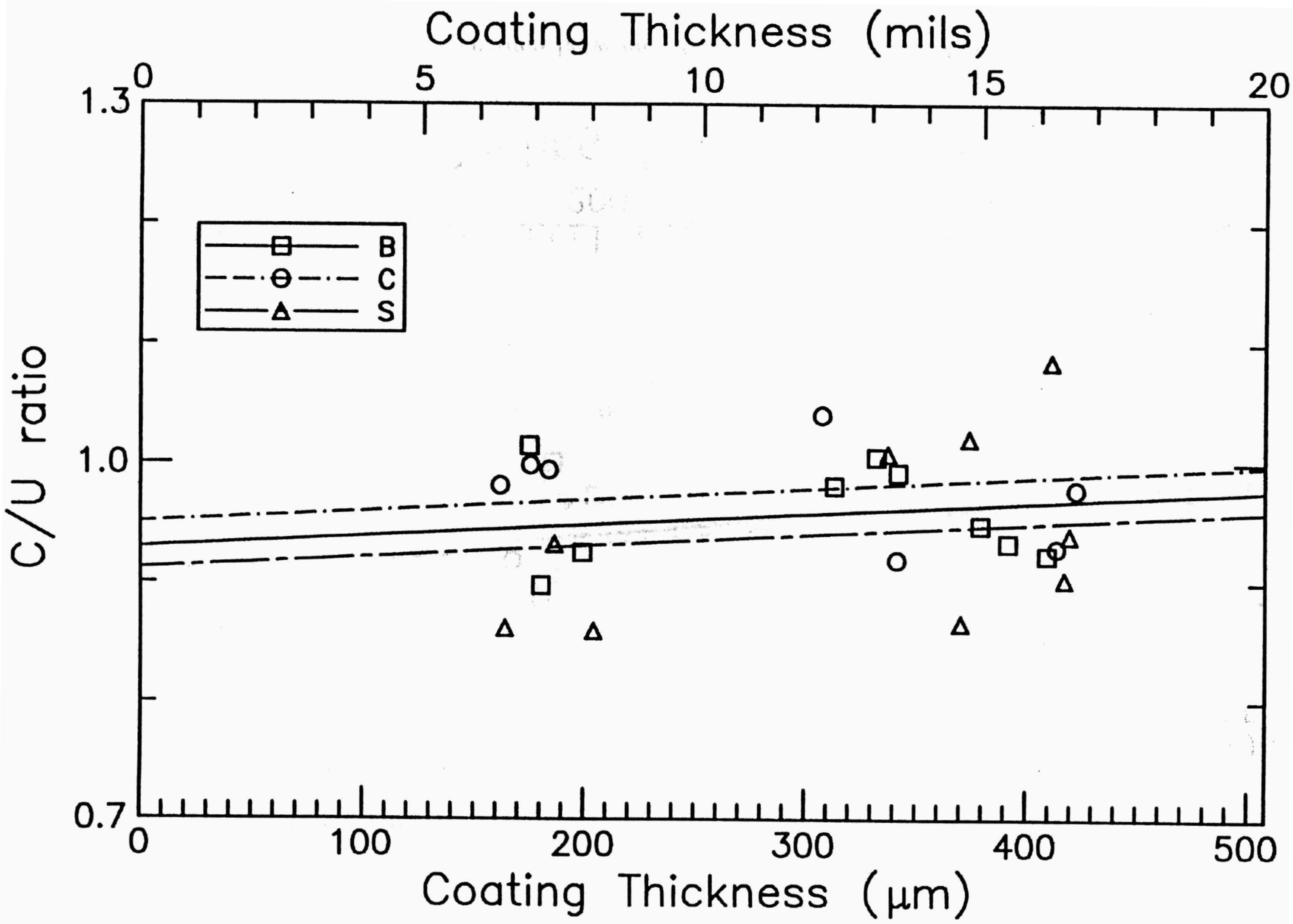

Fig. 6 C/U ratio versus coating thickness for coatings between 160 and 420 μm (6.4 to 16.5 mils)

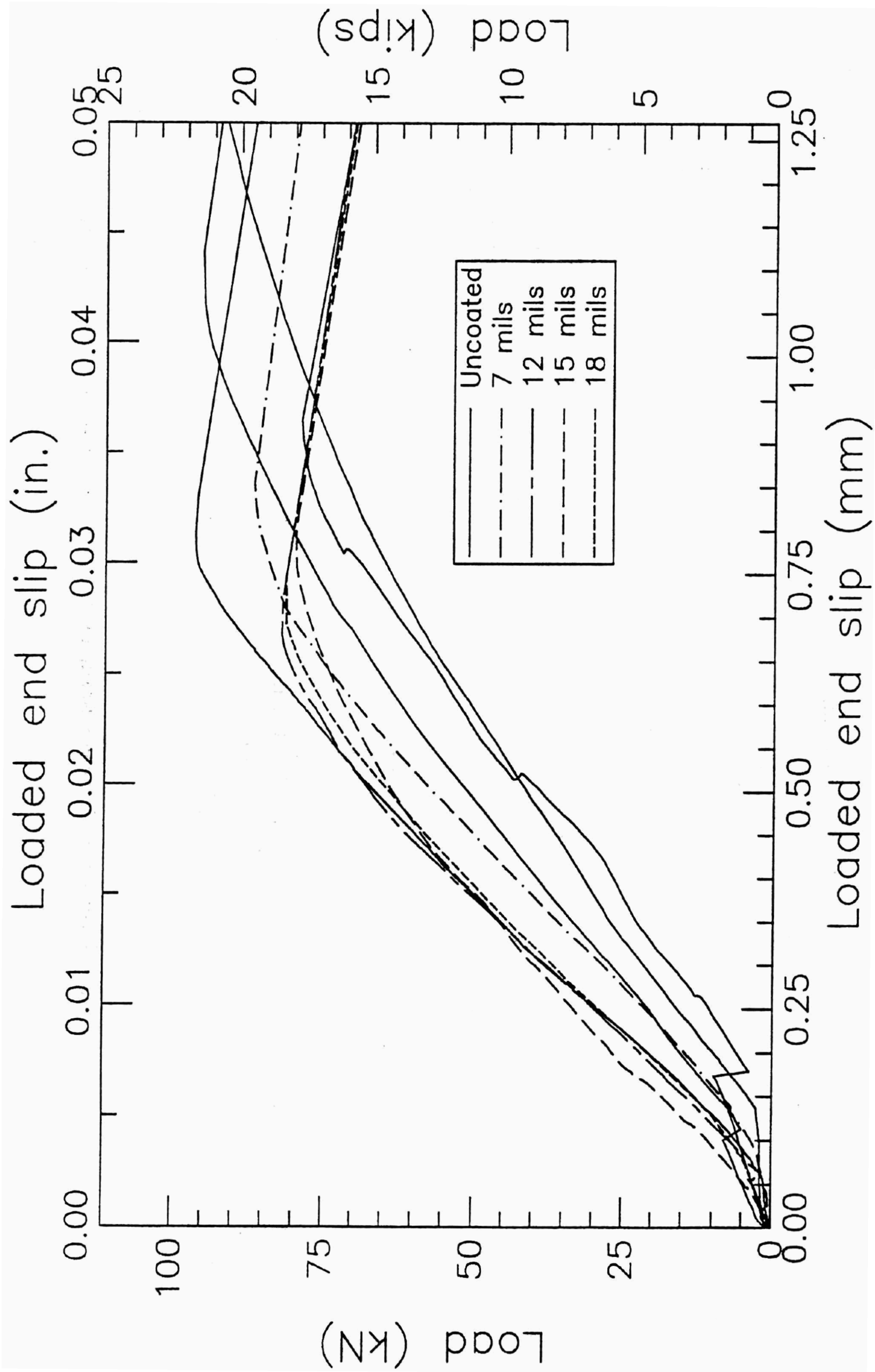

Fig. A.1 Load versus loaded end slip for B-pattern bars (Test group B)

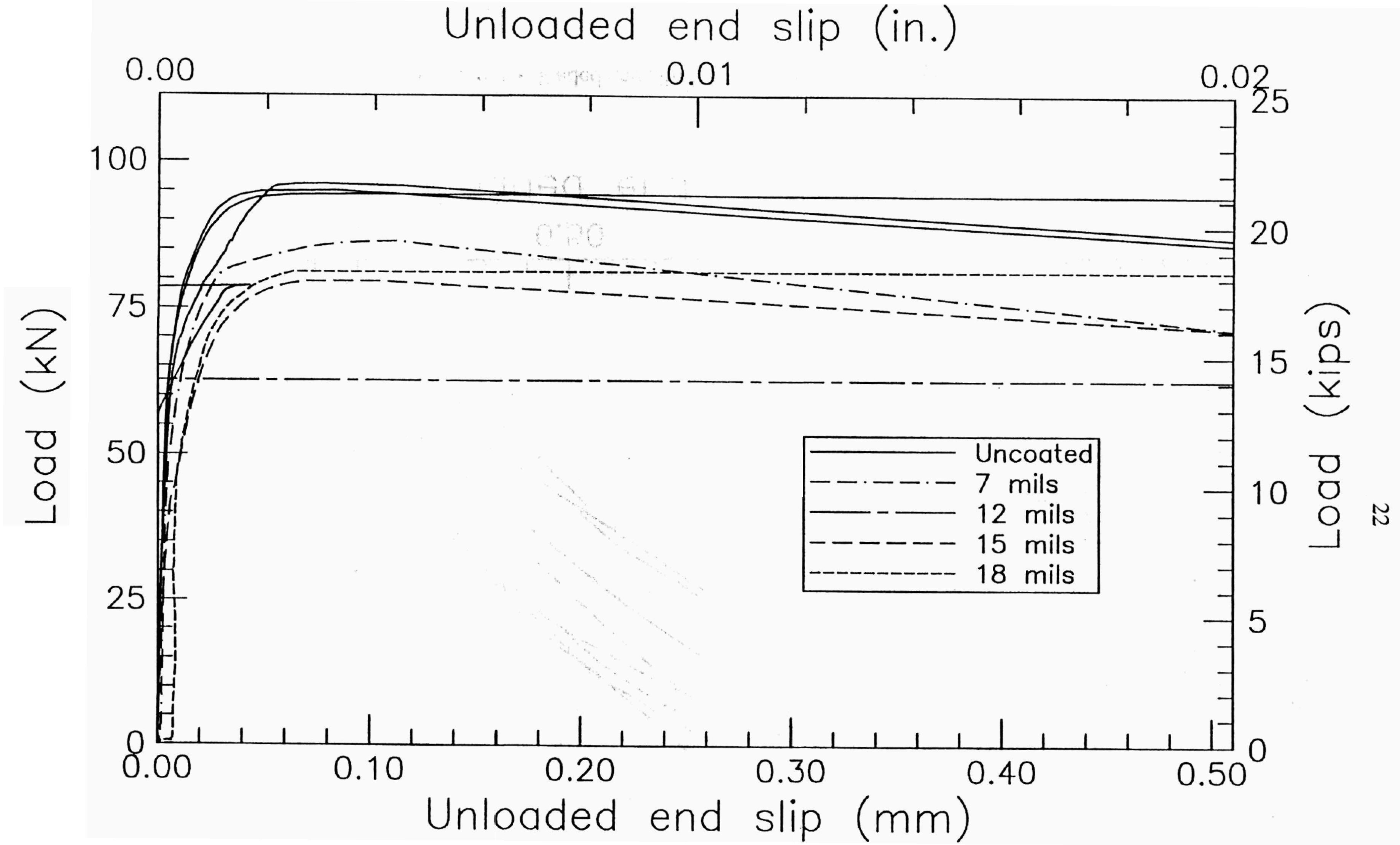

Fig. A.2 Load versus unloaded end slip for B-pattern bars (Test group B)

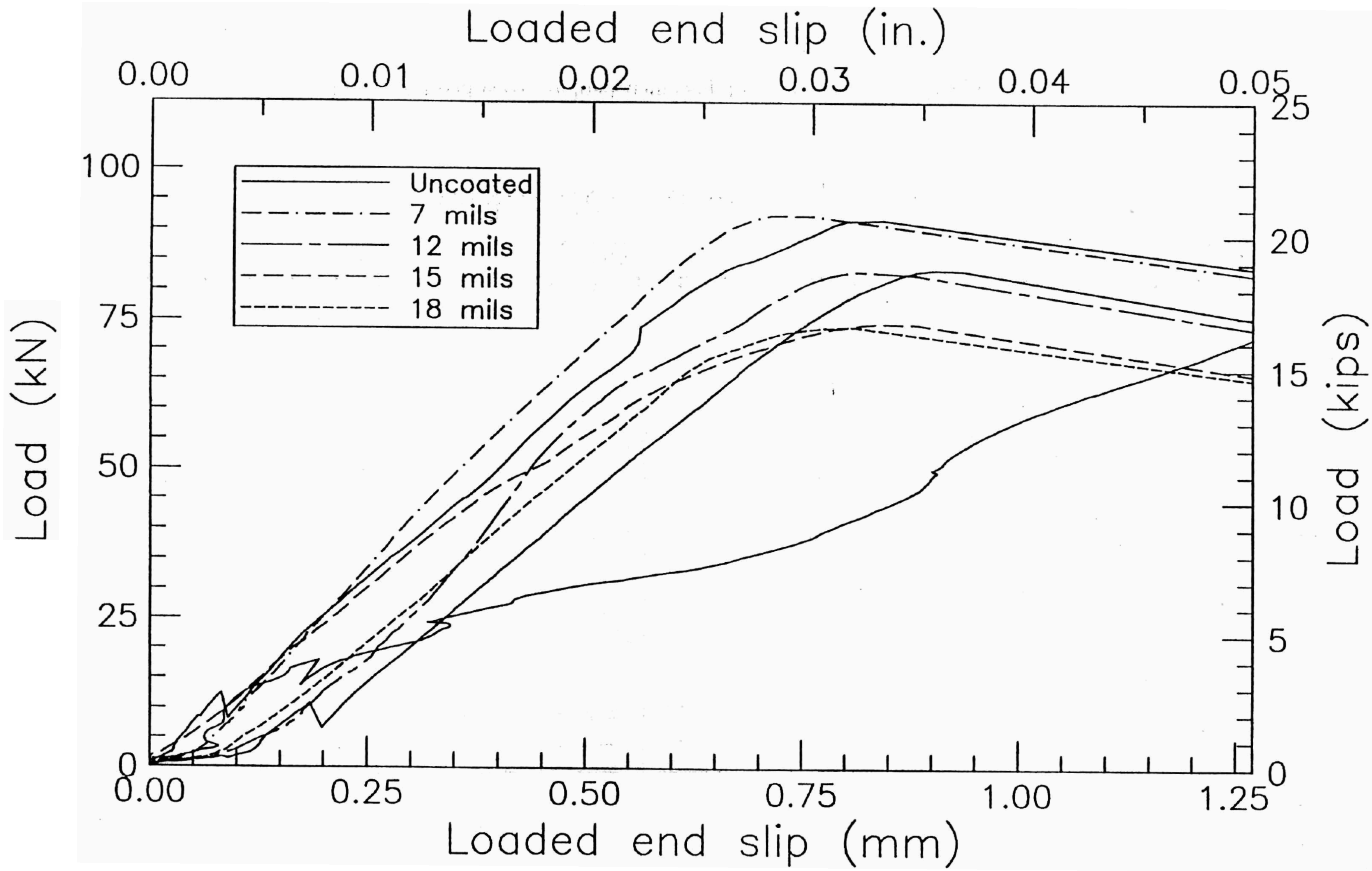

Fig. A.3 Load versus loaded end slip for C-pattern bars (Test group B)

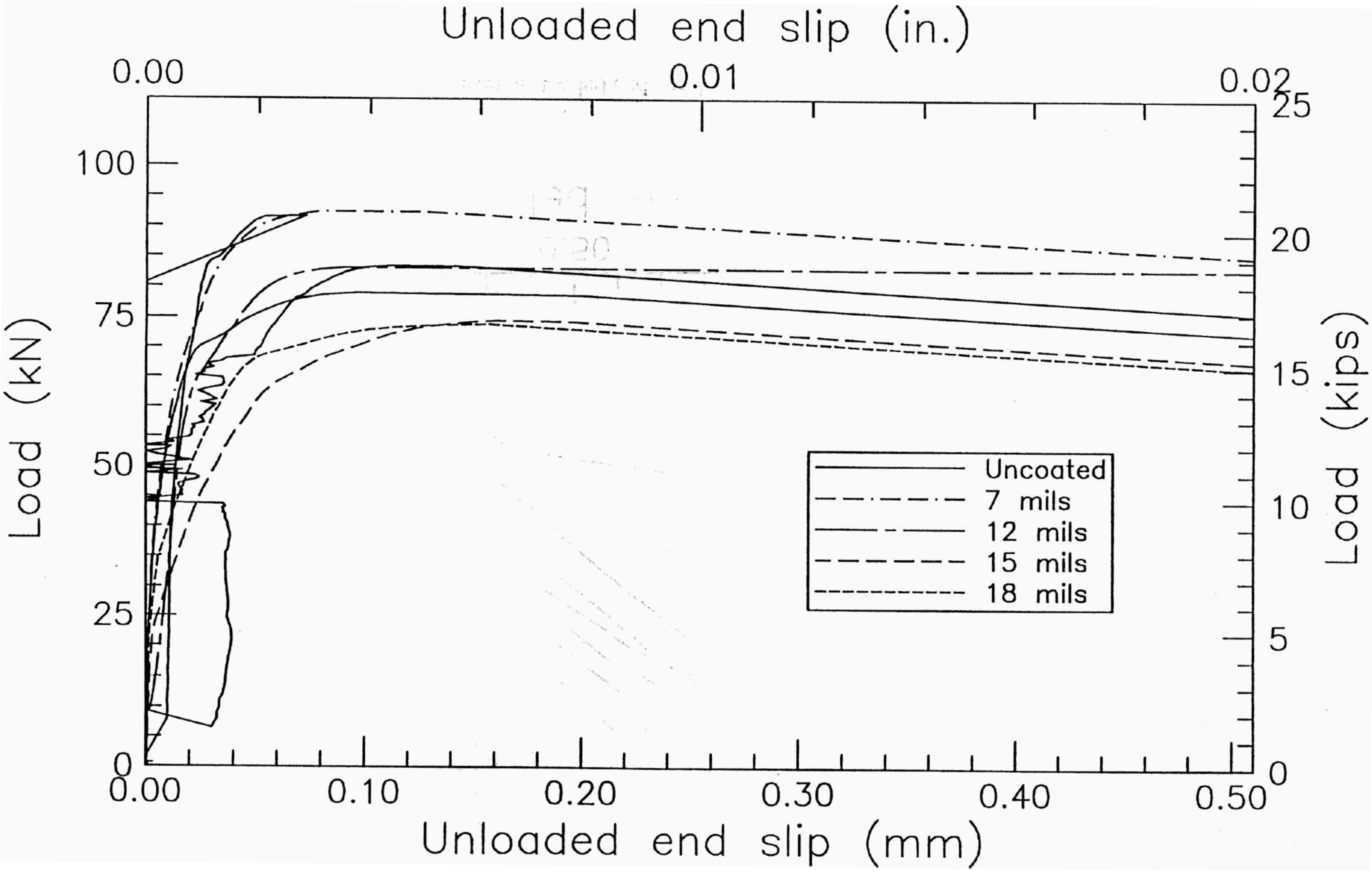

Fig. A.4 Load versus unloaded end slip for C-pattern bars (Test group B)

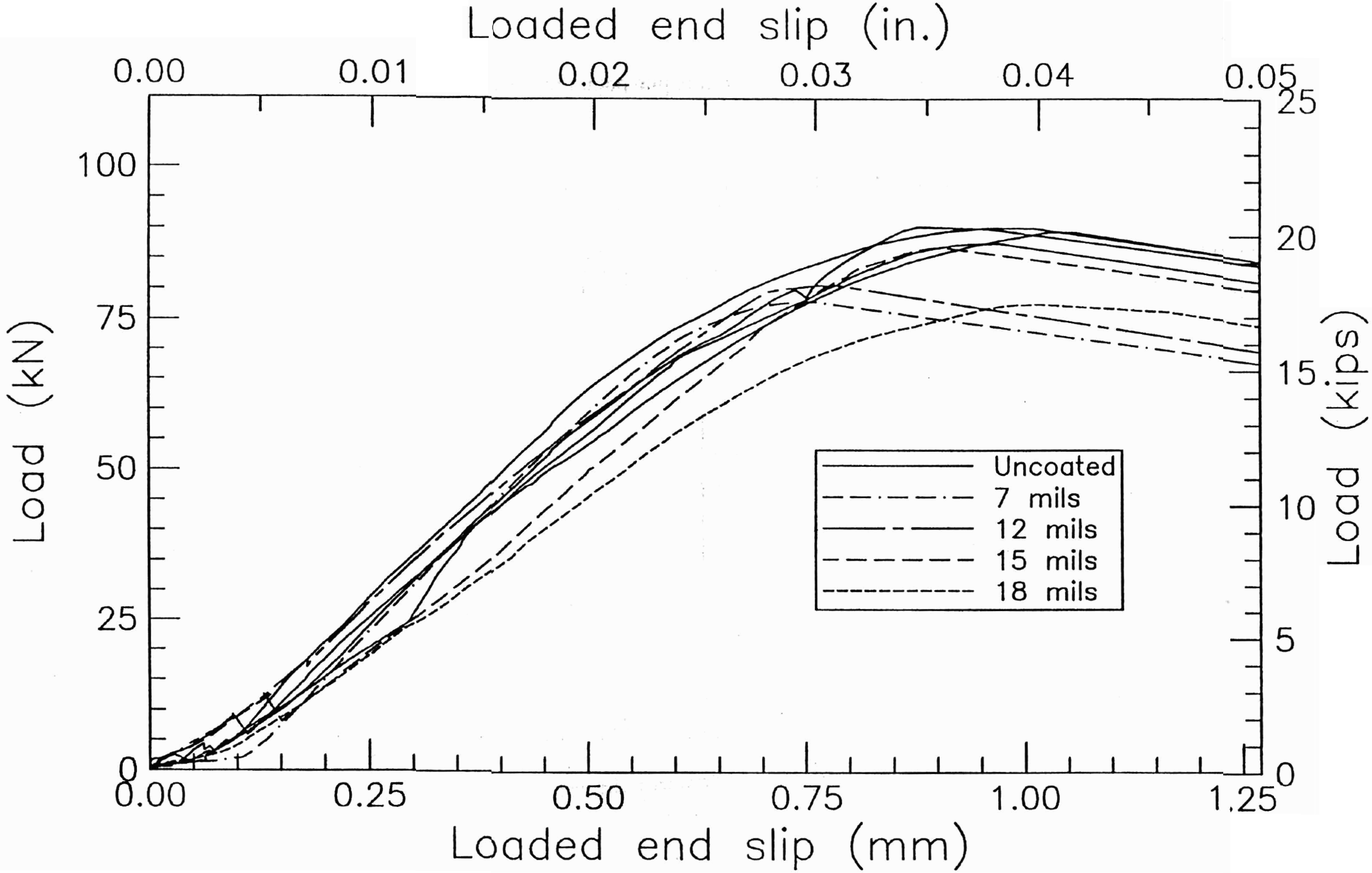

Fig. A.5 Load versus loaded end slip for S-pattern bars (Test group B)

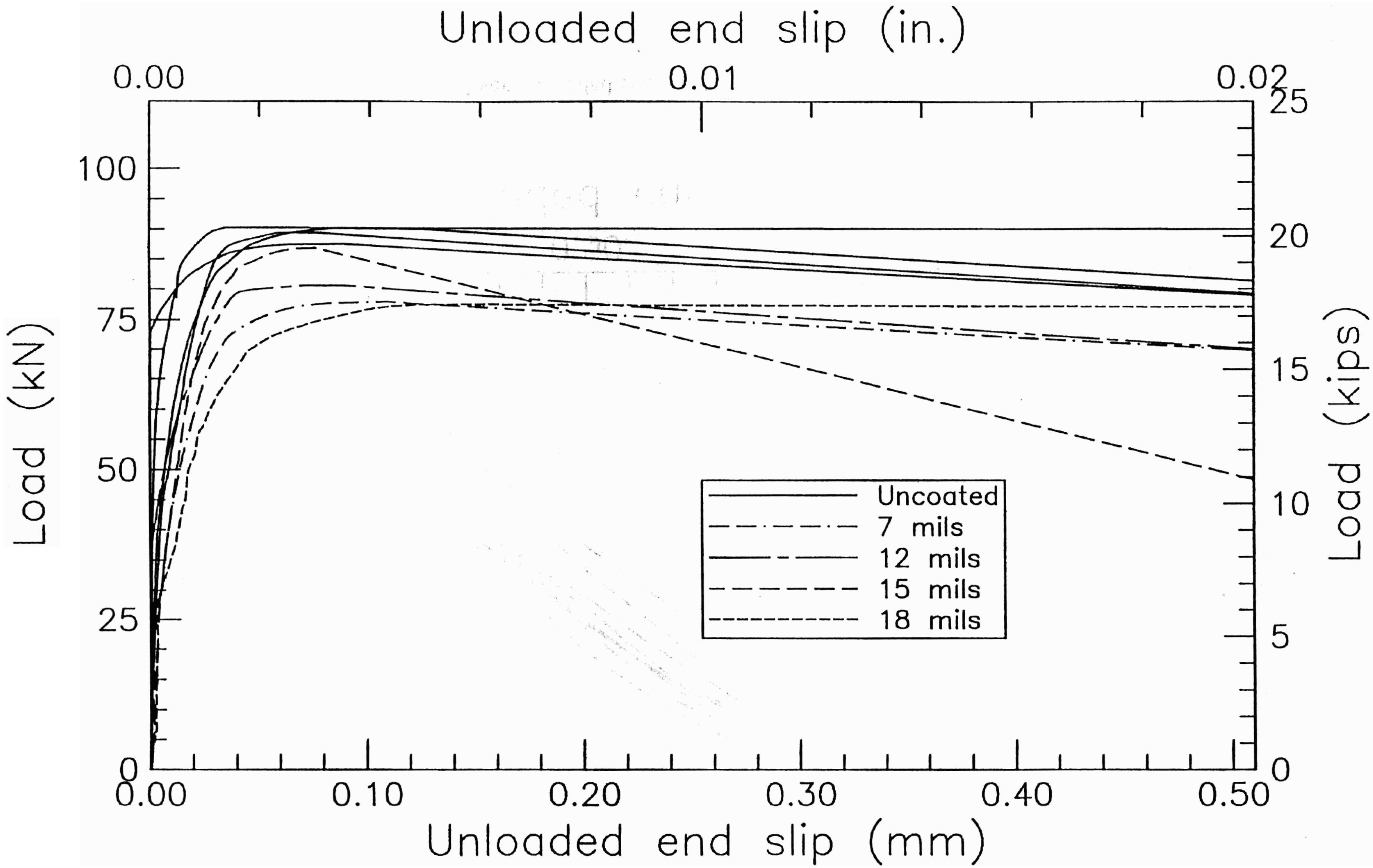

Fig. A.6 Load versus unloaded end slip for S-pattern bars (Test group B)