Bending and straightening

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Bending and straightening tests were conducted on Grade 60 reinforcing bars. Three sizes of billet steel bars were included in the tests #5, #8, and #11. The bars were obtained from three sources, one supplying all three sizes and two only the #11 bars.

Tests were done at cold and room temperatures. Bars were bent to the minimum diameter specified in the American Concrete Institute's "Building Code Requirements for Reinforced Concrete (ACI 318-83)," and to as small a diameter as possbile. Bending was done around the weak and strong axis. Some bars were flame heated to approximately 1500F (820C) to reduce breakage. Tensile tests were conducted on straightened bars, for comparison to tensile tests of unbent control bars.

Keywords: bending (reinforcing steels); bend tests; heating; **reinforcing steels;** research; temperature; tensile properties; yield point.

During construction, a partially embedded reinforcing bar may need to be bent because of incorrect fabrication or inaccurate placement, or to provide access. A bent bar may need to be straightened for any of the same reasons or because it was bent accidentally. Field bending or straightening is usually accomplished by placing a steel pipe over the bar and pulling on the bar.

It is generally not considered desirable to bend a bar to less than the minimum diameter specified in Paragraph 7.2.1 of the American Concrete Institute's "Building Code Requirements for Reinforced Concrete (ACI 318-83)[1]." However, this is not a mandatory requirement for field bending. In some instances a sharper bend may be needed to improve access. The bend may be around the weak or strong axis of the bar.

The diameter of a bend may be defined as the diameter of a circle having a portion of its arc matching the inside surface of the bent bar. ACI 318-83 in Paragraph 7.3.2 allows field bending, as follows:

> "Reinforcement partially embedded in concrete shall not be field bent, except as shown on the design drawings or permitted by the Engineer."

The Commentary[2] for Paragraph 7.3.2 provides guidance on the use of heat:

> ". . . The inspecting engineer must determine whether the bars can be bent cold without damage, or if heating is necessary. . . . Partially embedded reinforcing bars can be successfully rebent (or bent for the first time, which should be less critical) if they are first preheated to 1100-1200F and then bent as gently and in as gradual an arc as possible . . ."

The recommended preheat in the Commentary was based on testing by Black[3] on #10 and #11, Grade 40 and 60 reinforcing bars. His study showed that straightening of Grade 60 bars can be improved without a loss of tensile strength by preheating to 1100F (590C). Some bars were broken during straightening. However, higher temperature was not used at that time because of concern over loss of tensile strength due to the heating.

Later unpublished tests by Black on #11 bars indicated that field bending and straightening could be improved by heating the bars to between 1400F (760C) and 1500F (820C). Although a minor loss of strength was noted, the yield and tensile strength of the bars was apparently acceptable.

Lalik and Cusick[4] conducted cold bending and straightening tests on #8, Grade 60 reinforcing bars. These bars were bent to 45 or 90 degrees at diameters as small as 8 in. (200 mm) and straightened. This bend is less severe than a bend around a 6 in. (150 mm) diameter pin allowed by ACI 318-83 for #8 bars. No breakage occurred during bending or straightening. The straightened bars had yield and tensile strength comparable to unbent bars.

In 1981, Erasmus[5] expressed a different view, stating that cold straightening of reinforcing bars appreciably changes the steel properties. According to Erasmus, brittle fracture during straightening becomes more likely with:

1. Decrease in bend diameter.
2. Increase in bar diameter.
3. Low temperature.
4. Forceful impact.
5. Time delay causing strain aging of the bent bar.

# of Grade 60 reinforcing bars

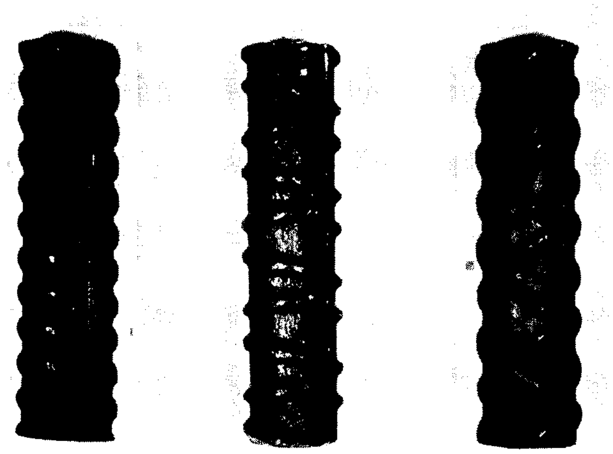


Fig. 1 — The type of reinforcing bar obtained from suppliers A, B, and C (left to right).

The research described in this paper addressed the points raised regarding bend diameter, bar diameter and low temperature. However, it was considered that bars should be straightened with a slow pull rather than by pounding. The effect of aging before straightening was not studied.

Significance of the research

This research provides guidance to field engineers who are confronted with the need to approve a procedure for field bending of reinforcing steel. It is shown that reinforcing bars can be bent and straightened under field conditions without damage. Under difficult conditions, use of heat to higher levels than is presently recommended in the Commentary to ACI 318-83 may be advantageous.

Description of test program

The primary variables were bar size and supplier, bend diameter, bend axis and temperature. ASTM A615 Grade 60 reinforcing bars were obtained from three sources, #11 bars from Supplier A, #5, #8 and #11 from Supplier B and #11 from Supplier C. As shown in Fig. 1, bars from Supplier A had transverse deformations consisting of semielliptical "crescents." The ends of the crescents taper before intersecting the longitudinal rib. Bars from Supplier B had a diagonal deformation pattern with straight transverse lugs that were almost perpendicular to the rib. Bars from Supplier C had an x-shaped deformation pattern with transverse lugs that cross each other midway between ribs. The transverse lugs on the bars from both Suppliers B and C extend to the longitudinal ribs.

Transverse deformations are needed for bond between the bar and concrete. Previous research[6,7] has shown that the stress concentration caused by a deformation depends on the sharpness of the lug base radius and the height, width and flank angle of the lug. Lug geometry was obtained by cutting a section through the bar, enlarging a photograph of the cut section, and measuring the geometry. Steel chemistry was provided by the suppliers. Deformation geometries and steel chemistries are presented in Table 1.

The American Society for Testing and Materials (ASTM) specification for A615 Grade 60 reinforcing bars[8] requires minimum elongations of 7 percent for #11 bars, 8 percent for #8 bars, and 9 percent for #5 bars. ACI 318-83's recognition of Supplement S1 of ASTM A615 requires #5 or smaller Grade 60 bars to be test bent to 180 degrees around pins equal to 3.5 bar diameters (3.5d), #6 through 8 to 5d and #9 though 11 to 7d. Sizes tested were the largest in each group.

Two bend diameters were used for each bar size, the minimum bend diameter allowed by ACI 318-83 for fabrication and the smallest practical bend. ACI 318-83 in Paragraph 7.2.1 specifies a minimum bend diameter of 8 times the bar diameter (8d) for #11 bars and 6d for #8 and #5 bars. For the procedures used in this program, the smallest practical bend was about one-half of the minimum diameter allowed by ACI 318-83.

Bends were made with the longitudinal rib at the neutral axis (weak axis bending) for all three bar sizes. All of the #11 bars were also bent with the longitudinal rib at the extreme fiber (strong axis bending).

Most bars were bent and straightened at laboratory temperatures of 60F (16C) to 80F (27C). No. 11 bars from Supplier B were also bent and straightened at cold temperatures, 25F to 35F (−4C to 2C). Flame heating to a temperature of approximately 1500F (820C) was also used to improve bendability and to evaluate loss of strength caused by heating.

The tests were done in four phases:

1. Room temperature bending and straightening.
2. Room temperature bending followed by heated straightening.
3. Heated bending and straightening.
4. Cold temperature bending and straightening.

Straightened bars, in addition to a set of control bars, were tested in tension to obtain their yield point and tensile strength.

Bars from all three suppliers were included in the first phase. Bends were made around the weak and strong axis to the ACI minimum diameter and to the smallest practical diameter. Sixteen combinations of variables were examined, as follows:

Room Temperature Bending and Straightening

Bar Size	Supplier	Weak Axis ACI Min. Diameter	Weak Axis Smallest Diameter	Strong Axis ACI Min. Diameter	Strong Axis Smallest Diameter
	A	W	W	W	W
#11	B	W	W	W	W
	C	W	W	W	W
#8	B	W	W		
#5	B	W	W		

Each "W" represents a test sequence where bends were made to angles from 15 deg to 90 deg. For a typical test sequence, a reinforcing bar was bent to a 15 deg angle and then straightened. A second bar was bent to 15 deg and straightened. Additional pairs were bent to increasing angles and straightened. The bend angle was increased in 15 deg increments to a maximum of 90 deg or until breakage occurred in a pair of specimens.

Cracking was observed in some bars that were straightened. These cracks typically occurred at the base of the transverse lugs. With some exceptions at the start of the program, a crack observed at the conclusion of a test was considered the same as a fractured bar.

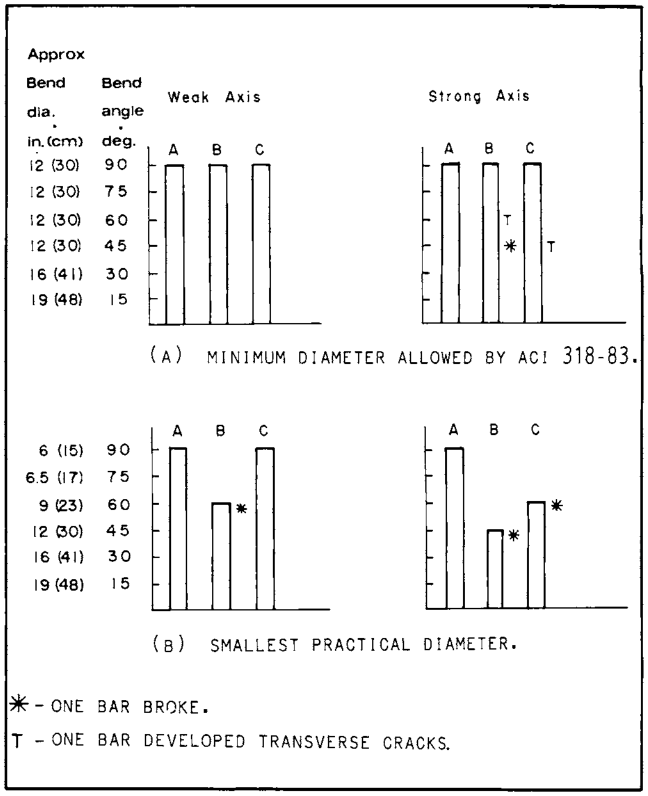


Fig. 2 — Bending of #11 bars at room temperature. Each bar of the graph represents the bending of a pair of reinforcing bars from each supplier to the diameter and angle indicated. A separate pair of reinforcing bars was bent to each angle shown and then straightened. The results of straightening the bars are shown in Fig. 3.

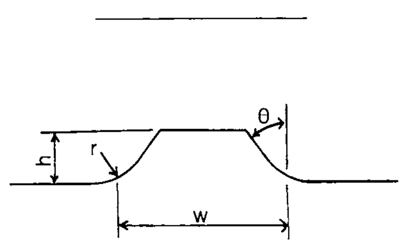
Some difficulty was encountered in restoring the straightness of a bar. If the bar had an offset, or kink, in the bend region of more than one bar diameter after straightening, the test was repeated.

The second phase of the testing program examined improvement in straightening obtained by heating the bent bar to 1500F (820C). Heated straightening was used whenever breakage occurred during room temperature straightening in the previous phase. The

TABLE 1 — Properties of test bars

Bar Size	Bar Supplier	Geometry' r/h	Geometry' h/w	Geometry' Flank angle (degrees)	Chemistry*	C (percent)	Mn (percent)	P (percent)	S (percent)
	A	0.1	0.4	30	Heat 1	0.39	1.01	0.016	0.033
					Heat 2	0.36	0.91	0.009	0.035
#11	B	0.3	0.4	45		0.42	1.29	0.008	0.041
	C	0.3	0.2	60		0.37	1.06	0.020	0.019
#8	B	0.3	0.3	30		0.39	1.19	0.010	0.021
#5	B	0.2	0.3	10		0.43	1.27	0.012	0.035

*From mill test reports
'Geometry defined at right.



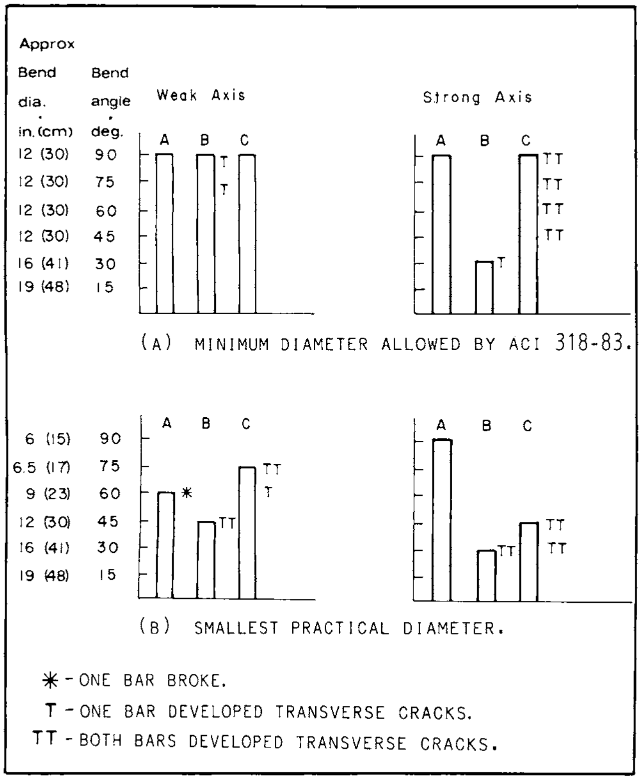


Fig. 3. — Straightening of #11 bars at room temperature. Each bar of the graph indicates the results of straightening the pair of reinforcing bars successfully bent to the angles shown in Fig. 2.

combinations of variables that were examined in this phase are as follows:

Room Temperature Bending and Heated Straightening

		Weak Axis		Strong Axis	
Bar Size	Supplier	ACI Min. Diameter	Smallest Diameter	ACI Min. Diameter	Smallest Diameter
#11	A		X		
	B	X	X	X	X
	C		X	X	X

Each test sequence, represented by an "X", consisted of bending a pair of bars in 15 deg increments to increasing angles. Two bars were bent to the angle that first caused cracking or breakage during straightening at room temperature. Each bent bar was then flame heated and straightened. This was repeated on additional pairs at increasing angles until breakage occurred or until two 90 deg bends were straightened.

The third phase was conducted to study a method of obtaining tighter bends by the use of heat. This testing was done on combinations of variables that caused cracking or breakage during room temperature bending in either the first or second phase, as follows:

Heated Bending and Straightening

		Weak Axis		Strong Axis	
Bar Size	Supplier	ACI Min. Diameter	Smallest Diameter	ACI Min. Diameter	Smallest Diameter
#11	B		Y	Y	Y
	C				Y

For each "Y", a pair of bars was flame heated and then bent to the angle at which cracking or breakage had previously occurred at room temperature. Each bar was then straightened. This was repeated. In all cases it was possible to continue until a pair of bars was bent to 90 deg and straightened.

Two sequences of bending and straightening were performed in the fourth phase to examine the effect of winter temperatures, 30F (−1C). The two combinations of variables that were examined are:

Cold Temperature Bending and Straightening

		Weak Axis	
Bar Size	Supplier	ACI Min. Diameter	Smallest Diameter
#11	B	Z	Z

Procedures and test results

The reinforcing bars were bent and straightened using a device that was built for this test program. This device consists of a horizontal steel tube that holds the reinforcing bar and a c-shaped frame that rotates about a hinge on the tube. The frame is powered by a two-way hydraulic ram.

The test bar was encased in three oak blocks, and then inserted into the tube. A steel pipe slightly larger than the bar was placed over the bar. A chain was wrapped around this pipe and around the top arm of the frame. Bending was accomplished by pulling the frame backward with the ram.

The bend diameter was controlled by placement of the pipe. Initial increments were made with the pipe placed close to the oak blocks. For bend angles of 45 deg or greater, the pipe was moved sufficiently away from the oak blocks to maintain the desired bend diameter. The smallest practical bend was obtained by keeping the pipe as close as possible to the oak blocks.

Straightening was accomplished by placing the frame in its rearmost position, moving the chain to the bottom arm and then powering the arm forward. This process was also repeated in increments until the bar was straightened.

Several methods of heated straightening were used. Temperature of the flame heated bars was monitored with 1400F (760C) and 1500F (820C) crayons. Initially, attempts were made to improve straightening by uniformly heating the bar to 1400F (760C). At this temperature, the color of the bar was black with a faint orange glow. Several trials with bars at this temperature did not show an improvement in straightening. Subsequently, bars were heated until the 1500F (820C) crayon mark was on the verge of melting. At this temperature, the bar had a bright orange glow. Trials at this temperature showed significant improvement in bendability. Based on this work, 1500F (820C) flame heating was used.

Field bending at room temperature

The results of the bending tests on #11 bars at room temperature are shown by the four bar graphs in Fig. 2. Each bar represents a testing sequence of bending pairs of reinforcing bars from 15 deg up to 90 deg. It may be noted that the ACI minimum diameter was not achieved for 15 and 30 deg bend angles. At a 90 deg bend angle, the smallest diameter that could be achieved for the #11 bars was 6 in. (150 mm).

The upper graphs show that bars from all three suppliers were bent to the minimum diameter specified in ACI 318-83 around the weak axis at angles increasing to 90 deg. One bar from Supplier B broke during bending about the strong axis at 45 deg. However, the remaining specimens in that sequence were bent to angles up to and including 90 deg without breakage. Transverse cracking was observed in two specimens after bending to 45 and 60 deg around the strong axis.

As shown in the lower graphs, a bend diameter smaller than the ACI minimum diameter was not achieved until the bend angle was 60 deg. When bent around the weak axis, one bar from Supplier B broke while attempting a 60 deg angle bend; the other bar of that pair was successfully bent. Bars from Suppliers A and C were bent up to a 90 deg angle without breakage. For bends around the strong axis, one bar from Supplier B broke at 45 deg, the second specimen was bent without breakage. One bar from Supplier C broke at 60 deg. The second specimen did not break. Reinforcing bars from Supplier A could be bent around the strong axis to bends as tight as 4d and 90 deg.

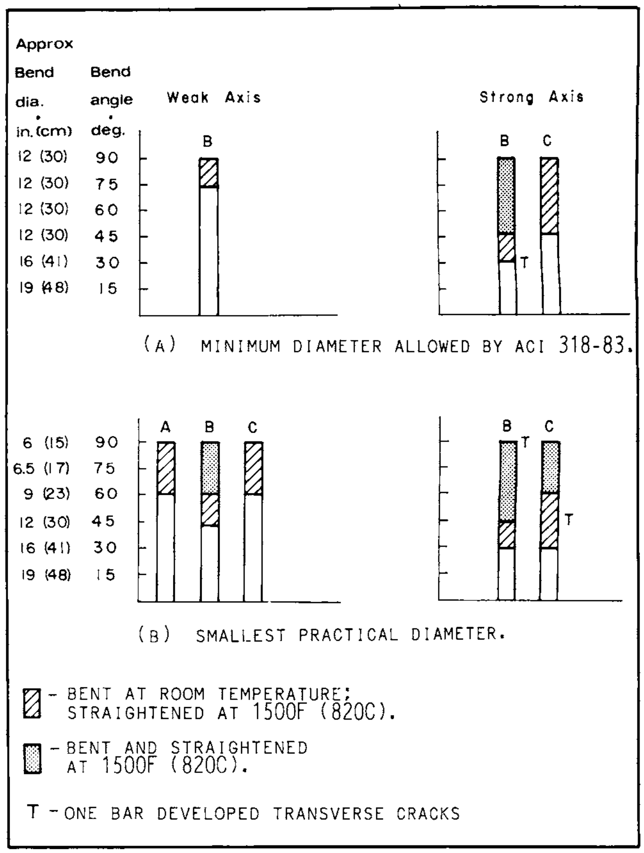


Fig. 4 — Heated bending and straightening of #11 bars.

All of the #5 and #8 bars were bent around the weak axis to a diameter as small as 3d and to 90 deg without breakage.

Field straightening at room temperature

Fig. 3 shows the results of straightening the bent #11 bars at room temperature. Each bar on the graphs represents straightening of a sequence of bent specimens. The upper limit of each bar indicates that one or both bars were straightened without breakage. At the next larger angle, either both bars broke during straightening or one bar broke during straightening and the other had broken during bending.

TABLE 2 — Averages of tensile test results

		Control bars		Unheated straightened bars		Heated straightened bars	
Bar size	Supplier	Yield point (ksi) (MPa)	Tensile strength (ksi) (MPa)	Yield point (ksi) (MPa)	Tensile strength (ksi) (MPa)	Yield point (ksi) (MPa)	Tensile strength (ksi) (MPa)
#11	A	64.4 (444)	106.4 (734)	63.8 (440)	103.7 (715)	61.7 (425)	91.8 (633)
	B	65.1 (449)	105.1 (725)	64.7 (446)	103.9 (716)	65.1 (449)	93.5 (645)
	C	64.8 (447)	105.1 (725)	64.6 (445)	103.6 (714)	65.1 (449)	97.5 (672)
#8	B	68.2 (470)	96.5 (665)	66.2 (456)	95.6 (659)	—	—
#5	B	—	—	64.5 (445)	104.5 (720)	—	—

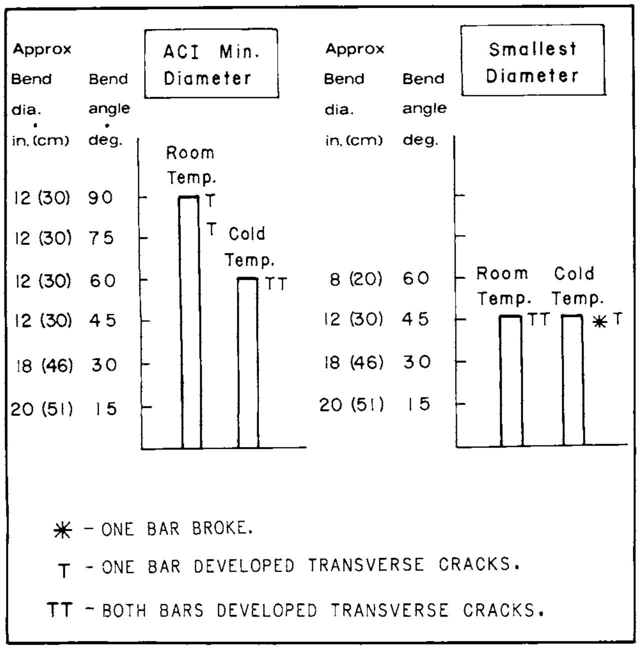


Fig. 5 — Straightening of #11 bars from Supplier B at cold temperature.

All of the bars that were bent to the minimum ACI diameter around the weak axis at angles up to 90 deg could be straightened without breakage. Bars from suppliers A and C that were bent to the minimum ACI diameter around the strong axis could also be straightened. However, for Supplier B, one 45 deg bend specimen broke during straightening. Since the other specimen had broken during bending, the graph is terminated at 30 deg.

The results of straightening #11 bars that were bent as tightly as possible around the weak axis are shown in the lower left graph of Fig. 3. Two #11 bars from Supplier A that were bent to 45 deg around the weak axis with a 10 in. (250 mm) diameter were straightened without breakage. At 60 deg, one specimen had a 7 in. (180 mm) bend; the other had an 8 in. (200 mm) bend. The 8 in. (200 mm) bend was successfully straightened; the 7 in. (180 mm) bend broke during straightening. At 75 deg, both specimens had a 6 in. (150 mm) bend and both broke during straightening.

For Supplier B, two bars with a 45 deg, 12 in. (300 mm) diameter bend around the weak axis were straightened. However, both had transverse cracks. At an angle of 60 deg, both specimens had an 8 in. (200 mm) bend. One specimen broke during straightening. The other had already broken during the initial bend.

For Supplier C, two bars with a 75 deg angle bend around the weak axis were straightened but had transverse cracks. One bar had a 6 in. (150 mm) diameter bend; the other had an 8-inch (200 mm) bend. At 90 deg, both bars had a 6 in (150 mm) bend and both broke during straightening.

The three test sequences of straightening bars with the smallest practical bends around the strong axis are shown in the lower right graph of Fig. 3. For Suppliers B and C, breakage occurred at smaller angles than the weak axis bending. However, for Supplier A, straightening of bends around the strong axis was more successful. Bends as sharp as 90 deg and 6 in. (150 mm) diameter were straightened without breakage or cracking.

No. 5. and No. 8 bars that had been bent around the weak axis, as tightly as 3d and to 90 deg, were straightened without breakage or cracking.

Heated bending and straightening

Results of tests on #11 bars are presented in Fig. 4. Bars bent at room temperature and straightened at 1500F (820C) are represented with cross-hatching. Bars that were bent and straightened at 1500F (820C) are shown with solid shading. The cross-hatching starts at the angle at which heat was first used during straightening. The shading starts at the angles at which flame heat was used during bending as well as straightening. Although tests were not performed at smaller angles, it is expected that a reinforcing bar could be straightened with heat at bend angles smaller than those tested.

Heating to 1500F (820C) allowed bars bent to the minimum ACI diameter or the smallest practical diameter around the weak or strong axis to be straightened without breakage. In most cases, the heating also eliminated cracking.

Heated straightening was not used on #5 or #8 bars because no breakage occurred during room temperature straightening.

Cold temperature straightening

Results of straightening #11 bars around the weak axis at cold temperatures 25F to 35F (–4C to 2C) are presented in Fig. 5. These results are compared to the results of room temperature straightening taken from Fig. 3.

Straightening of the test sequence at the minimum ACI diameter was halted at a bend angle of 60 deg. Transverse cracks developed in both specimens. Straightening of the smallest diameter test sequence was halted at a bend angle of 45 deg. One specimen broke during straightening; the other developed a transverse crack.

Tensile tests

Results of tensile tests on uncracked, straightened bent bars and control bars for each manufacturer are summarized in Table 2. Yield was obtained only for bars that exhibited a distinct plateau. Approximately 60 percent of the unheated bars and 80 percent of the heated bars had a distinct yield point.

The average yield point of the straightened bars, whether heated or not, was nearly the same as the yield point of the control bars. For the unheated bars, the yield point varied from a low of 57 ksi (390 MPa) to a high of 68 ksi, (470 MPa) with only one result less than 60 ksi (410 MPa). Yield point of the specimens that were bent or straightened using flame heat

Fig. 6 — A 1/4-in. long crack in a #11 bar.

varied from 59 ksi (410 MPa) to 66 ksi (460 MPa). Two results were less than 60 ksi (410 MPa).

Average tensile strength of the unheated straightened bars was essentialy the same as that of the control bars. Tensile strength varied from 79 ksi (540 MPa) to 108 ksi (740 MPa). Four specimens had a strength below 90 ksi (620 MPa). Tensile strength of the heated bars was 7 to 14 percent less than that of the control bars. These strengths varied from 80 ksi (550 MPa) to 102 ksi (700 MPa). Three specimens had a strength less than 90 ksi (620 MPa). Of the 58 flame straightened specimens, only 5 did not meet Grade 60 yield or tensile strength requirements.

Tensile tests were also performed on six bars obtained from Supplier C that developed transverse cracks during straightening. These results are given in Table 3. Crack sizes were categorized as small, medium and large. Two bars from each category were tested. Tensile test results are compared to the average yield point and tensile strength of the uncracked bars from Supplier C. Cracks described as small had a length of 0.10 in. (2.5 mm) and were hairline wide. The two cracks described as medium were 0.20 in. (5.1 mm) long by 0.01 in. (0.25 mm) wide and 0.15 in. (3.8 mm) long and 0.005 in. (0.13 mm) wide, respectively. Large cracks were 0.25 in. (6.4 mm) long and 0.015 in. (0.38 mm) wide and 0.25 in. (6.4 mm) long and 0.02 in. (0.5 mm) wide. A 0.25 in. (6.4 mm) long, transverse crack is shown in Fig. 6.

TABLE 3 — Supplemental tensile tests on bars with cracks

Crack size	Yield point (ksi) (MPa)	Tensile strength (ksi) (MPa)	Break location
Uncracked (from Table 2)	64.6 (445)	103.6 (714)	Varies
Small	64.3 (443)	102.1 (704)	In bend area
Medium	64.4 (444)	96.5 (665)	In bend area
Large	65.5 (452)	104.7 (722)	Outside of bend area

*These bars were tested one year after being straightened.

Bars with small and medium sized cracks were tested shortly after straightening. Their average yield point was virtually the same as the average yield point of the uncracked straightened bars. Tensile strength was slightly reduced when compared to the uncracked bars. However, the strength was above the minimum requirement of ASTM A615. Fracture initiated at a crack formed during straightening.

Specimens with large cracks were tested one year after straightening. Yield point and tensile strength increased to above the strength of the uncracked specimens, and was essentially equal to that of the control bars.

Evaluation and discussion of results

Effect of bend diameter, angle and orientation

Bend diameter and orientation had a strong effect on the ability to bend or straighten a #11 bar. This effect is demonstrated in Fig. 7 where the percentage of bars that was straightened without breakage is plotted as a function of bend diameter. The probability of straightening without breakage increased with increasing bend diameter. For weak axis bends, 100 percent of the bars were straightened at a bend diameter of 12 in. (300 mm) or greater. For strong axis bends, the bend diameter required for straightening of all the bars was 18 in. (460 mm).

When the bend was oriented with the longitudinal rib at the extreme fiber of bending, breakage during straightening occurred at a larger bend diameter for bars obtained from Suppliers B and C. However, straightening of bars from Supplier A was more successful. It appeared that the improved performance of the A bars about the strong axis was due to smoother geometry at the intersection of the transverse deformation and the longitudinal rib.

A similar effect was observed during the bending tests. Cracks and breakage occurred in some bars from Suppliers B and C that were bent to the ACI specified minimum diameter around the strong axis, while no cracking or breakage occurred in the weak axis bends. For tighter bends, breakage in Supplier B and C bars occurred in less sharp bends when the bend was oriented around the strong axis.

The bend angle at a given bend diameter did not appear to have a strong influence on bending and straightening. For example, in the test sequence for a strong axis bend at the minimum diameter permitted by ACI 318-83, breakage occurred in one #11 specimen at an angle of 45 deg. The same bend diameter was maintained, and bending was continued to an angle of 90 deg. No further breakage occurred. In straightening these bends, breakage occurred in approximately half the specimens. Both specimens bent to 75 deg were straightened even though breakage occurred in one of the specimens bent 60 deg.

Effect of bar size

No. 5 and No. 8 bars from one supplier were bent to a diameter as small as 3d without breakage. This is well below the bend diameter that is required in ASTM A615. By comparison, the bend diameter at which 100 percent of the #11 bars from the same supplier could be straightened was 8d.

Chemistry of the #5 and #8 bars does not appear to be significantly different than that of the #11 bars. The deformation geometry on the #8 bar was approximately the same as that of the #11 bar furnished by Supplier B. The lug base radius of the #5 bar is smaller. However, this apparently did not reduce the bendability of the #5 bar.

One difference of the #5 and #8 bars was that their elongation, as reported by the mills, was 16 to 17 percent as compared to approximately 10 percent for the #11 bars. The relationship of elongation, as measured for ASTM, to bendability is obscure.[9]

Effect of source of bars

There was a distinct difference in the bendability of the #11 bars produced by each of the Suppliers A, B and C. Bars obtained from Supplier A were the most bendable. Bars from Supplier B had the poorest bendability.

Chemistry of the bars from all three suppliers was similar. Supplier A bars had a sharper lug base radius than either the B or C bars. The higher stress concentration associated with the smaller base radius was therefore not related to the greater bendability of the A bars. There may be other factors that affect the performance of bars from different suppliers.

Effect of cold temperature and flame heating

Cold temperatures apparently slightly increase the probability of breakage during straightening. At room temperature, two bars were bent at a 12 in. (300 mm) diameter to 90 deg and straightened without breakage. Breakage occurred at 60 deg when the bend diameter was decreased to 8 in. (200 mm). When the temperature was decreased to between 25F (−4C) and 35F (2C), one of the 12 in. (300 mm) diameter bends broke during straightening. Transverse cracks also occurred at a smaller bend angle with straightening at cold temperatures.

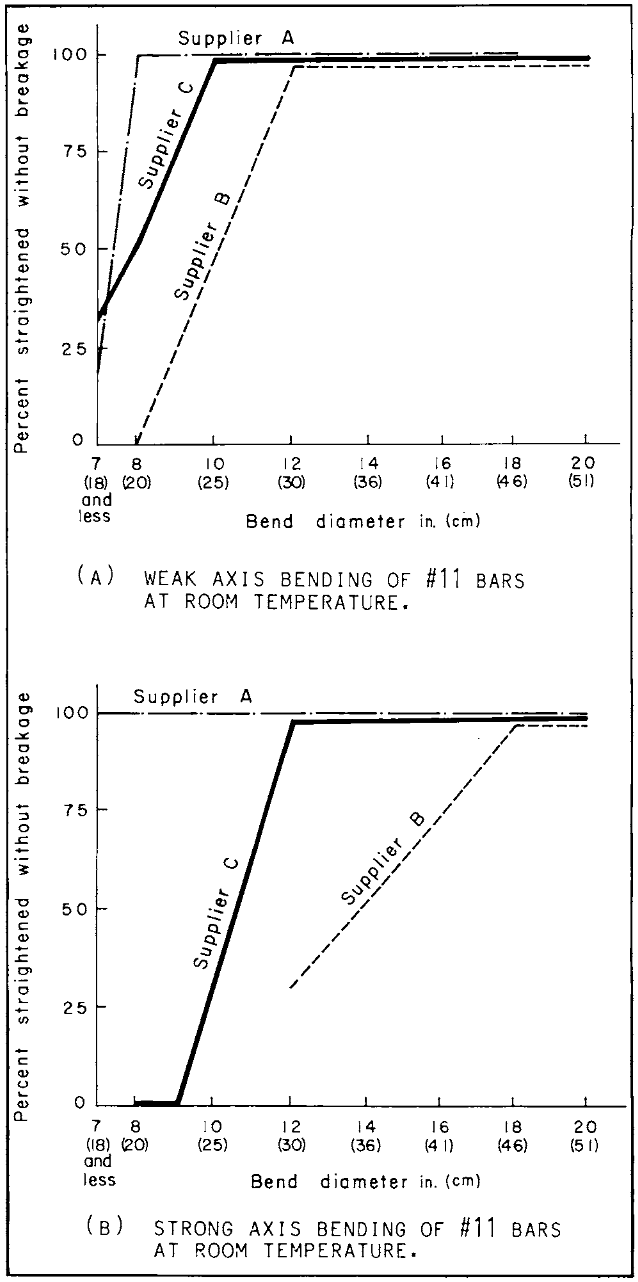


Fig. 7 — Straightening as a function of bend diameter.

Flame heating significantly improved the bending and straightening performance. No. 11 bars could be bent to a diameter as small as 4d and straightened without breakage. Cracking occurred in a few of the heated specimens, but the incidence of cracking was minimal.

Heating temperature was important. Early trials of heating to 1400F (760C) did not noticeably improve bendability. However, when the bar temperature was raised to 1500F (820C), a marked improvement was noted.

Tensile properties of straightened bars

The cracked reinforcing bars that were tested soon after straightening had a slight reduction in tensile strength. However, tensile testing of two cracked bars that were exposed at room temperature for one year after straightening indicated an apparent increase in yield and tensile strength when compared to the uncracked specimens. The fracture occurred outside the bend area. This behavior is consistent with the increased yield and tensile strength due to strain age hardening as described in Erasmus' paper. The tendency toward brittle behavior caused by the existing cracks and embrittlement due to aging in the bend region was not sufficient to cause a fracture in the bend area. Apparently, the tensile strength in the strained, bend region was raised sufficiently by the aging process to cause failure outside of the bend region.

Summary and conclusions

Bending and straightening tests were performed on 254 Grade 60 reinforcing bars. Three sizes were included in the tests, #5, #8, and #11. The major variables were bend diameter, bar size and supplier, bend axis and temperature. Procedures simulated field conditions.

Observations based on this testing are are follows:

1. The #5 and #8 reinforcing bars performed better than the #11 bars from the same supplier. They were bent at room temperatures to a diameter as small as three times the bar diameter and straightened without breakage or cracking.
2. No. 11 bars from all three suppliers could be bent at room temperatures to the minimum diameters permitted by ACI 318-83 around the weak axis. Some of these bars broke when they were bent around the strong axis or when bent to the smallest practical diameter around either the weak or strong axis. Breakage increased with decreasing bend diameter.
3. No. 11 bars bent to 90 deg at the minimum ACI diameter around the weak axis could be field straightened at room temperature without breakage. Breakage during straightening occurred in some bars with minimum ACI bends around the strong axis and for smaller diameter bends around either axis. Breakage increased with decreasing bend diameter.
4. Breakage and cracking is more likely when straightening is done at cold temperatures.
5. The two deformation patterns in which the transverse lugs run into the rib had a greater incidence of breakage when bent around the strong axis. The deformation pattern in which the lugs tapered before meeting the rib showed improved bendability around the strong axis.
6. Heating the bars to 1500F (820C) significantly improved the ability to bend and straighten #11 reinforcing bars. Bends as small as 5 in. (130 mm) diameter around the strong axis could be straightened without breakage.
7. Tensile properties of bars straightened without flame heat were virtually the same as that of the unbent control bars.
8. Yield strength of #11 reinforcing bars flame heated during bending or straightening was the same as unheated bars. Tensile strength was approximately 10 percent less than that of the corresponding control bars.
9. Tensile strength of #11 reinforcing bars that developed transverse cracks during bending and straightening, tested shortly after straightening, were less than that of specimens without cracks.
10. Yield and tensile strength of two cracked straightened #11 bars allowed to age for one year were higher than for uncracked specimens. The fractures occurred outside the bend region.

It is concluded from this investigation that field bending and straightening of reinforcing bars up to #11 should generally be permitted. Although variability must be anticipated, it is expected that most bars can be bent about the weak axis up to 90 deg at the ACI specified minimum diameter and straightened at normal temperatures. Under more severe conditions, flame heating to 1500F (820C) may be desirable. The very minor reduction in strength from local heating to this temperature, compared to the present limit recommended by ACI 318-83 of 1200F (650C), is more than offset by the minimization of breakage and the ability to restore the bar to a straight or desired alignment.

Recommendations

The Commentary[2] for Paragraph 7.3.2 of ACI 318-83 should be revised as follows:

7.3.2—Construction conditions may make it necessary to bend bars that have been embedded in concrete. Such field bending should not be done without authorization of the inspecting engineer. The inspecting engineer must specify whether the bars should be bent cold, or if heating should be used.

Tests* have shown that most A615 Grade 40 and Grade 60 reinforcing bars can be bent and straightened, preferably about the weak axis, up to 90 degrees at or near the minimum diameter specified in Section 7.2. Tighter bends may also be successful. If cracking or breakage is encountered, heating to a maximum temperature of 1500F should be beneficial. Minor cracks in the bend region, less than about 0.010 in. in width, should not adversely affect the performance of the bar. Bars that fracture during bending or straightening can be spliced outside the bend region.

Heating must be performed in a manner that will avoid damage to the concrete. If the bend area is within 6 in. or so of the concrete, some protective insulation may have to be applied. Heating of the bar

*This paper and Ref. 7.2 of the Commentary.

should be controlled by temperature indicating crayons or other suitable means. The heated bars should not be artificially cooled (such as by water or forced air) until after cooling to at least 600F.

Acknowledgments

The work reported in this paper was carried out by Wiss, Janney, Elstner Associates, Inc. under the direction of the Technical Committee of the Associated Reinforcing Bar Producers. Bertrand K. Thornley was chairman of the committee at the start of this project. Members of the committee were: Paul F. Rice (Secretary), R. Ben Alexander, Carlos Bonacich, William C. Black, Joseph H. Dixon, Ward Dobbin, Merle E. Kersten, and Raymond J. Warren.

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Received and reviewed under Institute publication policies.

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