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16. ABSTRACT

This report describes the results of laboratory experiments in which concrete reinforcing steel of various sizes was "cold" and "hot" bent under different conditions and was subsequently straightened. The bent/straightened steel was inspected for cracking and tested in tension for strength and ductility.

The laboratory data were analyzed to determine the conditions that may cause reinforcing bars to crack during bending/straightening operations, or that may render the engineering properties of bars unsuitable for reinforcing the concrete. The results of those analyses were used to propose standard specifications for bending/straightening reinforcing bars, for WSDOT's considerations.

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Research Project GC 8719, Task 1
Rebar—Bending/Straightening Standard Specifications

DEVELOPMENT OF STANDARD SPECIFICATIONS FOR BENDING/STRAIGHTENING CONCRETE REINFORCING STEEL

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Washington State Transportation Commission, Department of Transportation, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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SUMMARY

Reinforcing bars partially embedded in concrete and protruding from it are frequently subjected to bending and straightening in the field. Often field workers must bend the protruding bars to provide clearance for construction operations. Furthermore, field bending and/or straightening may be required because of incorrect fabrication or accidental bending. Whatever the cause, the success rate of bending and straightening bars in the field has been unpredictable, and bar cracking has sometimes been reported. Even in the absence of cracking, engineers are concerned about the effects of bending and straightening on the engineering properties of concrete reinforcing bars.

In 1988 WSDOT initiated a research project to review its specification guidelines for field bending/straightening reinforcing bars. The result of this research effort was a report that made a number of recommendations concerning WSDOT's current procedures for field bending bars. (1) Those recommendations were tentative and needed to be verified through supplementary laboratory research. WSDOT initiated the current project to conduct laboratory experiments in which reinforcing steel of various sizes was "cold bent" (bent at ambient temperature) and "hot bent" (bent at elevated temperatures) under different conditions to develop standard specifications for bending/straightening concrete reinforcing bars.

The first task of the project was to design laboratory experiments to test bars bent and straightened according to the recommendations of the Phase One research and also to test bars bent and straightened under field conditions that deviated from those recommendations. The deviant field conditions were necessary to determine the tolerance on recommendations of the Phase One research. Subsequently, reinforcing bars were bent and straightened and inspected for cracking caused by those operations. Finally, bars bent and straightened were tested in tension for strength and ductility. The laboratory data obtained were then analyzed to determine the conditions that may cause reinforcing bars

to crack during bending/straightening operations, or that may render the engineering properties of bars subjected to such operations unsuitable for reinforcing concrete. The results of those analyses were used to modify the findings of the Phase One research and to prepare standard specifications for bending/straightening reinforcing bars, suitable for WSDOT's consideration.

On the basis of the results of this work, the prior tentative specifications for bending/straightening concrete reinforcing steel were refined. Those refinements involved the limit on bar size above which cold bending is not practical, the bend diameter for cold bending, the length of bar to be heated in hot bending, the number of heat tips to be used in hot bending, and the range of temperature to be applied in hot bending. In addition, information was added to allow engineers to calculate the possible loss in the strength and ductility of bars that are to be bent and straightened.

FINDINGS

COLD BENDING

1. Bending/straightening No. 4 bars (with a bend diameter of 6 times the bar diameter) increased their strength so that the fracture of those bars in subsequent tension tests occurred in the unbent metal. This condition did not allow the elongation of the bent metal to be accurately determined. However, two cycles of bending/straightening No. 4 bars weakened the steel through the development of microcracking at the inner radius surface of the bar with each cycle of straightening. This condition caused the metal to fracture in the bent/straightened region in subsequent tension tests. The reduction in strength caused by the bending/straightening of those No. 4 bars was not significant, but their elongation was 23 percent lower than the elongation of undisturbed No. 4 bars. Thus, for No. 4 bars that are subjected to one bend/straighten cycle, a 12 percent reduction in the elongation should be considered a conservative figure.
2. Regardless of the steel hardening caused by cold bending, bending/straightening No. 6 bars (with bend diameter of 8 times the bar diameter) decreased their strength so that the fracture of those bars in subsequent tension tests occurred in the bent/straightened metal. Those bars developed relatively extensive microcracking at the inner radius surface upon straightening, and that microcracking caused the fracture. The reduction in yield strength was 6 percent, and the reduction in ultimate strength was 1 percent. The reduction in the elongation was 20 percent. Generally, the Charpy Transition Temperature increases with bar size. Thus, the larger the bar is the more susceptible it is to cracking caused by bending/straightening operations.
3. Bending/straightening No. 6 bars around a sharper than normal former (with a bend diameter of 4 times the bar diameter) caused relatively wide cracking at the inner radius surface upon straightening. The reduction in yield strength was 9

percent, and the reduction in ultimate strength was 3 percent. The reduction in elongation was 57 percent.

4. Accelerated aging of both bent/straightened No. 4 and bent/straightened No. 6 bars in the laboratory (the equivalent of 6 months aging in the field) caused further hardening of the steel. Fracture of the bent/straightened No. 6 bars (with a bend diameter of 8 times the bar diameter) in subsequent tension tests shifted from the bent/straightened metal to the undisturbed metal once the steel had been strain aged. Since the location of the fracture was always outside of the bent/straightened metal, the elongation measured in those tension tests was therefore not representative of the strain aged metal.

5. An analysis of laboratory data obtained in these tests and laboratory data obtained elsewhere indicated that the elongation of No. 6 bars that are bent/aged/straightened/aged (with a bend diameter of 8 times the bar diameter) may decrease 38 percent. The decrease in elongation for No. 5 bars may be, conservatively, 31 percent, and for No. 4 bars, 23 percent.

6. Manually bending/straightening No. 6 bars was very difficult and is unlikely to be practical in the field.

HOT BENDING

1. Bending/straightening of No. 7 bars heated to 1,200° F (with a bend diameter of 8 times the bar diameter) caused a 6 percent reduction in yield strength, a 7 percent reduction in ultimate strength, and a 25 percent reduction in elongation.

   When No. 7 bars were heated to 1,425° F instead of 1,200° F, the fracture in the bars in subsequent tension tests generally shifted to the unbent region, indicating that the steel hardened in the bent/straightened/heated region rather than in the unbent/heated region. This condition did not allow the properties of the bent/straightened/heated metal to be measured. However, for the unbent/heated steel, the reduction in yield strength was 2 percent, the reduction in ultimate strength was 4 percent, and the reduction in elongation was 15 percent.

When No. 7 bars were bent and straightened twice after having been heated to 1,425° F, they fractured in the bent/straightened region and the reductions in yield strength and ultimate strength were 3 percent and 6 percent, respectively. In this case, the reduction in elongation was only 15 percent, indicating that hot bending at this higher temperature reduced the adverse effect of the operation on the elongation. It is likely that when temperature crayons indicate that the bar surface is heated to 1,200° F, the temperature of the core is still in the blue brittle range (i.e., 400° to 700° F). That condition causes microcracking in the core during subsequent bending/straightening the bar, which in turn can decrease the strength and ductility.

2. Manual bending/straightening of No. 9 bars heated with only one tip to 1,200° F (with a bend diameter of 8 times the bar diameter) was not possible. Apparently, regardless of the surface temperature, the inside of the bar was not hot enough to facilitate the bending operation. Heating of those bars to 1,425° F made the bending operation possible. In that case, yield strength decreased 9 percent, ultimate strength decreased 8 percent, and elongation decreased 7 percent.

3. Bending/straightening of No. 9 bars heated to 1,425° F around a sharper than normal former (with a bend diameter of about 6 times the bar diameter) caused a 1 percent reduction in yield strength, a 7 percent reduction in ultimate strength, and a 10 percent reduction in elongation. As evident from these results, contrary to cold bending, hot bending around a sharper former did not significantly increase the adverse effect of bending/straightening on elongation.

4. Bending/straightening No. 9 bars heated to extremely high temperatures (with a bend diameter of 8 times the bar diameter and heating temperature of 1,800° to

2,000° F) caused the fracture in the subsequent tension tests to occur in the unbent region, indicating that the steel hardened in the bent/straightened/heated region rather than the unbent/heated region. This behavior was similar to the behavior of No. 7 bars when they were heated to 1,425° F. Apparently, the larger the bar is, the higher is the surface temperature at which hardening takes place. The ultimate strength of the No. 9 bars (the strength of the unbent/heated steel) was 3 percent less than the control ultimate strength (i.e., the unbent/unheated condition). This means that the ultimate strength of the bent/straightened/heated steel was, at the most, 3 percent less than the control ultimate strength.

5. Manual bending/straightening of No. 9 bars heated to 1,200° F (with a bend diameter of 8 times the bar diameter) was possible when two heat tips were used. Apparently, heating the bars with two tips produced sufficient temperature in the core to facilitate bending. In this case, yield strength decreased 6 percent, ultimate strength decreased 11 percent, and elongation decreased 17 percent. When the same bars were heated to 1,425° F with two heat tips, the reductions in yield and ultimate strength were both 6 percent, and the reduction in elongation was 10 percent. Comparison of these results with the results obtained for No. 9 bars bent/straightened/heated under the same conditions, but with only one heat tip, showed that the use of two tips slightly increased the strength, but also slightly decreased the elongation.

RECOMMENDED SPECIFICATIONS FOR BENDING/STRAIGHTENING REINFORCING BARS

If plans call for field bending of steel reinforcing bars, the contractor shall bend the bars in accordance with the structural configuration and plan requirements.

Bending steel reinforcing bars partly embedded in concrete shall not be done until the Engineer has given written approval of a field-bending plan to the Contractor. Approval for such bending will be given only for bars smaller than Size No. 14.

Field bending shall not be done:

1. On bars Size No. 14 and 18, or
2. When the air temperature is lower than 45° F, and the application of heat is not required, or
3. By means of hammer blows or other impact loading, or
4. While application of heat is required, and the bar temperature is in the range of 400° to 700° F.

In field bending steel reinforcing bars, the Contractor shall

1. Make the bend gradually;
2. Apply heat as described in these specifications in bending bars Sizes No. 6 through No. 11, or in bending bars Sizes No. 5 and smaller when those bars have been previously bent. Previously unbent bars of Sizes No. 5 and smaller may be bent without heating;
3. Use a bending tool equipped with a bending diameter as follows:

	Bend Inside Diameter/Bar Diameter Ratio	
<u>Bar Size</u>	<u>Heat Not Applied</u>	<u>Heat Applied</u>
No. 3 through No. 5	8	8
No. 6 through No. 9	Not permitted	8
No. 10 and No. 11	Not permitted	10

4. Limit any bend to a maximum of 90 degrees; and

5. Straighten by moving a hickey bar (if used) progressively around the bend.

In applying heat for field-bending steel reinforcing bars, the Contractor shall:

1. Use a method that will avoid damage to the concrete;
2. Insulate any concrete within 6 inches of the heated bar area;
3. Ensure by means of temperature-indicating crayons, or other suitable means, that the steel temperature will be at or above the minimum shown below at the end of the heating operation and does not exceed the maximum shown below during the heating operation:

	Temperature (° F)	
Bar Size	Minimum	Maximum
No. 3 and No. 4	1,200	1,250
No. 5 and No. 6	1,350	1,400
No. 7, No. 8, and No.9	1,400	1,450
No. 10 and No. 11	1,450	1,500

4. Heat the entire length of the bar to be bent (or the entire length of the bend to be straightened) plus a 2-inch additional length at each end.
5. Maintain the steel temperature within the required range shown above during the entire bending process;
6. Apply two heat tips simultaneously at opposite sides of bars larger than Size No. 9 to assure a uniform temperature throughout the thickness of the bar;
7. Bend the bar immediately after the required temperature has been reached;
9. Never cool bars artificially with water, forced air, or other means.

Before giving written approval of a field-bending plan to the contractor, the Engineer shall evaluate the significance of possible reductions in the properties of bent/straightened bars, as indicated below.

	Percent Reduction in		
Bar Size in Cold Bending	**Yield Strength**	**Ultimate Strength**	**Elongation**
No. 3 and No. 4	—	—	20
No. 5	5	—	30

	Percent Reduction in		
Bar Size in Hot Bending	**Yield Strength**	**Ultimate Strength**	**Elongation**
All sizes	10	10	20

The Engineer shall not approve a plan that premits a hot bent bar to be loaded before it has reached the ambient temperature.

INTRODUCTION

Reinforcing bars partially embedded in concrete and protruding from it are frequently subjected to bending and straightening in the field. Often field workers must bend the protruding bars to provide clearance for construction operations. Furthermore, field bending and/or straightening may be required because of incorrect fabrication or accidental bending. Whatever the cause, the success rate of bending and straightening bars in the field has been unpredictable, and bar cracking has often been reported. Even in the absence of cracking, engineers are concerned about the effects of bending and straightening on the engineering properties of concrete reinforcing bars.

In 1988 WSDOT initiated a research project to review its specification guidelines for field bending/straightening reinforcing bars. The result of that research effort was a report that made a number of recommendations concerning WSDOT's current procedures for "cold bending" (bending steel at ambient temperature) and "hot bending" (bending steel at elevated temperatures) bars in relation to factors such as bar size, bend diameter, cyclic bending, strain aging, and temperature of heating. (1) Those recommendations were intended to prevent cracking of the bars during the operation and to assure satisfactory engineering properties after the operation. However, those recommendations were tentative and needed to be verified through supplementary laboratory research before standard specifications for WSDOT were developed.

OBJECTIVE

WSDOT initiated this project to conduct laboratory experiments in which reinforcing steel of various sizes was "cold" and "hot" bent under different conditions to develop standard specifications for bending/straightening concrete reinforcing bars.

RESEARCH APPROACH

The first task of the project was to design laboratory experiments to test bars bent and straightened according to the recommendations of Phase One research and also to test bars bent and straightened under field conditions that deviated from those recommendations. The deviant field conditions were necessary to determine the tolerance of the Phase One recommendations. Subsequently, reinforcing bars were bent and straightened and inspected for cracking caused by those operations. Finally, bars bent and straightened were tested in tension for strength and ductility. The laboratory data obtained were then analyzed to determine the conditions that may cause reinforcing bars to crack during bending/straightening operations, or that may render the engineering properties of bars subjected to such operations unsuitable for reinforcing the concrete. The results of those analyses were used to modify the findings of the Phase One research and to propose standard specifications for bending/straightening reinforcing bars, for WSDOT's consideration.

RESULTS OF PHASE ONE RESEARCH

As a result of Phase One research, tentative specifications for bending/straightening reinforcing bars were prepared for WSDOT's consideration. Those proposed tentative specifications (PTS), taken from reference 1, are shown below.

PROPOSED TENTATIVE SPECIFICATION FOR BENDING/ STRAIGHTENING REINFORCING BARS

If the plans call for field bending of steel reinforcing bars, the Contractor shall bend them in keeping with the structure configuration and the plans.

Bending steel reinforcing bars partly embedded in concrete shall not be done until the Engineer has given written approval of a field-bending plan to the Contractor. Approval for such bending will be given only for bars smaller than Size No. 14.

Field bending shall not be done:

1. On bars Size No. 14 and 18,
2. When air temperature is lower than 45° F,
3. By means of hammer blows or pipe sleeves, or
4. While the bar temperature is in the range of 400 to 700° F.

In field-bending steel reinforcing bars, the Contractor shall:

1. Make the bend gradually;
2. Apply heat as described below in bending bar Sizes No. 7 through No. 11 and in bending bars Sizes No. 6 and smaller when the bars have been previously bent. Previously unbent bars of Sizes No. 6 and smaller may be bent without heating;

3. Use a bending tool equipped with a bending diameter as follows:

	Bend Diameter/Bar Diameter Ratio*	
Bar Size	Heat Not Applied	Heat Applied
No. 3, No. 4	6	8
No. 5, No. 6	8	8
No. 7, No. 8, No. 9	Not permitted	8
No. 10, No. 11	Not permitted	10

4. Limit any bend to these maximums: 135 degrees for bars smaller than Size No. 9, and 90 degrees for bars Size No. 9 through No. 11; and

5. Straighten by moving a hickey bar (if used) progressively around the bend.

In applying heat for field-bending steel reinforcing bars, the Contractor shall:

1. Use a method that will avoid damage to the concrete;

2. Insulate the concrete within 6 inches of the heated bar area;

3. Ensure by means of temperature-indicating crayons, or other suitable means, that the steel temperature never exceeds the maximum temperature shown below:

	Temperature (°F)	
Bar Size	Minimum	Maximum
No. 3, No. 4, No. 5, No. 6	1,100	1,200
No. 7, No. 8, No. 9	1,150	1,250
No. 10, No. 11	1,200	1,300

4. Maintain the steel temperature within the required range shown above during the entire bending process;

5. Apply two heat tips simultaneously at opposite sides of bars larger than Size No. 6 to assure a uniform temperature throughout the thickness of the bar. For Size No. 6 and smaller bars apply two heat tips, if necessary;

*Bend former should turn freely

6. Apply the heat for a long enough time that within the bend area the entire thickness of the bar — including its center — reaches the required temperature;

7. Bend immediately after the required temperature has been reached;

8. Heat at least as much of the bar as indicated below:

	Heated Length, Based on Bar Diameter		
Bar Size	**Bend Angle, Degrees**		
	45°	**90°**	**135°**
No 3 through No. 8	8d	12d	15d
No. 9	8d	12d	Not permitted
No. 10 and No. 11	9d	14d	Not permitted

9. Locate the heated section of the bar to include the entire bending length; and

10. Never cool bars artificially with water, forced air, or other means.

EXPERIMENTAL WORK PROCEDURE

REINFORCING STEEL

Grade 60 deformed ASTM A615 reinforcing bars were used in the experimental work. Two bar sizes, No. 4 and No. 6, were selected for cold bending (bending at ambient temperature), and two bar sizes, No. 7 and No. 9, were selected for hot bending (bending at elevated temperatures). The range in size for those bars conformed to those for the proposed tentative specifications (PTS) for cold and hot bending and also represented the range of bar sizes that are typically bent and straightened. Each size was from a single heat of steel. The chemistry of each heat and its carbon equivalent were supplied by the steel manufacturer and are given in Table 1.

EXPERIMENT DESIGN

Table 2 lists the different conditions associated with the cold bending to which the No. 4 and No. 6 bars were subjected before they were subsequently tested for strength and ductility. Similarly, Table 3 lists the different conditions associated with the hot bending to which the No. 7 and No. 9 bars were subjected before they were also subsequently tested for strength and ductility. Also, shown in Tables 2 and 3 are the number of test specimens in the program corresponding to a given bar condition and bar size.

All cold and hot bending was done around the strong axis (longitudinal rib uppermost) of the deformed bars to represent the most severe strain condition. All bend angles were 90 degrees. Detailed descriptions of bar conditioning for cold and hot bending are presented in the following sections.

COLD BENDING

For cold bending, bars were manually bent around the desired size of former at room temperature. To straighten a bent bar, the bar was supported at the beginning of the bend and was manually straightened. This action resulted only in partial straightening of the

Table 1. Chemical Analysis of the Steel Heats Used in the Experimental Work

Bar Size	Chemical Analysis %C	%Mn	%P	%S	%Si	Carbon* Equivalent
No. 4	0.35	1.02	0.017	0.043	0.34	0.55
No. 6	0.34	1.02	0.005	0.025	0.24	0.54
No. 7	0.39	1.22	0.009	0.026	0.24	0.61
No. 9	0.40	1.22	0.022	0.026	0.24	0.62

* Carbon Equivalent = $\%C + \%\frac{Mn}{6} + \%\frac{Cu}{40} + \%\frac{Ni}{20} + \%\frac{Cr}{10} - \%\frac{Mo}{50} - \%\frac{V}{10}$

Table 2. Bar Conditioning for Cold Bending and Number of Bar Specimens Tested

	No. of Bar Specimens Tested					
Bar condition / Bar size	Control	Condition No. 1	2	3	4	5
		Bend/ straighten	Bend/ straighten; two cycles	Bend/ straighten; sharp former	Bend/age/ straighten	Bend/age/ straighten/ age
#4	4	3	3	--	3	3
#6	7	6	--	3	6	6

Table 3. Bar Conditioning for Hot Bending and Number of Bar Specimens Tested

	No. of Bar Specimens Tested							
Bar condition / Bar size	Control	Condition No. 1	2	3	4	5	6	7
		One Tip					Two Tips	
		1,200°F	1,425°F			Extreme heating	1,200°F	1,425°F
		Bend/ straighten	Bend/ straighten	Bend/ straighten; two cycles	Bend/ straighten; sharp former	Bend/ straighten	Bend/ straighten	Bend/ straighten
#7	3	3	3	3	--	--	--	--
#9	3	2	3	--	3	3	3	3

bend. Subsequently, the support was progressively located along the bend and the bar was bent in increments till its straightening was completed. This condition simulated straightening in the field with a hickey bar moved progressively along the bend.

Condition 1 (Bending/Straightening)

In accordance with the PTS, No. 4 bars were bent/straightened around a 3-inch diameter former (i.e., with a bend diameter 6 times the bar diameter) and No. 6 bars were bent/straightened around a 6-inch diameter former (i.e., with a bend diameter 8 times the bar diameter). Bending/straightening of No. 6 bars was very difficult and required a leverage of about 8 ft. That leverage was provided by a steel pipe placed over the bar.

Condition 2 (Two Cycles of Bending/Straightening)

No. 4 bars were bent and straightened twice in accordance with Condition 1. Condition 2 represented the deviation from the PTS likely in the field when there is frequent bending/straightening.

Condition 3 (Bending/Straightening with Sharp Former)

No. 6 bars were bent and straightened around a 3-inch diameter former (i.e., with a bend diameter 4 times the bar diameter) to represent the deviation from the specified former diameter likely in the field. As mentioned previously, cold bending/straightening of No. 6 bars was very difficult.

Condition 4 (Bending/Aging/Straightening)

No. 4 and No. 6 bars were bent and straightened following Condition 1, but they were strain aged after bending and before straightening. Bars were strain aged at 212° F for 2 hours, which is equal to about six months of strain aging at 60° F, or 3 months of aging at 70° F. (2) That strain aging represented a typical field condition in which bars are not straightened immediately after bending.

Condition 5 (Bending/Aging/Straightening/Aging)

No. 4 and No. 6 bars were bent and straightened following Condition 1. They were then strain aged after bending and before straightening and also strain aged after straightening. Both strain aging cycles involved heating at 212° F for 2 hours. The second cycle of strain aging represented the condition of a straightened bar after construction and during service.

HOT BENDING

Bars were heated with an oxygen-acetylene torch and a "rosebud" heating tip. The heating tip was a Victor No. 10 MFA heating tip. Some bars in the experiment were heated with two tips. In those cases, the heating tips were two Victor No. 5 MFA tips. The two tips were assembled on the torch so that they were opposite to each other.

The heated length of the bar included the entire bend plus about 1.5 in. of additional length at each end. Heat was applied uniformly over the entire area. Melting of the temperature crayon indicated that the desired temperature had been reached. The heated bar was then gradually bent around the desired former manually. To straighten, heat was uniformly applied over the entire bend area plus about 1.5 in. of additional length at each end. The bar was then manually straightened following the procedure described for straightening "cold" bars. That straightening procedure simulates straightening in the field with a hickey bar moved progressively along the bend. If an excessive offset was observed before the straightening had been completed, a small section was heated and straightened to reduce the offset.

Condition 1 (Heating with One Tip to 1,200° F and Bending/Straightening)

No. 7 and No. 9 bars were heated to 1,200° F, using one tip, both before bending and before straightening. That heating procedure followed the PTS, except one heating tip was used instead of two tips. In accordance with the PTS, No. 7 bars were bent around a 7-inch diameter former (i.e., with a bend diameter 8 times the bar diameter), and No. 9 bars were bent around a 9-inch diameter former (i.e., also 8 times the bar diameter).

About one minute was required to raise the surface temperature of the heated length of a No. 7 bar (i.e., approximately 8.5 in.) to 1,200° F, and about 1.5 minutes were required to raise the surface temperature of the heated length of a No. 9 bar (i.e., 10 in.) to 1,200° F. At 1,200° F the color of the bar was dark red. Some extra heating was needed during bending and straightening operations to maintain the temperature at 1,200° F.

Condition 2 (Heating with One Tip to 1,425° F and Bending/Straightening)

Condition 2 was the same as Condition 1, except No. 7 and No. 9 bars were heated to 1,425° F. The temperature was increased from 1,200° F to 1,425° F because bending and straightening the bars were difficult at 1,200° F.

About 1.5 minutes were necessary to raise the surface temperature of the heated length of a No. 7 bar (i.e., approximately 8.5 in.) to 1,425° F, and about 2 minutes were required to raise the surface temperature of the heated length of a No. 9 bar (i.e., approximately 10 in.) to 1,425° F.

When a 1,425° F temperature crayon melted, the bar had an orange glow. Further examination of the bar temperature with a digital temperature gun showed that the actual temperature of the bar reached about 1,500° F when it had an orange glow. The reason for the difference in temperature was that after initial heating, further heating was done in increments, and at the end of each heat increment the crayon was tested for melting. Therefore, the nominal temperature of 1,425° F reported for the experiments of the research program was the minimum bar temperature, and the actual bar temperature was as high as 1,500° F.

Condition 3 (Heating with One Tip to 1,425° F and Two Cycles of Bending/Straightening)

No. 7 bars were twice bent and straightened following Condition 2. The repetition represented possible deviation from the PTS in the field when frequent bending/straightening is involved.

Condition 4 (Heating with One Tip to 1,425° F and Bending/Straightening with Sharp Former)

No. 9 bars were bent and straightened around a 7-inch diameter former (i.e., with a bend diameter approximately 6 times the bar diameter) while all other factors were the same as for Condition 2. This condition represented possible deviation from the specified former diameter in the field.

Condition 5 (Extreme Heating with One Tip and Bending/Straightening)

No. 9 bars were bent and straightened following Condition 2, except that after their temperature had reached about 1,425° F, the bars were heated for an additional 1 minute before bending and straightening. At this stage bars had a bright orange glow. The recorded bar surface temperature was 1,800° to 2,000° F, as measured by a digital temperature gun. This condition made bending very easy and represented possible deviation from the specified heating temperature in the field.

Condition 6 (Heating with Two Tips to 1,200° F and Bending/Straightening)

No. 9 bars were bent and straightened following Condition 1, except that, in accordance with the PTS, two heating tips were used instead of one tip.

Condition 7 (Heating with Two Tips to 1,425° F and Bending/Straightening)

No. 9 bars were bent and straightened following Condition 2, except that, in accordance with the PTS, two heating tips were used instead of one tip.

TENSION TESTING AND DATA INTERPRETATION

TENSION TESTS

None of the test specimens broke during the bending or straightening operations. Prior to the tension tests, bars were inspected with a 30X magnifier, equipped with a light, for potential cracking caused by the bending/straightening. The tension tests of the bent/straightened bar specimens and the control specimens were made with a universal testing machine with a 300,000 lb capacity. The loading rate was approximately 30,000 lb per minute. Elongations were measured on an 8-inch gage length. That length was centered on the 4-foot long bar specimens before initial bending, and bending was performed in the middle of the gage length. The allowance for the grips in the testing machine was 2 in. on each side of the gage length. Yield strength, ultimate strength, and elongation were recorded for control specimens and conditioned specimens. Yield strength was determined by a halt in the testing machine gage. However, when the steel did not have a well-defined yield point, the yield strength was determined when the gage length under load was 8.04 in., as measured by a divider (ASTM method A615). Ultimate elongation was calculated as the difference between the deformation of the 8-inch gage length after the tensile fracture had occurred.

TEST RESULTS, COLD-BENT NO. 4 BARS

Test results for No. 4 bars are summarized in Table 4.

Control Specimens

Control specimens (i.e., bars not bent, straightened, or conditioned) conformed to ASTM requirements for Grade 60 A615 reinforcing steel. Their average yield strength at 75,350 psi was 25 percent higher than the minimum required yield strength of 60,000 psi. Their ultimate strength at 105,541 psi was 17 percent higher than the minimum required ultimate strength of 90,000 psi. Their elongation at 0.129 in./in.was 43 percent higher than the minimum required elongation of 0.090 in./in.

Table 4. Test Results for Cold-bent Reinforcing Bars

	Average Test Results		Yield Strength, psi Ultimate Strength, psi 8-inch gage length elongation, in./in. x 100			
Bar condition / Bar size	Control	Condition No. 1 Bend/ straighten	Condition No. 2 Bend/ straighten; two cycles	Condition No. 3 Bend/ straighten; sharp former	Condition No. 4 Bend/age/ straighten	Condition No. 5 Bend/age/ straighten/ age
#4	75,350	75,923 a	77,027	--	76,518 a	76,050 a
	105,541	105,222 a	106,496	--	107,685 a	106,751 a
	12.9	12.6 a	9.9	--	12.3 a	11.3 a
#6	67,940 b	63,562 b	--	62,052 b	74,734 a,b	73,941 a,b
	99,904	99,147	--	97,343	100,369 a	100,008 a
	14.3	11.5	--	6.1	10.9 a	7.4 a

a: Fracture outside of bent metal; properties do not represent bent metal.
b: Yield determined by ASTM method at 0.04" elongation; no plateau.

Condition 1 (Bending/Straightening)

Bars bent in accordance with the PTS had a yield strength, ultimate strength, and elongation about the same as those of the control specimens. This similarity resulted because the fracture in those bars occurred in the unbent metal (undisturbed metal). Thus, those properties did not represent the bent/straightened metal. However, this phenomenon indicated that the strength of the bent/straightened metal was higher than that of the undisturbed metal. Nevertheless, the elongation of the bent/straightened metal can be less than that of the undisturbed metal, as discussed in the Phase One study.(1) "Condition 1 bars" had surface cracks around the deformations at the inner bend radius surface after they had been tested for tension. The cracks indicated that those bars developed some microcracks upon straightening that were not detected immediately after straightening. Those cracks later opened up when the bars were tensioned.

Condition 2 (Two Cycles of Bending/Straightening)

Bars twice bent and straightened in accordance with the PTS, developed some microcracking on the inner bend radius surface upon the first cycle of straightening. Those microcracks were intensified by the second cycle of straightening. The fracture of "Condition 2 bars" occurred within the bent/straightened metal at the location of a surface microcrack. Regardless of the cracking, the average yield strength of those bars and their average ultimate strength were not less than the corresponding control values. However, their average elongation was 23 percent lower than the control elongation. Nevertheless, the bars' average elongation of 0.099 in./in. still satisfied the ASTM minimum elongation requirement of 0.090 in./in. Clearly, two cycles of bending/straightening reduced the ductility. Logically, the elongation of a "Condition 1 specimen" would have to be higher than that of a "Condition 2 specimen," since the former had been bent/straightened for only one cycle. Therefore, for No. 4 bars that are bent and straightened for only one cycle, a 12 percent reduction in the elongation should be considered a conservative figure.

Condition 4 (Bending/Aging/Straightening)

Bars that were bent and straightened according to the PTS, and were strain aged after bending and before straightening, developed microcracking in the inner bend radius surface upon straightening. Even with that microcracking, the fracture of those bars during the tests occurred in the unbent metal, indicating that thebending/aging/straightening hardened the steel. As a result of the fracture in the undisturbed metal, the yield and ultimate strengths obtained for "Condition 4 bars" were about the same as those of the control values. The average yield strength was 2 percent higher, and the average ultimate strength was also 2 percent higher than the corresponding control values. Those percentages were within the range of variability normal in tension tests. These results indicated that the bars gained strength as a result of bending/aging/straightening, but the results did not provide definitive information regarding the elongation of bent/aged/straightened steel.

Condition 5 (Bending/Aging/Straightening/Aging)

Bars that were bent and straightened according to the PTS, and were strain aged both after bending and after straightening, generally performed the same as "Condition 4 bars". They developed microcracking in the inner bend radius surface upon straightening, but they fractured in the unbent metal when they were tested.

As a result of fracture in the undisturbed metal, the test results were similar to those of the control specimens. Both the average yield strength and the average ultimate strength were only about 1 percent higher than the corresponding control values. Similar to "Condition 4 specimens," these results showed that the bars gained strength as a result of bending/aging/straightening/aging, but the results did not provide definitive information regarding the elongation of "Condition 5 bars".

TEST RESULTS, COLD-BENT NO 6 BARS

Test results for No. 6 bars are summarized in Table 4.

Control Specimens

The control specimens conformed to the ASTM requirements. Their average yield strength at 67,940 psi was 13 percent higher than the minimum required yield strength of 60,000 psi. Their ultimate strength at 99,900 psi was 11 percent higher than the minimum required ultimate strength of 90,000 psi. Their elongation at 0.143 in./in. was 58 percent higher than the minimum required elongation of 0.090 in./in.

Condition 1 (Bending/Straightening)

Generally, bars bent in accordance with the PTS developed, upon straightening, relatively extensive microcracking around the deformations of the inner bend radius surface. Generally, the fracture of "Condition 1 bars" during the tests occurred within the bent/straightened metal at the location of a surface microcrack. The average yield strength of those bars was 6 percent lower than the control yield strength. Their average ultimate strength was 1 percent lower than the control ultimate strength. Nevertheless, the yield and ultimate strength of "Condition 1 bars" satisfied the ASTM strength requirements. Apparently, unlike the No. 4 bars, in the No. 6 bent/straightened bars microcracking was severe enough to cause fracture of the steel during the tension tests, regardless of the hardening that occurred as a result of the bending/straightening action. Charpy Transition Temperatures generally increase with bar size, (1) and, consequently, bar susceptibility to cracking while bending/straightening also increases with bar size. The average elongation of "Condition 1 bars" was 20 percent less than the control elongation. However, "Condition 1 bars'" average elongation of 0.115 in./in. still satisfied the ASTM elongation requirement of 0.090 in./in.

Condition 3 (Bending/Straightening with Sharp Former)

Upon straightening, bars bent and straightened around a sharp former (i.e., with a bend diameter 4 times bar diameter, as compared to 8 times the bar diameter as required in the PTS for No. 6 bars) developed relatively wide cracking on the inner bend radius surface. The fracture of those bars during the subsequent tension tests occurred within the bent/straightened metal at the location of a surface crack. The average yield strength of "Condition 3 bars" was 9 percent lower than the control yield strength. Their average ultimate strength was 3 percent lower than the control ultimate strength. Nevertheless, the strength of "Condition 3 bars" satisfied the ASTM requirements for yield and ultimate strength. The average elongation of those bars was 57 percent less than the control elongation. The average elongation of 0.061 in./in. obtained for those bars failed to satisfy the ASTM elongation requirement of 0.090 in.in. The loss in strength and ductility of bent/straightened steel in this case was the result of the severe cracking in the steel.

Condition 4 (Bending/Aging/Straightening)

Upon straightening, bars that were bent and straightened according to the PTS, and were strain aged after bending and before straightening, generally developed relatively extensive microcracking on the inner bend radius surface around the bar deformations. However, unlike "Condition 1 specimens," the fracture of "Condition 4 specimens" during the subsequent tension tests occurred outside of the bend region. These results indicated that the strain aging hardened the steel to the extent that even the presence of the microcracking could not cause tension fracture in the bent/straightened metal. Although the fracture occurred in the undisturbed steel, the yield strength obtained was not the same as the control yield strength. The average yield strength was 10 percent higher than the control yield strength, but the average ultimate strength was about the same as the control ultimate strength. The explanation for the higher yield strength is that the fracture in this case occurred either very close to a gage mark (0.5 in. or less from gage mark) or outside of the gage length because a large portion of the 8-inch gage length was bent/straightened metal. On the other hand, the yield strength had to be measured by the ASTM A615 method, which is based on the deformation of the gage length, because there was no plateau. That location of the tension fracture reduced the effects of the yielding of the bar on the deformation of the gage length. Thus, the recorded deformation of 0.04 in. of the gage length (indication of yielding) corresponded to the post-yield condition.

In one specimen that fractured during the test within the bent/straightened metal (not included in Table 4), the ultimate strength was 1 percent higher than the average ultimate strength obtained for the bent/straightened specimens. Logically, in this case microcracking in the disturbed steel was severe enough to cause its fracture. An attempt was made to fracture a bent/aged/straightened specimen within the bent metal (not included in Table 4). Before the tension test had been conducted, the testing machine's grips were moved into the bent region and placed 2 inches apart. That specimen fractured in the bent region, and its ultimate strength was 3 percent higher than the average ultimate strength obtained for the bent/straightened specimens (i.e., Condition 1). These data indicated that strain aging of "Condition 4 bars" did cause an increase in strength, but that increase was not significant. However, aging of bent steel can reduce its elongation. (1) The effects of strain aging on ductility will be discussed later.

Condition 5 (Bending/Aging/Straightening/Aging)

Upon straightening, bars that were bent and straightened according to the PTS, and were strain aged both after bending and after straightening, developed relatively extensive microcracking on the inner bend radius surface around the bar deformations. However, even with that cracking, all of those bars fractured outside of the bent/straightened metal during the subsequent tension tests, indicating that the two cycles of strain aging hardened the steel. Similar to "Condition 4 bars," although the average ultimate strength of "Condition 5 bars" was the same as the average control ultimate strength, those bars' average yield strength was 9 percent higher than the average control yield strength. As discussed previously in conjunction with "Condition 4 bars," the reason for the higher yield strength was that the location of the fracture was either too close to a gage mark or was outside of the gage length, while the yield strength had to be measured by the ASTM A615 deformation method.

An attempt was made to fracture a bent/aged/straightened/aged bar within the bent/straightened region (not included in Table 4). To do this, the grips were moved into the bent region and placed 3 inches apart prior to the tension test. However, unlike the "Condition 4 bar" tested under the same condition, that specimen fractured in the grip area and outside of the bend region. These results further indicated that strain aging contributed to the hardening of the bars. The effects of strain aging on the ductility are discussed in the next section.

EFFECTS OF STRAIN AGING ON THE DUCTILITY OF COLD BENT/ STRAIGHTENED STEEL

The results of laboratory tests by Erasmus can be used to quantify the effects of strain aging on the ductility of cold bent/straightened reinforcing steel. (3) In those tests, 1-1/8 inch diameter hot-rolled Grade 275 New Zealand bars (≈40 ksi yield) were bent and straightened 90 degrees around a former of 8 inch diameter (a bend diameter/bar diameter ratio of 7, or strain of 0.125 in./in.). The bent/straightened regions of those bars were tested in tension, and they showed a loss in elongation of about 45 percent (Figure 1). However, when the bent/straightened regions were heated to 212° F for 3 hours (equivalent to 6 months of aging at an ambient temperature of 70° F), both after bending and after straightening, the loss in the elongation of the steel was about 85 percent (Figure 1).

In this study's tests, Grade 60 No. 6 bars lost 20 percent of their elongation after they were bent and straightened 90 degrees around a former of 6-inch diameter (a bend diameter/bar diameter ratio of 8, or strain of 0.111 in./in.). In other words, the loss in the elongation of No. 6 bars in the current tests was less than that of bars of 1 1/8 inch diameter in the Erasmus' tests by a factor of 2.25. The lower loss of elongation in the current tests can be attributed to the lower Charpy Transition Temperature associated with smaller size bars (lower possibility for microcracking upon straightening) and also the lower strain in the steel caused by the bending action. If the same factor (i.e., 2.25) was applied to the No. 6 bars of these tests that were strain aged both after bending and after straightening, their loss of elongation would be 38 percent.

Specimen	Tensile strength (psi)	Remarks
A	64,525	Hot rolled
B	67,135	Bent 90°, straightened, tested
C	70,760	Bent 90°, straightened, aged 212 °F for 3 hr., tested
D	71,340	Bent 90°, aged 212 °F for 3 hr., straightened, aged 212 °F for 3 hr., tested

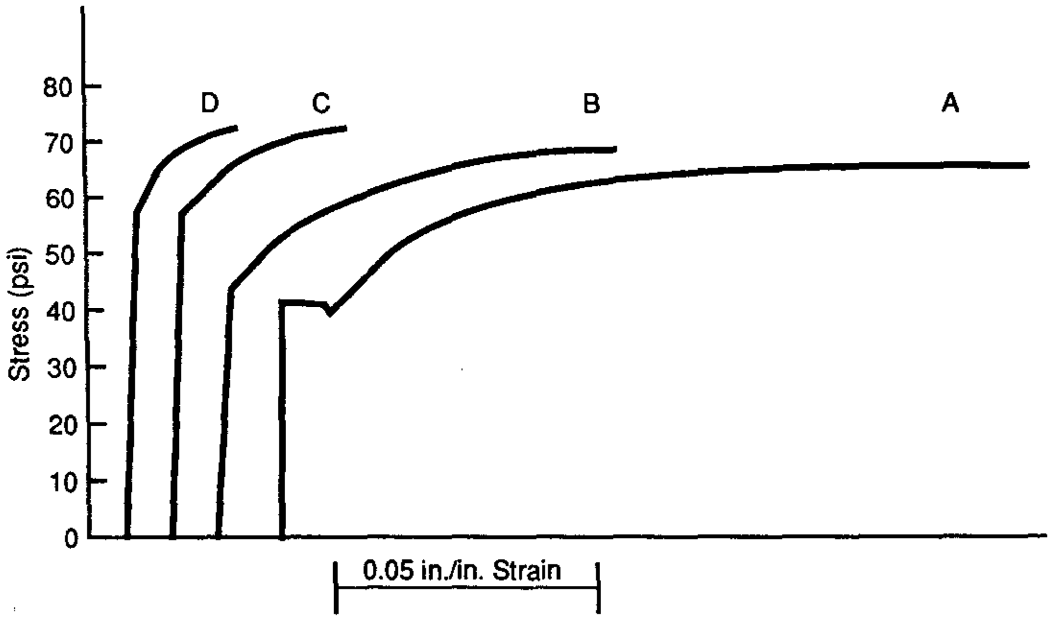

Figure 1. Tensile Test Stress-Strain Curves for 1-1/8 Inch Diameter Plain Bar Grade 275 New Zealand Steel (Adapted from Reference 3)

(85 percent loss in elongation for bent/aged/straightened/aged bars of 1 1/8 inch diameter / 2.25 = 38 percent loss in elongation)

Also, in these tests, the Grade 60 No. 4 bars lost 23 percent of their elongation after they had been twice bent and straightened around a former of 3-inch diameter (a bend diameter/bar diameter ratio of 6, or strain of 0.143 in./in.). Thus, as discussed earlier, for one cycle of bending and straightening the loss in elongation of No. 4 bars in these tests was conservatively 12 percent. Thus, the loss in elongation of the No. 4 bars in these tests was less than that of the 1 1/8 inch diameter bars in the Erasmus' tests by a factor of 3.75. Here again, if that factor was applied to the No. 4 bars in the current tests, which were strain aged both after bending and after straightening, their loss of elongation would be 23 percent.

(85 percent loss in elongation for bent/aged/straightened/aged bars of 1 1/8 inch diameter / 3.75 = 23 percent loss in elongation)

These tests did not include No. 5 bars. However, for No. 5 bars that are bent/aged/straightened/aged (with a bend diameter of 8 times the bar diameter), the loss in the elongation may conservatively be obtained by averaging the loss in the elongation of bent/aged/straightened/aged No. 6 bars (with a bend diameter of 8 times the bar diameter) and the loss in the elongation of bent/aged/straightened/aged No. 4 bars (with a bend diameter of 6 times bar diameter). Following this procedure, the loss in the elongation of the bent/aged/straightened/aged No. 5 bars would be 31 percent.

([(38 percent loss in elongation) + (23 percent loss in elongation)] : 2 = 31 percent loss in elongation)

TEST RESULTS, HOT-BENT NO. 7 BARS

The results for the No. 7 bars are summarized in Table 5.

Control Specimens

The control specimens' yield strength of 59,343 psi was 1 percent lower than the ASTM requirement of 60,000. psi. The ultimate strength of 98,444 was 9 percent

Table 5. Test Results for Hot-bent Reinforcing Bars

Average Test Results	Yield Strength, psi
	Ultimate Strength, psi
	8-inch gage length elongation, in./in. x 100

Bar condition / Bar size		Condition No.						
		1	2	3	4	5	6	7
		One Tip					Two Tips	
		1,200°F	1,425°F			Extreme heating	1,200°F	1,425°F
	Control	Bend/ straighten	Bend/ straighten	Bend/ straighten; two cycles	Bend/ straighten; sharp former	Bend/ straighten	Bend/ straighten	Bend/ straighten
#7	59,343	55,849 [b]	58,317 [a]	57,402 [b]	--	--	--	--
	98,444	91,844	94,589 [a]	92,759	--	--	--	--
	18.1	13.5	15.4 [a]	15.4	--	--	--	--
#9	67,101		61,398 [b]	--	66,430 [b]	67,437 [b,c]	61,901 [b]	62,907 [b]
	105,517	Not Practical	97,297	--	98,136	102,078 [c]	94,026	99,771
	15.2		14.1	--	13.7	8.1 [c]	12.6	13.7

a: Fracture outside of bent metal; properties do not represent bent metal.
b: Yield determined by ASTM method at 0.04" elongation; no plateau.
c: Fracture outside of bent metal and outside of gage length; strength does not represent bent metal and elongation does not represent gage length.

higher than the ASTM requirement of 90,000 psi. The elongation at 0.181 in./in. was 126 percent higher than the ASTM requirement of 0.080 in./in.

Condition 1 (Heating with One Tip to 1,200° F and Bending/Straightening)

Bars hot-bent and hot-straightened in accordance with the PTS, but with only one heat tip, fractured within the bent metal while tested for tension. The average yield strength of those bars was 6 percent lower, the ultimate strength was 7 percent lower, and the elongation was 25 percent lower than the corresponding control values. However, except for the yield strength, the reduced properties still satisfied the ASTM requirements. Apparently, hot-bending at 1,200°F decreased the strength and elongation of the steel even in the absence of surface cracking.

Condition 2 (Heating with One Tip to 1,425° F and Bending/Straightening)

Bars hot-bent and hot-straightened in accordance with the PTS, but with only one heat tip and heated to 1425° F, fractured within the unbent metal in the tension tests, indicating that the strength of heated/bent No. 7 bars can be higher than heated/unbent No. 7 bars when the bars are heated to 1,425° F. For those bars, the average yield strength was 2 percent lower, the ultimate strength was 4 percent lower, and the elongation was 15 percent lower than the corresponding control values. However, those average properties still satified the ASTM requirements, except for the yield strength. They represented the heated/unbent steel and showed that heating unbent steel to 1,425° F reduced the strength and ductility, although not significantly. Also, those properties indicated that the average yield and ultimate strength of the heated/bent metal was at the most 2 percent and 4 percent lower than the control yield strength and control ultimate strength, respectively. Thus, heating bent No. 7 bars to 1,425° F did not decrease the strength as much as heating those bars to 1,200° F. The method by which bar temperatures were recorded indicated only the surface temperature of the bar. It is possible that when the bar surface was recorded as 1,200° F, the temperature of the core was less. If the temperature of the core was in the blue brittle range (i.e., 400° to 700° F), then microcracking in the core could have occured while the bar was bent/straightened. That cracking would in turn have decreased the strength and ductility.

Since failure occurred outside the bent metal, the results of Condition 2 tests did not give definitive data regarding the effects on elongation of heating/bending steel at 1,425° F. However, one of the "Condition 2 specimens" (not included in Table 5) fractured within the bent metal. That specimen showed intense cracking in the "neck down" region after being tested in tension. Even with that unusual behavior, the yield strength was 1 percent higher than the control yield strength, and the ultimate strength was only 4 percent lower than the control ultimate strength. The elongation of that specimen was 29 percent lower than the control elongation (i.e., 0.129 in./in.). Those properties satisfied the ASTM requirements, and they were better than, or about the same as, the average properties of "Condition 1 specimens".

Condition 3 (Heating with One Tip to 1,425° F and Two Cycles of Bending/Straightening)

Bars twice hot-bent and hot-straightened following Condition 2, generally fractured within the bent metal in subsequent tension tests (one of the bars fractured in the unbent metal with an ultimate strength of 92,343 psi; it is not included in Table 5). The average yield strength of those bars was 3 percent lower, the ultimate strength was 6 percent lower, and the elongation was 15 percent lower than the corresponding control values. Those properties, which represented heated/bent metal, still satisfied the ASTM requirements, except for the yield strength. Even with the two cycles of bending/straightening, those properties were superior to the properties of "Condition 1 bars" which were bent/straightened only one cycle but heated to 1,200° F. These results further indicated that heating No. 7 bars to 1,425° F was more effective than heating them to 1,200 F.

TEST RESULTS, HOT-BENT NO. 9 BARS

The results for No. 9 bars are summarized in Table 5.

Control Specimens

The control specimens' yield strength at 67,101 psi was 12 percent higher than the ASTM required 60,000 psi yield strength. The ultimate strength at 105,517 psi was 17 percent higher than the ASTM required 90,000 psi ultimate strength. The elongation at 0.152 in./in. was 117 percent higher than the ASTM required 0.070 in./in. elongation.

Condition 1 (Heating with One Tip to 1,200° F and Bending/Straightening)

Manually bending and straightening these bars was not practical. Apparently, regardless of the surface temperature, the inside of the bar was not hot enough to facilitate the bending operation. This result reinforced the conclusion for No. 7 bars that surface temperature records were not a good indicator of the temperature of the bar.

Condition 2 (Heating with One Tip to 1,425° F and Bending/Straightening)

Bars hot-bent and hot-straightened according to the PTS, but with only one heat tip and heated to 1,425° F, fractured within the bent metal in the subsequent tension tests. For those bars, the average yield strength was 9 percent lower, the ultimate strength was 8 percent lower, and the elongation was 7 percent lower than the corresponding control values. Those average properties satisfied the ASTM requirements.

Condition 4 (Heating with One Tip to 1,425° F and Bending/Straightening with a Sharp Former)

Bars hot-bent and hot-straightened following Condition 2, but with a sharper former (i.e., with a bend diameter of approximately 6 times the bar diameter instead of 8 times) used in the bending operation generally fractured in the bent metal in the subsequent tension tests. Those bars had greater strength than the "Condition 2 bars". The average yield strength was 8 percent higher, and the ultimate strength was 1 percent higher than the average yield strength and ultimate strength of "Condition 2 bars". This finding was contrary to that for cold-bending of No. 6 bars, in which bending around a sharper radius reduced the strength. However, there was a 3 percent reduction in the elongation of "Condition 4 bars" in comparison to "Condition 2 bars". One of the "Condition 4 specimens" fractured outside of the bent metal (ultimate strength of 99,000 psi; not included in Table 5) further indicating that the strength increased with bending. The average yield strength of the "Condition 4 specimens" was 1 percent lower, the ultimate strength was 7 percent lower, and the elongation was 10 percent lower than the corresponding control values. Those properties of the "Condition 4 specimens" still satisfied the ASTM requirements.

Condition 5 (Extreme Heating with One Tip and Bending/Straightening)

Bars hot-bent and hot-straightened following Condition 2, except that they were heated to temperatures in the range of 1,800° to 2,000° F, all fractured outside of the bent metal and outside of the gage length in subsequent tension tests indicating, that the strength of heated/bent No. 9 bars can be higher than heated/unbent No. 9 bars if those bars are heated to 1,800°-2,000° F. Their behavior was similar to the behavior of No. 7 bars when those bars were heated to 1,425° F (Condition 2 for No. 7 bars). Apparently, the larger the bar size is, the higher is the surface temperature at which the strength hardening takes place. Since the fracture was outside of the gage length, the yield strength (obtained by the ASTM deformation method) and the elongation did not represent the properties of the heated/unbent metal. However, since about 90 percent of the 8-inch gage length was heated/bent metal, the elongation of the heated/bent metal should be more than the "elongation" measured for the gage length in Table 5 (i.e., deformation of the gage length with no necking down in it), which was 53 percent of the control elongation. The "elongation" measured for the gage length satisfied the ASTM requirement. On the other hand, the ultimate strength represented the heated/unbent metal, and it was 3 percent lower than the ultimate strength obtained for the control specimens. These results showed that the ultimate strength of the heated/bent metal of "Condition 5 bars" satisfied the ASTM requirement, but the results did not clearly indicate the yield strength and elongation.

Condition 6 (Heating with Two Tips to 1,200° F and Bending/Straightening)

Unlike "Condition 1 bars," manual bending/straightening "Condition 6 bars" was practical, although it was relatively difficult. Apparently, heating the bars with two tips produced sufficient temperature in the core to facilitate bending. "Condition 6 bars," which were hot-bent and hot-straightened following the PTS, all fractured in the bent metal in the subsequent tension tests. The yield strength of "Condition 6 bars" was 6 percent lower, the ultimate strength was 11 percent lower, and the elongation was 17 percent lower than the corresponding control values. Although those properties satisfied the ASTM requirements, they were generally not superior to the properties of "Condition 2 bars," which were heated to 1,425° F with one tip.

Condition 7 (Heating with Two tips to 1,425° F and Bending/Straightening)

"Condition 7 bars" hot-bent and hot-straightened following the PTS, except heated to 1,425° F instead of 1,200° F, generally fractured in the bent metal in the subsequent tension tests. The yield and ultimate strength of those bars were respectively 2 percent and 3 percent higher than the yield and ultimate strength of "Condition 2 bars" in which only one heat tip was used. Their elongation, on the other hand, was 3 percent less than the elongation of "Condition 2 bars". Compared with the control specimens, both the yield and ultimate strength of "Condition 7 bars" were 6 percent lower than the corresponding control values. Their elongation was 10 percent lower than the control elongation. However, those properties still satisfied the ASTM requirements.

One of "Condition 7 bars" fractured outside of the gage length in the unbent metal (ultimate strength of 101,000 psi; not included in Table 5) indicating that its strength hardened in the bent metal. That increase in strength was consistent with the behavior of the bars when subjected to higher levels of heat, either because of an increase in surface temperature or an increase in the number of heat tips.

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