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THE EFFECTS OF COLD WORKING ON THE MACROSCOPIC AND MICROSCOPIC PROPERTIES OF REINFORCING STEELS

Submitted as a partial fulfillment of requirements for the degree: Master of Science.

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PURPOSE:

The purpose of the studies conducted at the University of Manitoba in connection with cold bending (cold working) of reinforcing steel was to determine load carrying capacity and mode of failure when such bent bars are subjected to "shear loading" or "direct tensile loading".

INTRODUCTION:

It is difficult to imagine reinforced concrete or pre-stressed concrete structures that would contain straight reinforcing only.

The stirrups in the beams, the lateral ties in the columns, the hooks provided for anchorage, bent bars in webs of beams, and bent bars welded to masonry plates for anchorage of pre-cast concrete connections, are only a few examples of bent bar applications.

One would not hesitate for a moment to specify a hook at the end of a straight bar if embedment requirements set forth by one code or another cannot be met due to physical limitations.

Due to rapid development of the materials sciences there are quite a variety of reinforcing steels available.

The range of minimum yield strengths cover a fairly wide field from 30,000 p.s.i. to 75,000 p.s.i.

The two most popular grades of steel are probably the A.ST.M. A15 intermediate grade with 40,000p.s.i. minimum yield and the A.S.T.M. A432 hard grade steel with 60,000 p.s.i. minimum yield strength.

The later of the two steels mentioned is gaining wide

popularity due to its higher allowable stress in tension and especially in compression.
It is needless to say that the use of high strength reinforcing results in saving of reinforcing, increased space due to reduced column sections, and reduction of story height in multi-story buildings.
The various concrete, prestressed concrete and reinforcing steel institute codes provide the designer with fairly safe and moderately conservative guides and tools with which he can design safe and economical structures.
Thanks to the general acceptance of the various codes by the designers of concrete structures failures of violent nature are a rare occurrance.
Notwithstanding the relatively blemishless record of reinforcing in service the author is aware of a few situations where failure of reinforcing at the bend manifested itself in a very sudden and brittle type of failure.
The very fact that designers are using the higher strength reinforcing prompts the author to ask these questions:

(i) Are the bends in reinforcing steel capable of doing the job they were intended for in spite of the fact that a fair percentage of them actually fail during bending?

(ii) What are capacities of precast concrete column-to-beam connections with bent bars welded to plates that provide seating for beams?

(iii) Or, what are the actual capacities of hooks and bends once in the confines of concrete?

The intent of this paper is to answer the foregoing questions and hopefully, eliminate some of the hazardeous practices that may still exist in the design of precast concrete connections.

In addition, the paper will review some of the limitations set on "hooks" by the A.C.I. Code of 1963.

SCOPE OF STUDY:

The study encompassed two sets of mechanical testing:

(1) Bent bars welded to plates

(2) Direct tensile testing of "hooks"

and one set of micro-analysis of bends .

(1) Bent Bars Welded to Plates

This series of tests involved bending two grades of reinforcing, A.S.T.M. A15, and A.S.T.M. A432, into "U" shapes. The straight portion of the "U" was welded onto one edge of a plate as shown in figure 1. Then the free standing legs of the "U" were embedded in concrete having the welded portion of the bar flush with the top of the concrete. The testing apparatus shown on page 41 was used to pull the anchorages out of the concrete while ultimate load and mode of fracture were recorded.

Stress and strain analysis were done for a number of bars in an attempt to varify the actual behaviour of the bent-welded bars under, what one might call, "shear loading".

(2) 90 degree hooks embedded in concrete.

Again, two grades of reinforcing, A432 and A15, were used.

Reinforcing bars were bent 90 degrees about pin

diameters specified by A.C.I. 318 - 63 801(b).
The hooks were embedded in blocks of concrete.
To be able to determine the capacity of the hook only, the straight portion of the bars were wrapped in paper to prevent bonding to the concrete.
See details of specimen in figure 7, on page 47.
The bars were then subjected to "direct tensile loading" until failure occured.
Ultimate loads and modes of failure were recorded.

Micro - Analysis of Bends

This examination involved taking longitudinal sections out of bends of various sizes of reinforcing bars from both types of steels.
After all specimen were polished and etched various techniques were used to detect possible "microcracks" in the extreme tensile fibers.
Compression and tension zones were compared.
A number of photographs were also taken showing the effect of cold working on both the tensile and compressive zones. See micrographs 1 to 4.

DESCRIPTION OF TESTS AND DISCUSSION OF RESULTS

(1) Bent Bars Welded to Plates

To simulate actual conditions that occur in precast concrete connections bars of different grades of steel in different sizes were bent, as shown in figure 1, observing the minimum radii of bend allowed by the A.C.I. code. Low hydrogen electrodes were used in order to reduce hydrogen embrittlement of the weld due to entrapping hydrogen gasses within the weld metal. The welding was done at room temp. by qualified welders as specified by A.W.S. and the Canadian Welding Bureau.

In precast concrete connections bent reinforcing when welded to masonry plates is usually intended to carry only loading perpendicular to the plane of the bent-welded bars. It is easy to see, however, that say a beam seat on a precast column is subjected not only to vertical beam reaction but also to horizontal frictional loading which may be either tensile or compressive depending on whether contraction or expansion is taking place in the beam.

The horizontal load on beam seats could easily be as high as 50% of the vertical load depending on the roughness of the sliding surfaces.

In this series of tests the effect of the vertical reaction on the bent-welded bars was excluded and only the horizontal tensile load was simulated to occur.

The thickness of the plate was selected to be such that it was always at least $\frac{1}{4}$ of an inch to $\frac{1}{2}$ of an inch thicker than the diameter of the bars to facilitate deposition of weld metal.

The results of the test for the bent - welded condition are shown in Table 1, on page 42.

There did not appear to be any deformation prior to fracture other than a slight displacement of the welded portion of the bar accompanied by spalling of the concrete.

Shortly after spalling of concrete, very sudden failure occured invariably for every assembly.

Only a few double fractures and a few partial double fractures (where one leg failed completely and the other failed partially) have occured.

Approximately 20% of the fractures appeared clearly a distance away from the ends of the welds having the majority break at the ends of the welds.

For location of fracture planes see figures 4 & 5, on pages 44, and 45.

The appearance of the fracture surfaces clearly identified the mode of failure to be of the cleavage (I)* type, appearing granular, thus pointing to a brittle type of failure. See photographs 1 to 4.
The load carrying capacity of the bent-welded bars showed a marked reduction compared to the straight bar capacity, as can be seen in Table 1 & Table 2, on page 42.
Looking first at the ultimate capacity of bent-welded bars in the A.S.T.M. A432 steel one can notice a strength reduction of 70 - 80% as compared to straight bar capacities. The milder steel, in A.S.T.M. A15, showed that the bent-welded bar capacity reduction was only 47 - 69% of the straight bar capacity, see figure 3, on page 43.
The explanation for the brittle behavior and the large reduction in load carrying capacity lies in the following:

- (i) cold working of material
- (ii) residual stresses due to welding
- (iii) residual stresses due to inelastic bending
- (iv) triaxial state of stress when load is applied.

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*Roman numerals in perenthesis stand for reference identification. Please see list of references on page 39.

(i) Let us look at the first and most dominant reason for reduced capacity and brittleness.
Cold working or plastic working of steel can be examined at the "macroscopic" and "microscopic" levels.
Only the "macroscopic" aspect of plastic working shall be examined now, while the microscopic aspects will be discussed under the appropriate heading later in this paper.
Macroscopic plasticity begins with certain observations concerning plastic deformation of polycrystalline metals in simple mechanical tests, such as the tension test, and from the results of the direct tension test proceeds to develop some theory of gross plastic flow.
In the macroscopic viewpoint, the metal is thought of as a"continuum" (II) having properties such as density, stress and velocity at all points within its outer surface.
Stress and strain play a central role in continuum theory and describe in an average way the forces between the atoms in the crystal lattice and the deformation of the lattice respectively.
Stress and strain are described by "tensors".
One of the properties of tensors is that they have three principal values corresponding to three perpendicular planes through a point. These planes

of course, do not contain shear stresses.

The theory of macroscopic plasticity depends very largely on three macroscopic observations concerning stress and strain rate.

Firstly, that volume remains essentially constant during gross plastic deformation.

Secondly, that yielding occurs at any point only after the maximum shear stress in some direction on some plane attains a critical value.

Thirdly, that the direction of greatest shear strain rate coincide with the directions of greatest shear stress. It can also be noted that plastic flow of the metal under stress must be possible if work-hardening is to result, (III) (IV).

Under the extreme case, if a metal were to be subjected to equal triaxial tensile forces, there could be no flow and hence any such metal should behave as if it were completely brittle.

Also, a material which is severly work-hardened may behave like a brittle material, (III) (V).

It is believed by the author that reinforcing bars when bent to the minimum radii specified by, say the A.C.I. Code, undergo very severe work-hardening process.

To illustrate the point, let us take a one inch diameter bar, bend it about a six inch diameter pin, then the tensile and compressive strains at the extreme fibers would be in the order of 14.3% The strain at yielding for the mild steel is in the order of 0.16% and for the hard grade steel it is approximately 0.20% . This implies that only approximately 1.5% of the steel area has not gone under plastic deformation for the mild steel and only about 2.0% of the steel remains elastic for the hard grade steel.

(ii) It is a known fact that welding introduces residual stresses. Welding stresses are not caused soleley by the freezing and shrinkage of the weld metal as shown in figure 6, on page 46. As a matter of fact, stresses of the same nature and magnitude are introduced in the edge of the plate and the weld metal in a longitudinal direction of the bar. The reason for this is as follows: When the arc is moved along the edge of the plate, the metal in the heated region expands. Since only a small volume is hot at any time, the expansion of the heated material is restrained along the edge (I).

Thus expansion or plastic flow can occur only in the two unrestrained directions normal to the edge, and so upsetting occurs whenever temperatures are high enough to induce compressive yielding. The heating, being done progressively along the plate edge from one end to the other, and the material along this entire length becomes thicker.

After cooling, the upset edge is too short to conform to the adjacent portion of the plate, thus residual tensile stresses are induced along the edge of the plate.

To sum up residual stresses caused by welding one can say that there are longitudinal and transverse stress fields set up in the weld metal and in the fibers of the bent-welded bar adjacent to the weld.

(iii) When a bar is bent beyond the elastic limit, permanent set is produced, and the deformation does not vanish after the removal of the load.

The fibers which have suffered a permanent set prevent the elastically stressed fibers from recovering their initial length after unloading, and in this way residual stresses are produced (VI).

It is assumed that the material, which is stressed beyond the yield point, follows Hook's law during unloading resulting in bending stresses that follow the linear law as indicated in figure 6(a), on page 46.

When the rectangular loading and the triangular unloading stress diagrams are superimposed on one another the areas in between the two stress curves represent the residual stresses within the bar.

Since the deformations of the reinforcing bars due to cold bending is so great, that only 1.5 to 2.0% of the cross-sectional area remains elastic, and that a large percentage of the cross-sectional area of the bars have undergone strain hardening, rebound is greatly inhibited by dislocations within the crystal structure of the steel.

Residual stresses caused by inelastic bending in the opinion of the author is not as critical as it may appear from figure 6(a), which was prepared after S. Timoshenko's reasoning, which may have been based upon bars or beams bent passed the yield point but not as far that work hardening could have taken place.

However small these stresses may be their existance can easily be verified by observing the actual process of cold bending. It is a known fact that for instance if a 90 degree bend is required the operator of the bending machine bends the bars a few degrees beyond 90, knowing from his experience that the bars will rebound or "spring back" a certain amount as soon as the bending forces are removed.

(iv) Finally, when the bent-welded bars were subjected to a loading condition that simulated horizontal load on column-to-beam brackets, the bent-welded bars were already subjected to cold working, residual stresses due to welding and inelastic bending.

It was not surprising at all that only a relatively small amount of additional strain energy could be absorbed by the bent-welded bars.

The average applied shear stress at the end of the weld for the different bars and grades of steel varied between 25,000 p.si. and 37,000 p.si. at the ultimate load. It is also a know fact that a material like steel if loaded by shear alone to a stress level of approximately 57.7% of the yield point in tension then the material failes by diagonal tension. Most of the bent-welded bars failed at a shear stress much less than 57% of the yield strength (which yield strength varied from 56,000 p.si. average for the mild steel to 71,800 p.s.i. for the hard grade steel), indicating that strain hardening, residual stresses and other effects due to welding are a contributing factor in the marked reduction of strength.

The granular appearance as can be seen in photographs 1 to 4, may be explained by the fact that in the outside of the bend where tension governs during bending the grains are elongated and drawn tightly against one another. When a load is applied in a direction perpendicular to the elongated body of the grains there is just no possibility for deformation and the microcracks created by plastic flow quickly develop into a very unstable cleavage type of crack.

Thus the reason for the sudden failure is threefold: restraint (residual stresses), possible microcracks, and high applied shear stresses.

Microcracks will be discussed at the end of this paper.

(2) 90 degree Hooks Embedded in Concrete

According to A.C.I. 318 - 63 801(a) a "standard hook" may be defined as a "90 degree turn plus an extension of at least 12 bar diameters at the free end of the bar".

In this series of test two grades of reinforcing steel A432 and A15 were bent 90 degrees to minimum radii specified for #4, #5 and #6 bars. An extension of only four bar diameters were provided at the free ends of the bars as specified by the British Standards.

The straight portion of the bars were wrapped in paper to prevent bond developing between concrete and reinforcing. The hooks were embedded as shown in figure 7, on page 47.

The hooks were attemted to be pulled out when concrete strength of the blocks reached 3,500 p.s.i. minimum. Failure was anticipated at approximately 50% of the straight bar capacity and it was thought to occur somewhere in the bend.

A surprising thing happened. All the eighteen hooks tested, developed the full strengths of the bars and failure occured in a normal cup-and-cone fashion in the straight portion of the bars on the outside of the blocks.

Actually, two out of the eighteen blocks split during the test, but at a fairly high load of 44,250 lbs. and 37,500 lbs.

Both these blocks had an A.S.T.M. A432 hard grade #6 bar embedded in them and the tensile stresses in the straight portion of the hook were 100,000 p.s.i. and 85,000 p.si. respectively at the time when the blocks split.

Therefore, for all practical purposes one can assume that all the hooks developed the straight bar capacities in spite of the two blocks splitting.

To be absolutely sure that there was not any bond developed along the straight portion of the bars a few blocks were split open after the test to examine the wrapping, the concrete and the bar.

The wrapping was found to be loose, soggy and easily removable closing out any chance for any appriciable load transfer. (Please see photograph 11, page 53.)

According to the "Commentary" to the A.C.I. 318-63:

"No research to establish minimum bend radii related to stress in bar, or concrete strength to prevent crushing of concrete within the bend was available for the present bars".

in the light of the statement in the "Commentary" and the test results discussed earlier there appears to be some need for research to rationalize the relationship between

(i) radii of bends and capacity of hooks

(ii) radii of bends and behavior of concrete at the inside of the bend

(iii) capacity of hooks and extension length.

If the eighteen hooks tested by the author are only an indication of what might be expected of a comprehensive series of test, then the question may be asked: Why is it necessary to bend bars 180° when 90° would do?

Why is the 12 bar diameters extension required for a 90 degree bend when probably four bar diameters extension is sufficient?

There is an interesting observation that can be made in connection with the allocation of load carrying capacity to the various parts of the hook. If the results of the "bent-welded" bars test are examined closely, one can see that for the #4, #5 and #6 bars in question the ultimate shear load varied between 1/4 and 1/3 of the straight bar capacity. Having this in mind it is easy to see that the extensions of the hooks in the test could not have carried more than 1/4 to 1/3 since this would have resulted in a fracture.

Thus, the conclusion is that at least 2/3 to 3/4 of the load is developed in the 90 degree bend itself! Of course in order to be able to develop large loads in hooks one must provide sufficient concrete in volume as well as in strength and/or lateral reinforcing to prevent bursting or splitting of concrete.

In summary one may conclude that for the eighteen hooks tested, under the circumstances as described herein, all the hooks developed the full strengths of the bars. As it was pointed out earlier in the paper more research is needed to relate all the variables involved and it would be probably hasty to draw any definite conclusions about the possible results of such research project.

THEORY OF FRACTURE

From the point of view of the nature of the processes involved there are five different kinds of fractures which occur in metals: ductile, brittle, adiabatic shear, creep and fatigue fracture (VII).

The classification of fractures into ductile and brittle, is taking into account the various processes involved. In a scientific sense a fracture that would take place by the ductile mechanism could involve such little deformation that an engineer would classify such a behavior as brittle.

According to Dr. D. McLean, of the American National Physical Laboratory, the study of the fracture of metals is one of the weakest fields of metalurgy.

Within this paper, only ductile and brittle fracture will be discussed briefly and from an engineering point of view only.

A ductile fracture under tensile stress involves three basic sucsessive events.

First, the specimen necks, which involves the process of foundation of cavities that join together.

Second, a cavity eventually becomes large enough to

spread fairly rapidly in a transverse direction.
Finally, this crack, as it may now be called, extends to the outside fibers on an inclined plane at about 45 degrees to the axis of the tensile specimen.
This is what engineers call a "cup-and-cone" fracture as it can be seen on photograph 9 and 10.
In order for ductile fracture to occur plastic strain and tensile stresses are required.
The most predominant of the various processes that contribute to plastic deformation is slip.
Slip takes place only on definite crystallographic planes and directions, following the plane which is most densely packed with atoms.
Slip planes then combine and make up a slip system which is characteristic of each particular crystal.
For example, alpha iron has as many as 48 such slip systems.
When a force is applied to the surface of a crystal it is transmitted across each internal crystallographic plane by interatomic reactions.
Experiments have shown that slip in a particular system will occur if this force exceeds some critical

value on a unit area of the slip plane.
The critical value depends on the type of slip system. It was possible to predict critical shear stress values for perfect metal crystals based on inter-atomic forces. In this manner critical shear stress value was established at 10,000,000 p.s.i.
It is well known from experiments that the actual yield stress is some three orders of magnitude lower. The apparent discrepency could only be explained by the presence of many imperfections contained in metal crystals.
These imperfections are called "dislocations", which allow consecutive slip to occur at greatly reduced shear stresses. One of the characteristics of dis-locations is that they create internal forces between the atoms(II).
It is interesting to note that the theoretical stress required to move a single dislocation is very small, in fact it is much smaller than the yield stress of a typical metal crystal. However, other imperfactions in the typical crystal, i.e. vacancies, interstitial and substitutional foreign atoms, grain boundaries,

or other dislocations cause additional stress fields which oppose the motion of any dislocation. Thus, cavities form when thousands and thousands of dislocations combine. Cavities usually form at inclusions, because when the relatively deformable metal flows past a relatively underformable inclusion, large tensile forces are set up. These tensile forces succeed in tearing a gap at the interface of metal and inclusion.

The forgoing few paragraphs described some of the prerequisites of plastic flow which is related to ductile behaviour.

Brittle behaviour or brittle fracture would then imply that fracture occures without plastic flow. This extreme condition, which rarely if ever occurs in steel, is nevertheless, closely approached. But even with the most brittle specimens, small amounts of plastic flow have been detected by means of X-ray diffraction.

The dividing line between ductile and brittle behavior is an arbitrary one, depending upon the judgement of the observer.

In general, a Specimen having less than a few percent reduction in area is called brittle.

Describing fracture by crystallographic modes i.e. "cleavage" or "shear" has a more definite meaning while the terms brittle and ductile have not.

To illustrate the point one could talk about a mild steel bar with sharp deep notches. When tested, the bar would not elongate more than say a percent, yet the fracture might be by the shear mode. Conversely, many fractures occuring by cleavage are preceeded by large amounts of plastic flow, and these must, thus, be classified as ductile (I).

The terms used in this report to discribe fractures are those proposed by Low, and used by Gensamer & Parker.

BEHAVIOR DESCRIBED	TERMS USED
Crystallographic mode	Shear ---- Cleavage
Appearance of fracture	Fibrous -- Granular
Strain fracture	Ductile -- Brittle

Granular appearnce is associated with cleavage fractures, and fibrous appearance is typical of shear.
Fractures, however may be mixed, as in the case of a "cup-and-cone" fracture.
Important factors which influence the particular type of fracture to occur are:

(i) Strain history
(ii) Strain rate
(iii) Temperature
(iv) State of stress

Strain history is an important factor in formulating fracture. For example, the direction of strain during prior strain hardening may influence type of fracture depending on the relative strain.
The strain rate has the following effect: an increase in strain rate increases the yield and the ultimate

strength of the material but it initiates brittle fracture.

Similarly, the lowering of temperature also facilitates the occurence of brittle fracture.

The state of stress influences fracture to a considerable degree. For example: if a ductile material, at room temperature is subjected to triaxial state of tension, the material not being able to "flow", fractures in a brittle manner.

Or, for example, if the tensile testing of an ordinary mild steel bar is done submerged in a fluid under very high hydrostatic pressure, ductility increases to such an extent that the bar can actually be drawn to a point before fracture occurs.

Now, as far as the microscopic aspects of fractures are concerned, there are three basic types:

(1) grain boundary fracture
(2) cleavage fracture accross the grain
(3) shear fracture accross the grain

Grain boundary fractures in steel at room temperature is of little importance. Shear fractures are associated with ductile behavior, and brittle behavior is characterized by the cleavage mode of fracture. Cleavage fractures follow the faces of the cubes of the ferrite crystals, while shear fractures do not. The shear mode of fracture is associated with grey and silky appearance, whereas the cleavage mode of failure causes the surface to be bright and granular.

MICRO ANALYSIS OF BENT STEEL BARS

The reinforcing steel used in the study of bends was rolled by the Manitoba Rolling Mills.
The bending was done by a local supplier of reinforcing steel.
Two grades of steel were used in the study;

(1) A.S.T.M. A432
(2) A.S.T.M. A15,

rolled from new billet steel. The Carbon content averaged 0.45% for the A432 steel and 0.28% for the A15 steel.
The Manganese content was approximately 1.10% for the A432 steel and 0.65% for the A15 steel.
There could be a fair percentage of variation in the Carbon and the Manganese content from batch to batch and even within the same batch since reinforcing steels are not high quality steels.
The specimens were taken from as-bent and unfractured bars to reveal the extent of cold working and possible microcracks as a result of bending.
Longitudinal sections were taken out of the middle of

the bend as follows:

First, two cuts were made in a radial direction perpendicular to the plane of the bent bar approx. ¼ inch appart.

This provided circular slices about ¼ inch thick.

Specimens were taken out of #4, #5, #6, #7 and #8 bars of the A432 steel and out of #5 and #6 bars of the A15 steel.

Then, to obtain a relatively undisturbed longitudinal section the slices were placed flat on one of their sides and cut through at the largest diameter, with electric discharge.

The specimens were fully submerged in oil that was circulated to prevent temperature rise that might have caused "distortion" of the surfaces to be examined.

The electric discharge penetrated only a few microns which was easily eliminated by polishing.

The seven specimens were then mounted in one inch diameter thermosetting bakelite.

The polishing of the specimens were done according to A.S.T.M. E3-62.

Starting first on four different sand papers of consecutively finer abrasive surfaces. The specimens were cleaned ultrasonically after each grade of sand-paper, to prevent contamination of finer grades of paper with coarser particles.

After all specimens were finished on the sandpapers the polishing continued on polishing discs with diamond paste. There were three discs:

The first had 6 micron diamond paste on the polishing surface, the second and the third had 1 micron and $\frac{1}{4}$ micron, respectively.

To be absolutely sure that the fine scratches left on the polished surface of the specimens by the $\frac{1}{4}$ micron diamond paste, are not confused with micro-cracks the specimens were further polished by a vibratory polisher.

The specimens, mounted in a "rig", "floated" around in 0.05 micron diamond paste for an hour or so.

After the polishing achieved the acceptable standard of finish on the surfaces of specimens, they were examined first without etching, at 500 magnification for possible cracks.

The results were negative and the author proceeded

to etch the specimens lightly in 2% Nital.
At first the specimens were examined under "bright field illumination", again at 500 magnification. Cracks were not found. Then a considerable amount of time was spent traversing the surfaces of the specimens under "dark field illumination", where highly reflecting surfaces are not visible.
The smallest pits or the thinnest lines, such as scratches, cracks or grain boundaries stand out as bright spots or lines.
The results were again negative, that is "micro-cracks", the forerunner of fracture, were not found. The word "microcrack" refers to a crack, the length of which is less than or equal to a grain size.
Nothwithstanding the relatively fruitless search for microcracks, another study was conducted with a much refined technique.
The surface of one specimen was polished and etched very lightly, repeating the operation three or four times until just enough contrast was created to allow the examination of the pearlite nodules at 2,000 magnification.

For this magnification, which is just about the limit for optical microscopes, the surface of the specimen had to be coated with oil so that the lens when focussed on the specimen had its surface submerged in oil also.

According to (VIII), "microcracks form by shear in the pearlite colonies and these link up to form fibrous cracks which can develop into fast running cleavage cracks".

Then the author of reference (VIII) goes on saying: "In steels containing large-volume fractions of pearlite, deformation in the pearlite can initiate microcleavage crack formation at low temperatures and/or high strain rates".

So the object of the last phase of investigation was to find kinks in the pearlite colonies as shown in (VIII).

According to the foregoing reference, the crack should show up as a dark line at a kink within the pearlite colonies and extend through several colonies. Unfortunately, the reference does not give any clue as to the amount of strain, strain

rate or temperature at which the specimen developed such a shear crack through the pearlite colonies.
After traversing of the specimen's surface and having not been able to come across anything that definitely resembled shear cracking of pearlite, a conclusion was reached that perhaps the 14-16% strain in the outer fibers of the bent bars was not large enough to cause shear cracking of pearlite.
See micrograph 5.
It is most probable that when microcracks form the cracks combine, coalesce into a fast running, unstable cleavage crack.
According to (VIII), in connection with a tensile specimen, "necking" begins when fracture is initiated in the central part of the specimen.
When that happens, of course, fracture is quite imminent.
In the case of the bent bars the strain is probably not severe enough for most bars. For those bars which fracture during bending the stress-strain characteristics may be slightly different from the lot. The "stretching" of grains in the tensile

fibers and the compression of the grains in copressive fibers of the bend can easily be recognized in micrographs 3 and 4.

Micrographs 1 and 2 represent areas cold worked by tension and compression respectively in the A432 steel. Micrographs 3 and 4 represent similar conditions of cold work in the A15 steel.

The dark areas represent laminar formation of iron carbide and ferrite, called collectively as pearlite, on account of their pearl like appearance.

The light areas are basically pure iron called ferrite. The ability of the much softer ferrite to deform is quite apparent from the micrographs.

The apparent lack of microcracks is not a definite proof that such cracks do not form in the bends of cold bent reinforcing steels, it simply proves that microcracks are not a dominating by-product of cold bending.

CONCLUSIONS AND RECOMMENDATIONS:

(1) Bent - Welded Bars

(a) The capacities of "bent-welded" bars may be as low as one quarter to one fifth of their straight bar capacities.

(b) The great reduction in strength is due to residual stresses introduced by welding and triaxial state of stress due to the applied load.

(c) Fracture of "bent-welded" bars is of the brittle type, occurring very suddenly with negligible deformation prior to fracture and the appearance of the fracture surface is granular.

(d) "Bent-welded" bars should never be used in precast connections in such a manner that the "bent-welded" portion is directly subjected to loading.

(e) High strength bars, once bent and welded loose their advantage in strength over the mild steel bars.

(2) <u>90 degree Hooks</u>

(a) Regardless of the type of steel, reinforcing bars if bent to the minimum radii specified by the A.C.I. Code, can develope their straight bar capacity with only four bar diameter extension at the free end. Provided that there is sufficient volume of concrete or possibly lateral reinforcing to prevent splitting of concrete. (It should be mentioned in passing that the British Code requires only 4 bar diameter extension for 90° Hooks.)

(b) More research is needed in this field, to simplify the "90 degree hook" and perhaps to eliminate the "180 degree hook" altogether, much to the delight of fabricators.

(3) <u>Microanalysis</u>

(a) There appeared to be plastic flow taking place in the bend without the formation of microcracks.

(b) However the possibility that microcracks could still occur during bending of reinforcing bars is not closed out at all.

(c) It is quite possible that the strain in the outer fibers of the bent bars is not large enough to cause microcracks in most cases.

LIST OF REFERENCES

I. "Brittle Behaviour of Engineering Structures"
by Earl R. Parker

II. "The Making, Shaping and Treating of Steel"
8th eddition
by The United States Steel (USS)

III. "Metallic Materials in Engineering"
by C. H. Samans

IV. "Theory of Flow and Fracture of Solids"
by A. Nadai

V. "Cold Working of Metals"
by The American Society for Metals 1949

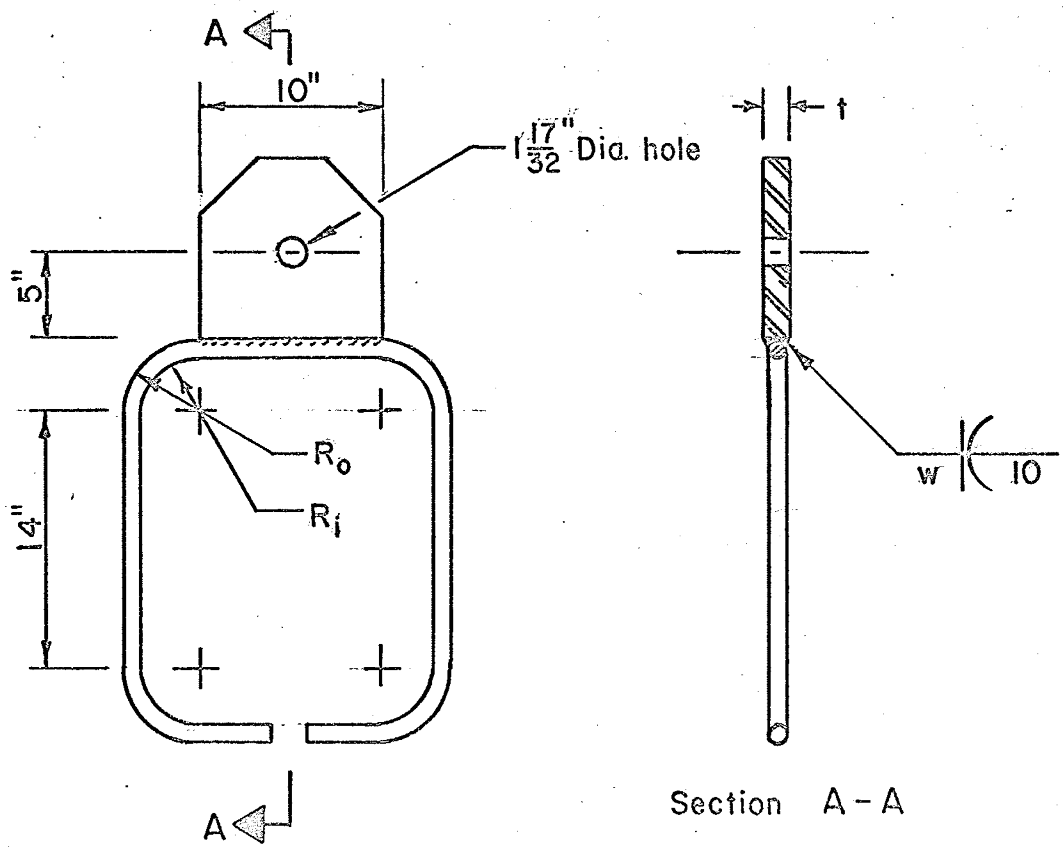
VI. "Strength of Materials" Part II
by S. Timoshenko

VII. "Mechanical Properties of Metals"
by D. McLean

VIII. "Fracture of Structural Materials"
by A. S. Tetelman and A. J. McEvily Jr.

Also referred to: "An Investigation into the effects of heat and cold working on the properties of reinforcing steel"

A graduation thesis by J. A. Mitchell 1967
University of Manitoba.



Dimension / Bar Size	"R_i" in inches	"R_o" in inches	"t" in inches	Weld Size "w" (in.)	Number of Specimens	
					ASTM·A·432 F_y = 60 ksi	ASTM-A15 F_y = 40 ksi
#3	0.9375	1.3125	0.75	1/4	3	3
#4	1.2500	1.7500	0.75	1/4	3	3
#5	1.5625	2.1875	1.00	3/8	3	3
#6	2.2500	3.0000	1.00	3/8	3	3
#7	2.6250	3.5000	1.50	1/2	3	3
#8	3.0000	4.0000	1.50	1/2	3	3

Note:

(1) Plate is of ASTM-A36 material

(2) Welding done at room temperature

(3) E60 electrodes used for welding

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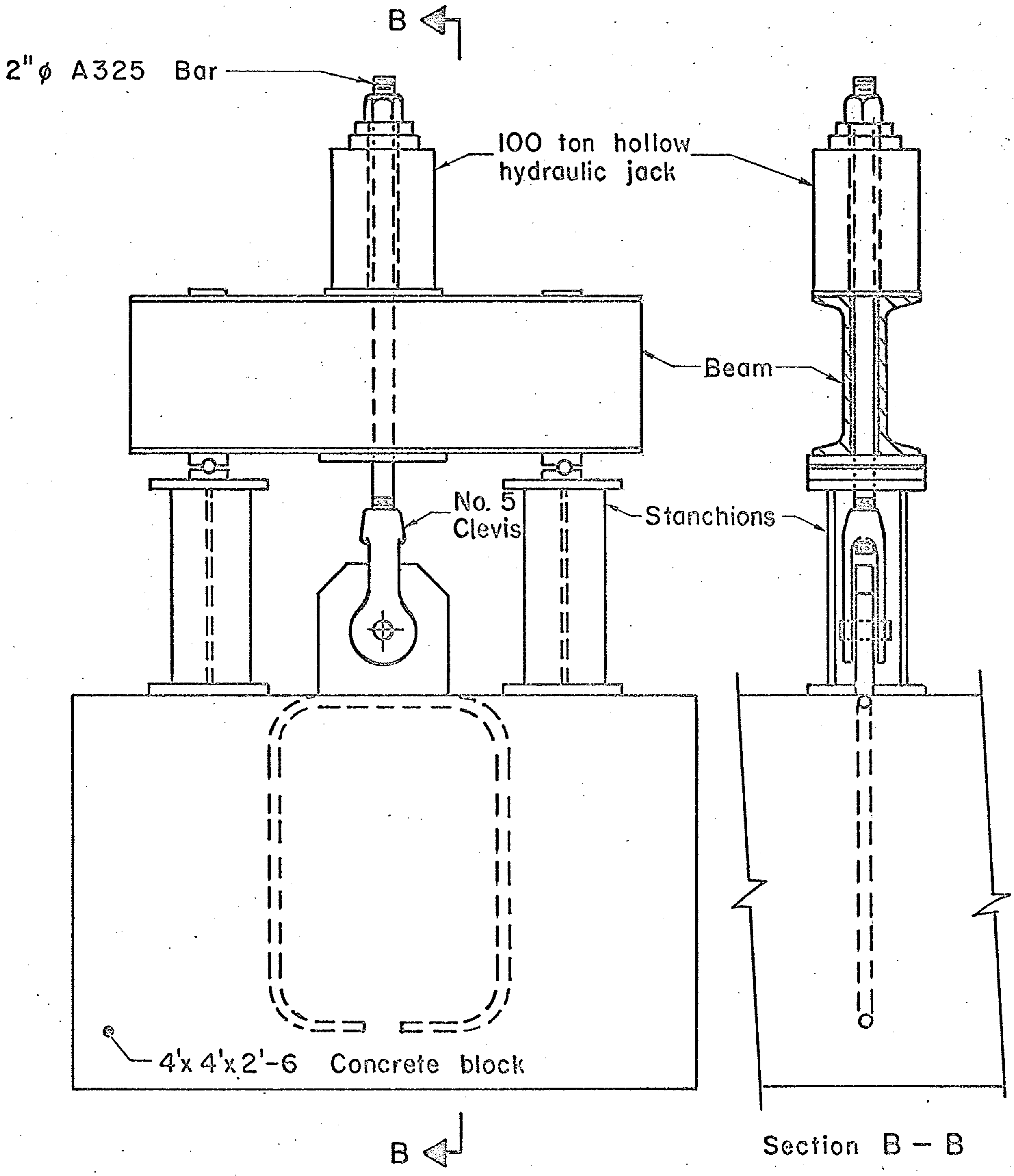
BENDING DIAGRAM AND ASSEMBLY DETAILS

Submitted by: T. Pataky | Date: Mar. 1969

FIGURE 1



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SCHEMATICS OF TESTING APPARATUS

Submitted by: T. Pataky | Date: Mar. 1969

FIGURE 2

Bar Size	Apparent yield load[a] (Average of three)		Ultimate load[b] (Average of three)	
	A432 (kips)	A15 (kips)	A432 (kips)	A15 (kips)
#3	—	—	2.5 (1.25)	5.0 (2.5)
#4	8.3 (4.15)[c]	—	9.1 (4.55)	10.0 (5.0)
#5	16.9 (8.45)	17.6 (8.8)	19.8 (9.9)	17.9 (8.95)
#6	29.3 (14.65)	23.8 (11.9)	30.2 (15.1)	26.1 (13.05)
#7	32.3 (16.15)	42.0 (21.0)	34.4 (17.2)	44.3 (22.15)
#8	—	48.2 (24.1)	48.2 (24.1)	52.2 (26.1)

a — displacement of the whole assembly rather than local yielding

b — fracture load

c — single bar values shown in brackets for comparison with table below

#3	7.20	5.40	10.70	8.65
#4	13.75	10.50	21.75	16.15
#5	24.80	16.90	36.90	23.70
#6	29.20	26.50	47.00	38.00
#7	39.60	37.80	59.90	41.90
#8	61.40	46.30	79.96	59.50

TABLE 1

Showing test results for bent bar assemblies

TABLE 2

Showing test results for straight bars in pure tension

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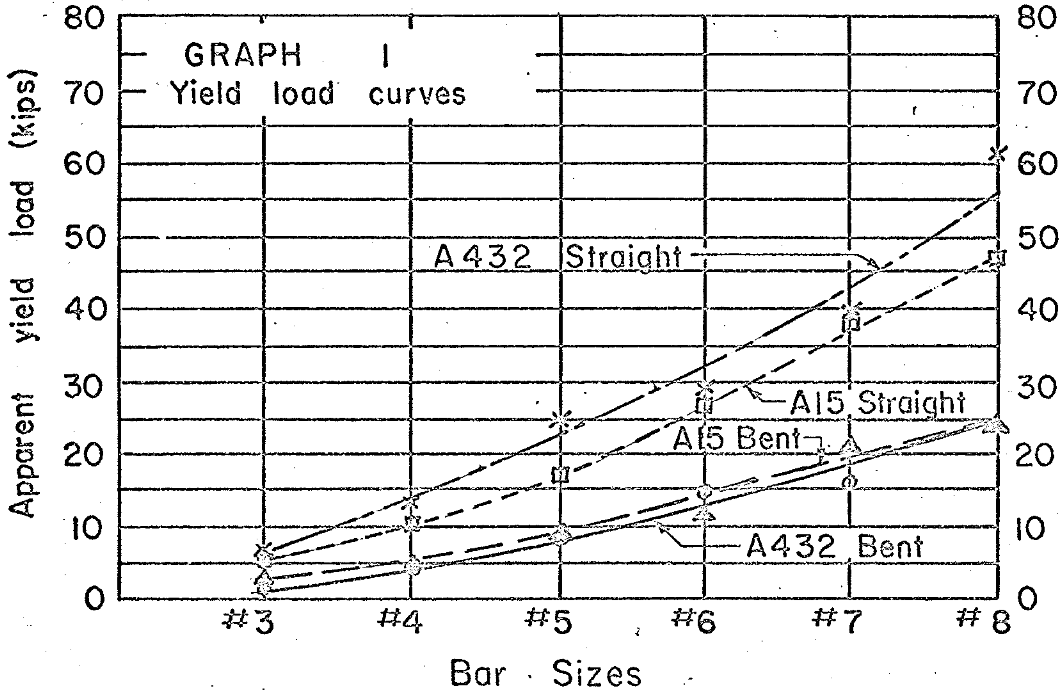
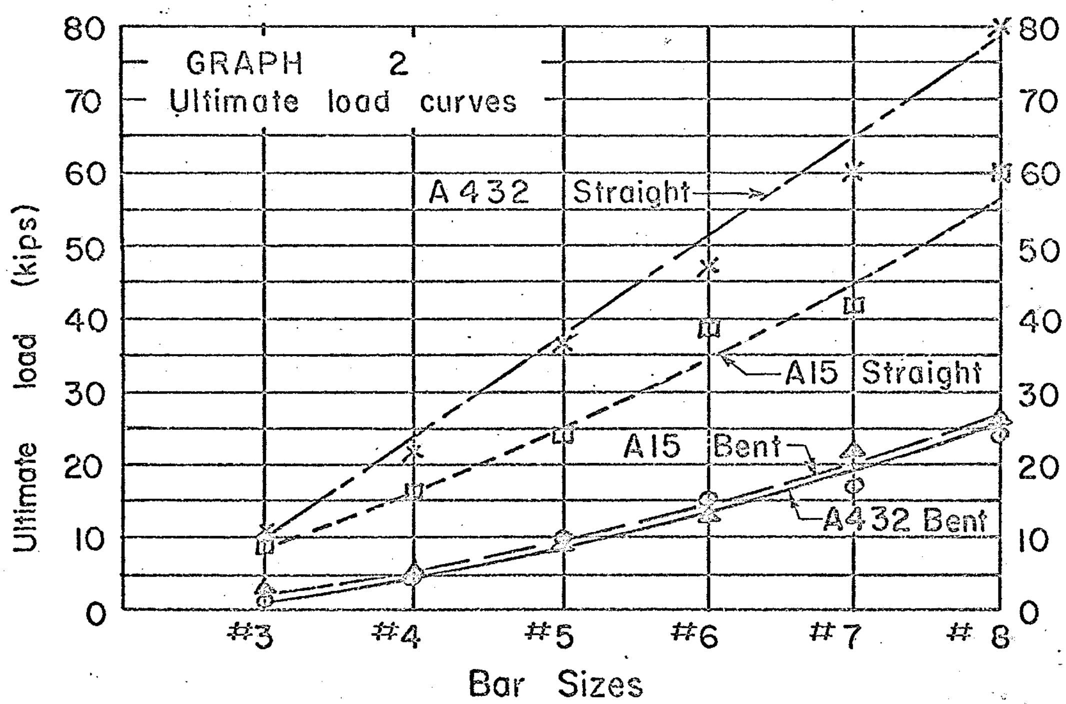
TEST RESULTS FOR BENT BAR ASSEMBLIES AND STRAIGHT BARS

Submitted: T. Pataky | Date: Mar. 1969

TABLES 1 & 2





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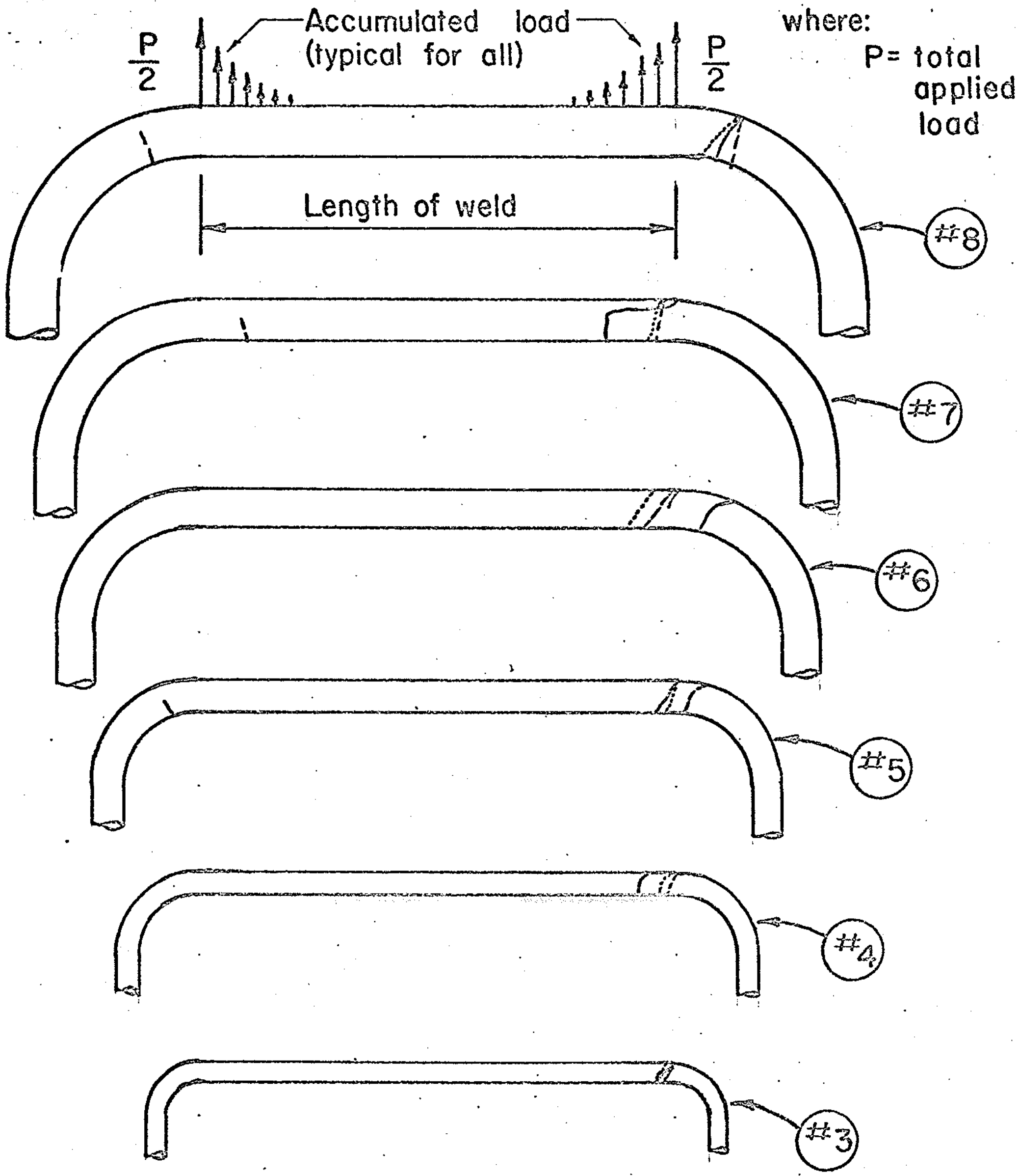
COMPARISON OF STRAIGHT AND BENT BAR CAPACITIES

Submitted by: T. Pataky | Date: Mar. 1969

FIGURE 3



Fracture plane designated thus:

——— Specimen 1
– – – Specimen 2
········ Specimen 3

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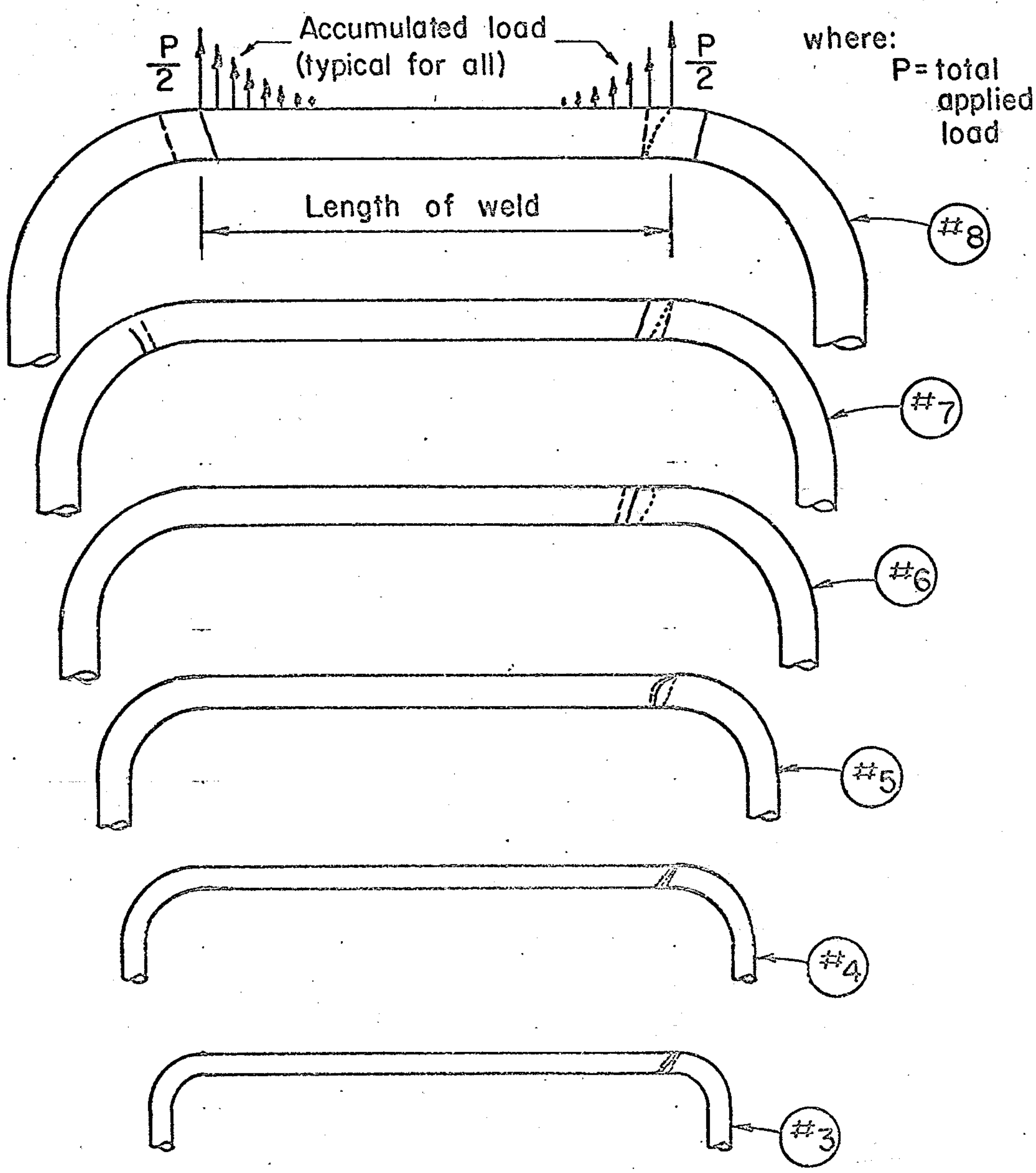
FRACTURE PLANES
FOR "A432" REINFORCING

Submitted by: T. Pataky	Date: Mar. 1969

FIGURE 4



Fracture planes designated thus:

———	Specimen 1
— — —	Specimen 2
··········	Specimen 3

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FRACTURE PLANES
FOR "A 15" REINFORCING

Submitted by: T. Pataky | Date: Mar. 1969

FIGURE 5

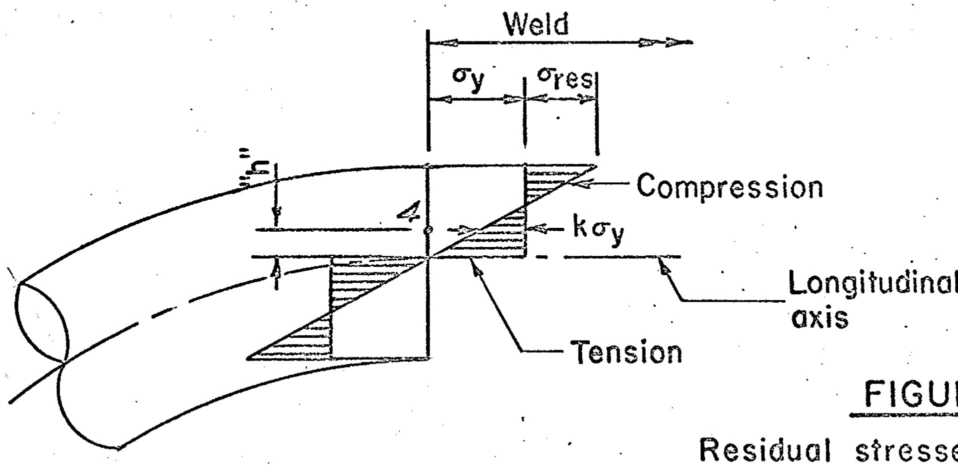

FIGURE 6(a)

Residual stresses produced by inelastic bending

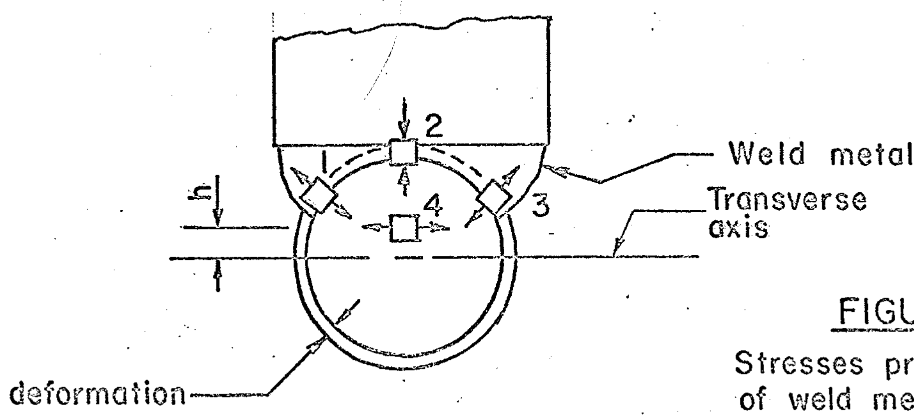

FIGURE 6(b)

Stresses produced by cooling of weld metal

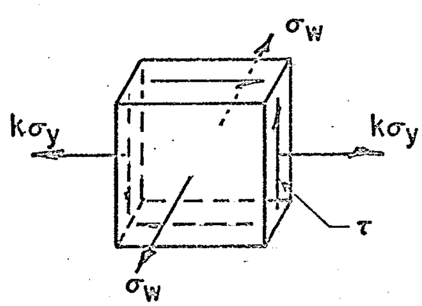

FIGURE 6(c)

Triaxial stresses on particle "4"

Note:

in figure 6(c) the flexural stresses are neglected since shear stress "τ" is beleived to be dominating

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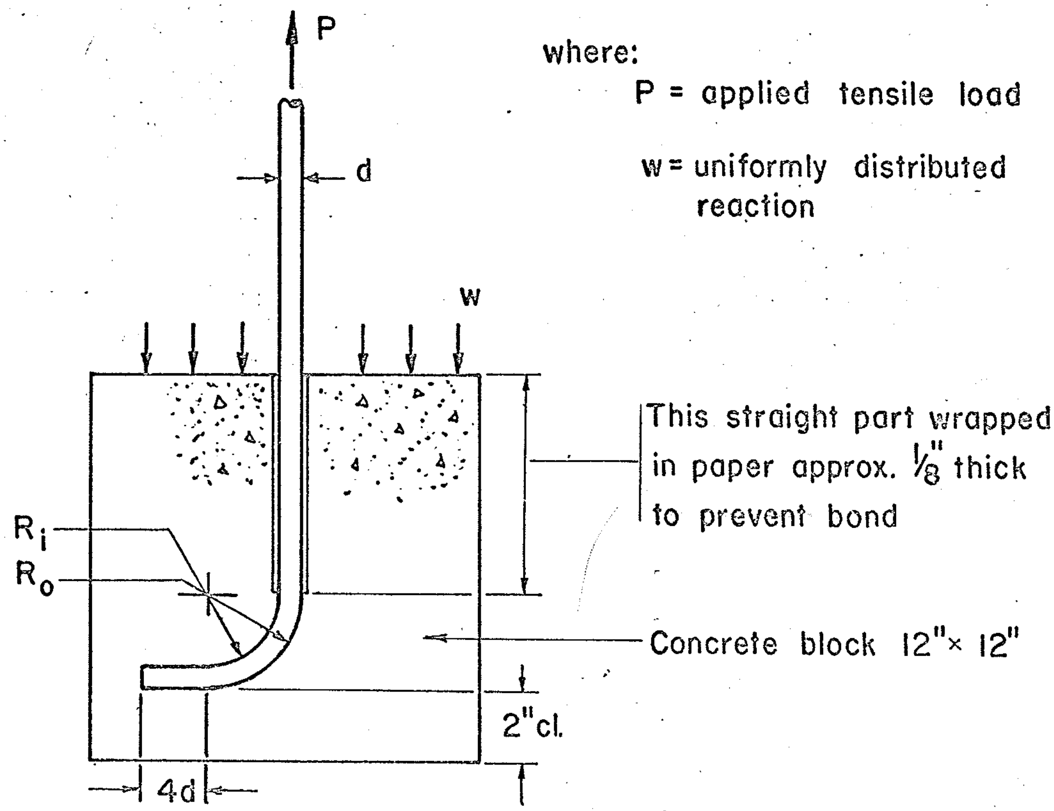
COMBINED STRESSES AT THE POINT OF TANGENCY OF THE BEND

Submitted by: T. Pataky	Date: Mar. 1969

FIGURE 6



d (inches)	R_i (inches)	R_o (inches)	Number of Specimens	
			ASTM · A432 F_y = 60 ksi	ASTM · A15 F_y = 40 ksi
0.500	1.2500	1.7500	3	3
0.625	1.5625	2.1875	3	3
0.750	2.2500	3.0000	3	3

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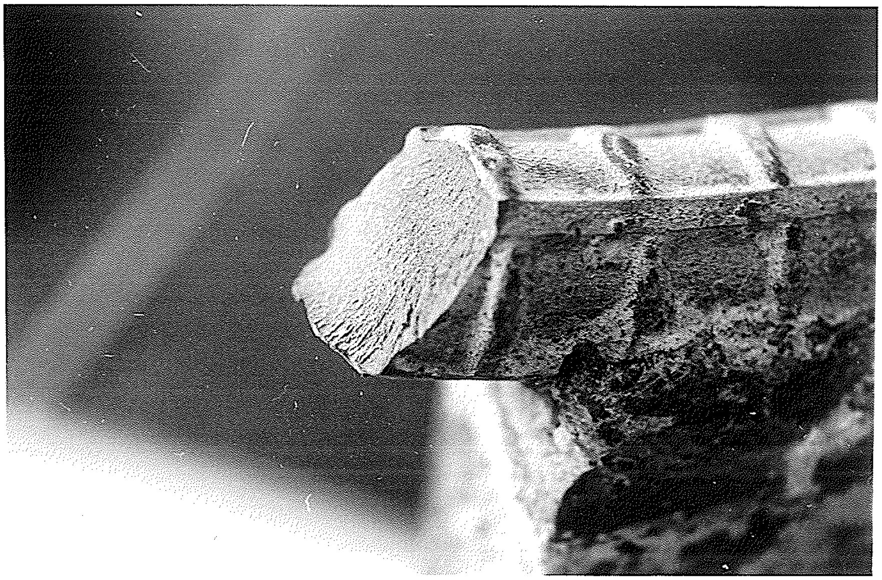
TENSILE TESTING OF 90° HOOKS

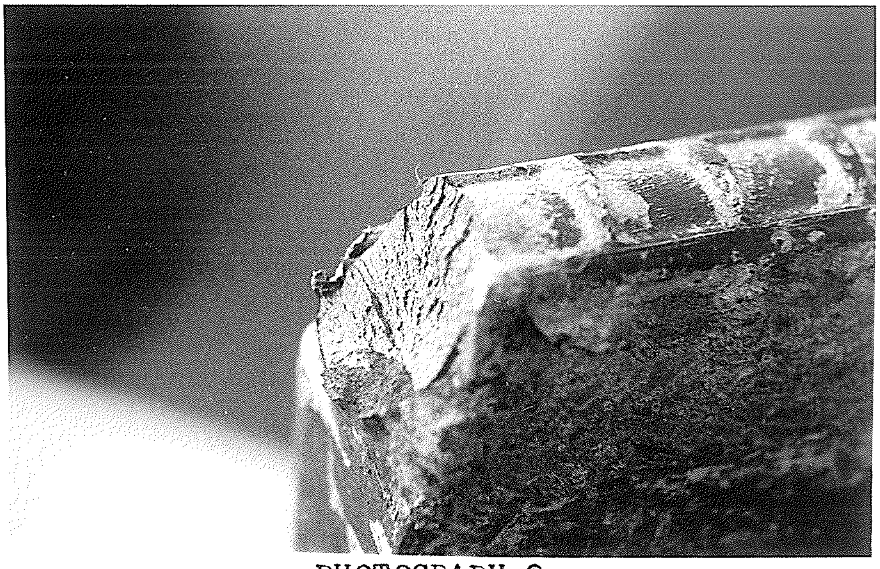
Submitted by: T. Pataky | Date: Mar. 1969

FIGURE 7



PHOTOGRAPH 1

Fracture surface of a one inch diameter, A432, "bent-welded" reinforcing bar. Note the granular appearance of the surface. Fracture occurred approximately one inch away from the end of the weld.



PHOTOGRAPH 2

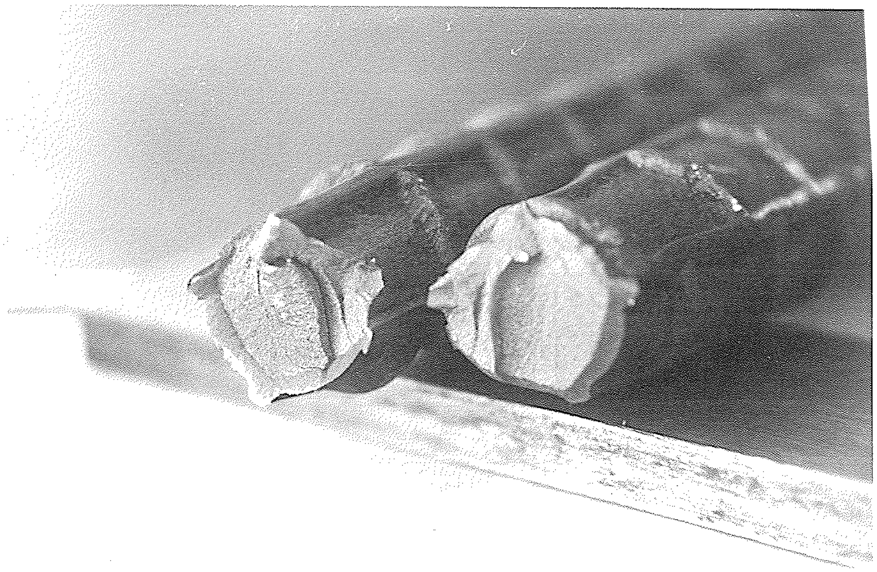
Fracture surface of a one inch diameter, A15, "bent-welded" reinforcing bar. The weld is definitely a contributing factor in this case.

PHOTOGRAPH 3

Fracture surface of a 0.875 inch diameter, A432, "bent-welded" reinforcing bar. Fracture initiated at a crack in the weld.

PHOTOGRAPH 4

Note granular appearance of the fracture surface of a 0.875 inch diameter, A15, "bent-welded" reinforcing bar. Fracture occurred in the heat affected zone.

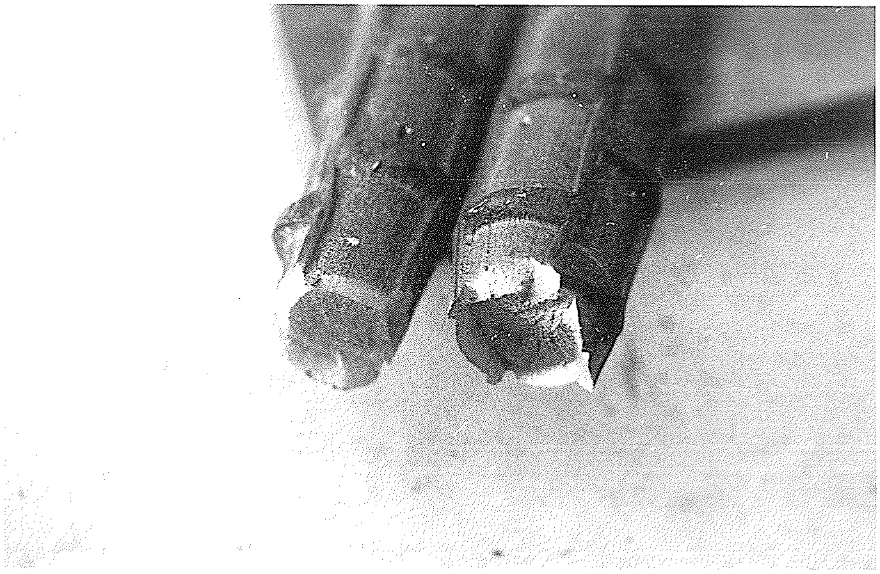


PHOTOGRAPH 5

One inch diameter, A432, straight reinforcing bars fractured by direct tensile load.

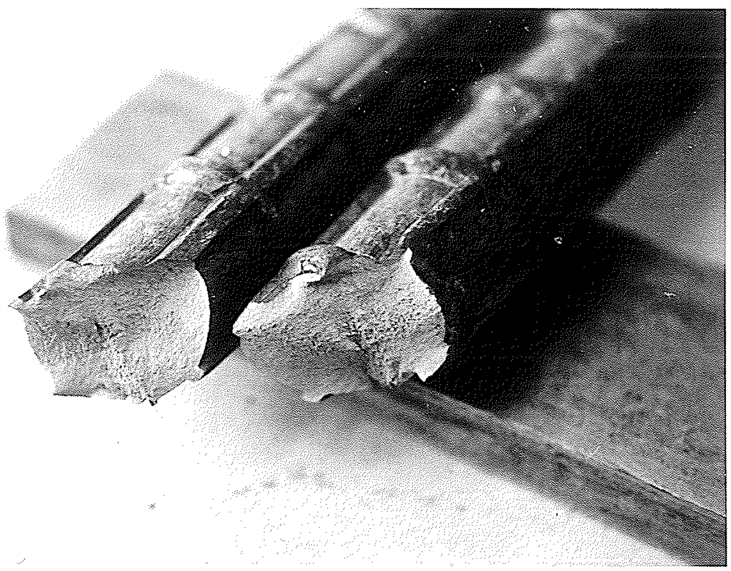
PHOTOGRAPH 6

Some of the one inch diameter, A15, straight reinforcing bars failed by shear when loaded in direct tension.



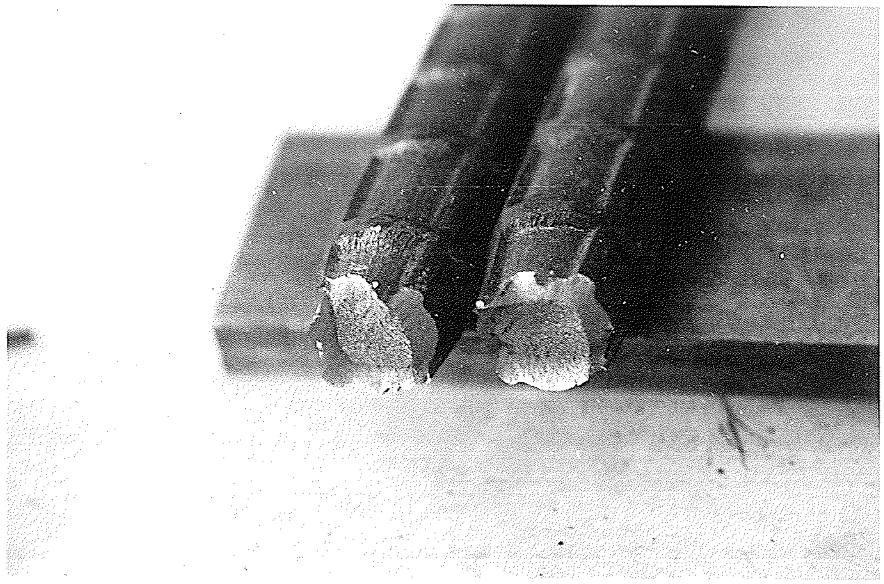
PHOTOGRAPH 7

The 0.875 inch diameter, A432, straight reinforcing bars showed consistent "cup-and-cone" fracture.



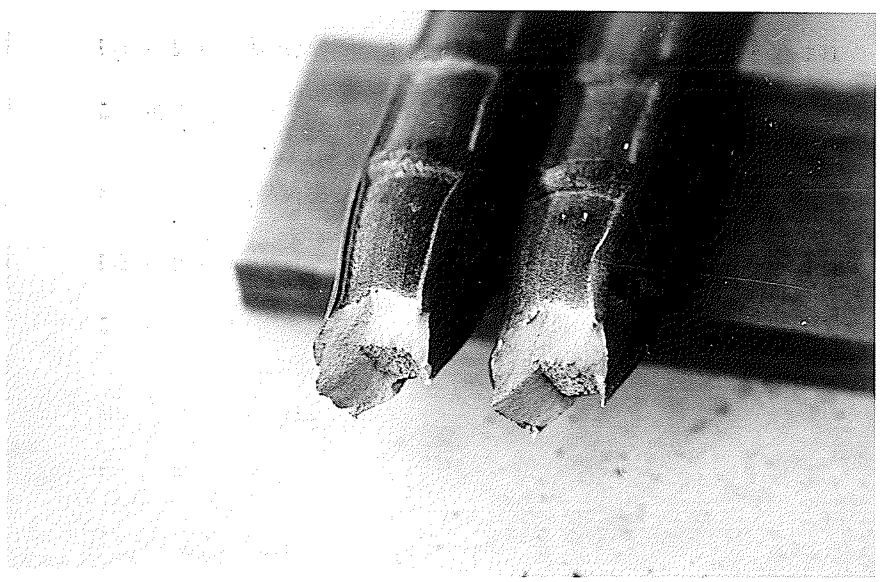
PHOTOGRAPH 8

Some of the A15 straight reinforcing bars in 0.875 inch diameter failed by shear when tested in direct tension.



PHOTOGRAPH 9

Typical "cup-and-cone" type of fracture was dominant for the $\frac{3}{4}$ inch, A 432, bars tested in direct tension.



PHOTOGRAPH 10

"Cup-and-cone" type of fracture was evident for all A15 bars invoving sizes $\frac{3}{4}$ inch in diameter and less.

PHOTOGRAPH 11

One of the 12 inch,3500 p.s.i,concrete cubes that split at a load of 44,000 Lbs.Note the paper sleeve used as a bond breaker on the straight portion of the bar.The reinforcing is a $\frac{3}{4}$ inch diameter,A432, bar bent 90 degrees with 4 bar diameter extension.

MICROGRAPH 1

Longitudinal section from a $\frac{3}{4}$ inch diameter, A432 reinforcing bar cold bent 90 degrees.

Extreme tensile fibers (strained 15%).

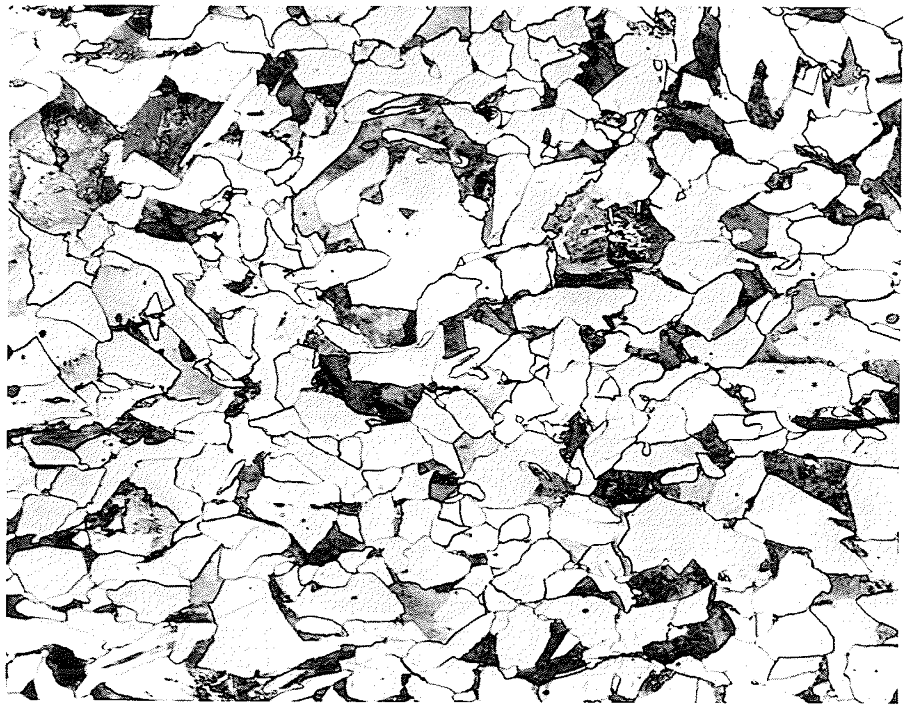
Carbon	0.45 %
Manganese	1.10 %
Etchant	2.0 % Nital
Magnification	500X

MICROGRAPH 2

Longitudinal section from a $\frac{3}{4}$ inch diameter, A432 reinforcing bar cold bent 90 degrees.

Extreme compressive fibers (strained 15%).

Carbon	0.45 %
Manganese	1.10 %
Etchant	2.0 % Nital
Magnification	500X

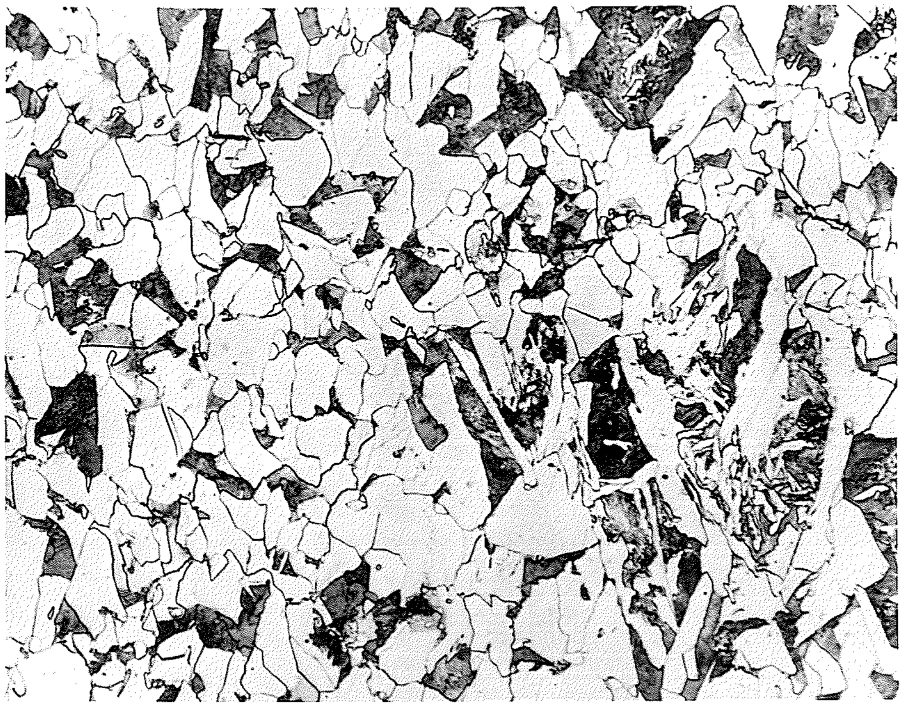


MICROGRAPH 3

Longitudinal section from a $\frac{3}{4}$ inch diameter, A15 reinforcing bar cold bent 90 degrees.

Extreme tensile fibers (strained 15%).

Carbon	0.28 %
Manganese	0.65 %
Etchant	2.0 % Nital
Magnification	500X



MICROGRAPH 4

Longitudinal section from a $\frac{3}{4}$ inch diameter, A15 reinforcing bar cold bent 90 degrees.

Extreme compressive fibers (strained 15%).

Carbon	0.28 %
Manganese	0.65 %
Etchant	2.0 % Nital
Magnification	500X

MICROGRAPH 5

Longitudinal section from a $\frac{3}{4}$ inch diameter, A432 reinforcing bar cold bent 90 degrees.

Extreme tensile fibers (strained 15%).

Carbon	0.45 %
Manganese	1.10 %
Etchant	2.0 % Nital
Magnification	2000X Lens submerged in oil.

Direction of cold work is horizontal.