Investigation of effects of cold forming on mechanical properties

Kenneth W. Karren
George Winter

Follow this and additional works at: http://scholarsmine.mst.edu/ccfss-library
Part of the Structural Engineering Commons

Recommended Citation
Karren, Kenneth W. and Winter, George, "Investigation of effects of cold forming on mechanical properties" (1964). Center for Cold-Formed Steel Structures Library. Paper 13.
http://scholarsmine.mst.edu/ccfss-library/13
Fourth Progress Report on
Investigation of Effects of Cold Forming on
Mechanical Properties

by

Kenneth W. Karren & George Winter

Sponsored by the American Iron and Steel Institute
September, 1964
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I  Introduction</td>
<td>1</td>
</tr>
<tr>
<td>II Materials</td>
<td>3</td>
</tr>
<tr>
<td>III Cold-Forming</td>
<td>4</td>
</tr>
<tr>
<td>IV Plastic Strains in Cold Formed Corners</td>
<td>5</td>
</tr>
<tr>
<td>V  Yield-Strength Versus Plastic Strain Relationships of Unidirectionally Prestrained Flat Sheets and of Virgin Tensile Specimens</td>
<td>15</td>
</tr>
<tr>
<td>VI Corner Tests and Correlation of Corner Test Results with Yield Strength-Strain Relationships</td>
<td>18</td>
</tr>
<tr>
<td>VII Extension of Corner Plastic Strain Effects into the Adjacent Flats</td>
<td>29</td>
</tr>
<tr>
<td>VIII Variation of Tensile Yield Strength and Tensile Ultimate Strength in Flats of Cold Formed Sections</td>
<td>33</td>
</tr>
<tr>
<td>IX Variation of Compressive Yield Strength in Flats of Cold Formed Sections</td>
<td>41</td>
</tr>
<tr>
<td>X  Full Section Tension Tests</td>
<td>42</td>
</tr>
<tr>
<td>XI Full Section Compression Tests</td>
<td>47</td>
</tr>
<tr>
<td>XII Prediction of the Effects of Cold Working</td>
<td>52</td>
</tr>
<tr>
<td>XIII Summary and Conclusions</td>
<td>58</td>
</tr>
</tbody>
</table>
I. INTRODUCTION

All of the divisions of this report consist of either experimental or theoretical investigations of the various aspects of predicting the magnitude and distribution of changes in the mechanical properties (particularly the yield strength) of cold-formed members. The prior work performed under this project was conducted to determine the changes brought about in the mechanical properties of structural sheet steels by (1) simple uniform uni-directional prestrain of varying amounts and (2) simple cold working caused by cold forming sheet into corners as is commonly done in light gage cold formed structural members. Included in this report are: a study of the plastic strains occurring in cold formed corners, a new look at strength versus permanent strain relationships of unidirectionally prestrained flat sheets in terms of true stress and true strain (using data from the First and Second Progress Reports), and an attempt to correlate corner test results for eight different sheet steel materials with yield strength-strain relationships. A brief investigation of the extension of corner plastic strain effects into the adjacent flats for a 10 gage coin press braked corner is also included. The remainder of the report comprises, primarily, an investigation into the full section tensile and compressive behavior of several cold formed structural shapes.

Section 3.1.1 of the AISI Specification for the Design of Light Gage Cold-Formed Steel Structural Members, 1962 Edition, permits, for certain types of sections, the utilization of
increases in material strengths due to the cold work of forming. Increased allowable stresses are permitted in the case of axially loaded members and in the flanges of flexural members. In order to better understand and to better exploit these increases in axially loaded members, an investigation into the performance of six different cold formed structural shapes was conducted. The members, shown on Figs. 35, 36, and 39, which have been tested are as follows:

(1) a 16 gage press braked hat section in two types of material
   (a) hot rolled semi-killed steel (HRSK16-37.5) and
   (b) cold reduced killed steel (CRK16-38.3),
(2) a 16 gage roll formed track section in HRSK16-37.5 steel,
(3) a 10 gage roll formed channel section in HRSK16-37.5 steel,
(4) a 16 gage press braked channel section in a hot rolled steel,
(5) a 16 gage press braked hat section in CRK16-38.3, and
(6) a 16 gage press braked lipped angle section in a hot rolled steel.

The abbreviations used above are defined in Section II. These sections were fabricated from the same five materials used in the previous phases of the investigation, for which properties are given by the first five items of Table 1. Sections (4) and (5) were fabricated from either HRSK16-37.5 or HRR16-40.5, but no record was kept as to exactly which of these two steels was used.
Full section tension tests were conducted on all six types of members shown on Figs. 35 and 36. Full section compression tests with lateral support were conducted on all of the specimen types shown on Fig. 39. Hydrostone was poured around each of these specimens in order to eliminate the possibility of decreased yield strengths due to local buckling. Full section compression tests without lateral support were conducted on the specimen types shown on Fig. 39 (b). In addition, to determine what the effects of cold forming are upon the flat portions of the sections, tension tests of 1/4" wide by 10" long strip specimens were performed for each of the first three types of members, Fig. 37. Similar tests were undertaken on compressive specimens from the flat portions of these sections, Fig. 40.

Information from the narrow tensile and compressive strip specimens, as well as from the corner tests, is related herein to that from tensile and compressive full section tests to show that the magnitude and distribution of effects from the cold forming of sections is reliably predictable from data from reasonably simple test procedures.

II. MATERIALS

The eight carbon steels used in this and previous phases of the investigation are listed on Table 1. The table contains the main properties of the virgin materials in their as-rolled state prior to further cold working. Chemical compositions are shown for each steel. The first four materials, all being of 16 gage thickness, were furnished by Stran Steel Corporation, while the
fifth and seventh of 10 gage thickness and the sixth and eighth of 16 gage thicknesses were furnished by U. S. Steel Corporation.

The following abbreviations are used in this report:

1. CRK16-38.3 - Cold reduced killed 16 gage sheet steel
2. CRR16-36.4 - Cold reduced rimmed 16 gage sheet steel
3. HRSK16-37.5 - Hot rolled semi-killed 16 gage sheet steel
4. HRR16-40.5 - Hot rolled rimmed 16 gage sheet steel
5. HRSK10-37.0 - Hot rolled semi-killed 10 gage sheet steel
6. HRSK16-39.7 - Hot rolled semi-killed 16 gage sheet steel
7. HRSK10-42.8 - Hot rolled semi-killed 10 gage sheet steel
8. HRSK16-40.7 - Hot rolled semi-killed 16 gage sheet steel

The last number in each designation is the tensile yield strength of the virgin sheet in ksi., taken in the direction in which the sheet was rolled. The first five materials were used in the work reported on by all of the previous progress reports. Corner yield strengths for the first five materials were taken from the Third Progress Report, while those of the last three materials are presented herein for the first time.

III. COLD-FORMING METHODS

It is felt that additional clarification should be made to the explanation given in the Third Progress Report of June, 1963, for the two press braking methods used for the cold forming of corners. The three forming methods listed in that report were (1) roll forming, (2) press braking, and (3) press braking with an undersized die. In most of the Third Progress Report this latter type of forming was purposely termed "bend braking" even
though it was, in reality, press braking. The terms which the fabricator used for (2) and (3) above were "coin" and "air". These terms are evidently industry terms and are more descriptive of what actually happens in the forming process than those which were used in the Third Progress Report. In coin press braking both the punch and the die match the final shape desired in the corner, the die having been cut to the same angle as is subtended by the flats of the final formed corner. The piece to be formed is "coined" or bottomed in the die to eliminate springback. For "air" press braking there are a variety of shapes which may be used for the dies. The corner is bent sharper than the desired final angle to allow for springback. Air press braking is illustrated on Fig. 1. Bending progresses from the centerline outward in this type of forming. The curvature is not constant in the final corner, being larger for the middle portion of the corner. At the point where bending is occurring, there is considerable pressure on the inside surface. However, this inside radial pressure is probably not as large as that which may occur in either the roll forming or coin press braking operations.

IV. PLASTIC STRAINS IN COLD FORMED CORNERS

The purpose of this section of the investigation was to study the strains occurring in the circumferential direction at the outside and inside surfaces of a cold formed corner as well as at any interior point. This was done for a simplified theoretical model of a corner and the results compared to experimental evidence
obtained using the photogrid method.

A. Test Procedure (Photogrid Method)

An accurately gridded contact negative with divisions of 200 lines per inch was purchased from Buckbee Nears Company, St. Paul, Minnesota. The grid covered an area of 6 1/2" by 6 1/2" on the negative, with clear spaces of 0.00456" width and lines of 0.00045" width. The spacing of the lines was reported to be accurate to ± 0.0001". It was found necessary to produce a new negative with dark spaces and clear lines in order to obtain black lines and clear spaces on the steel sheets being treated. Materials used for this were Kodak contact film and D-11 developer. The edges of the sheets were de-burred. It is necessary that the surface be free from surface irregularities which may prevent good contact between the negative and the metal during exposure. Pumice may be used for this purpose. Degreasing and cleaning of the surface was accomplished by the application of a paste of "Buff Powder" BPA #1 as manufactured by the Carborundum Company, Niagara Falls, N. Y. This was scrubbed down with a brush and warm water and dried under a fan.

An emulsion was applied to the surface of the steel sheets by simply dipping them in Kodak Photo Resist solution. The sheets were then drained in a vertical position. Directing a fan at the specimens helped produce a thin coating of emulsion. Sheets requiring a grid on one side only were dried on a photo-engraver's whirler, gradually increasing the speed.

Exposure time was determined by trial to be approximately 5 minutes with contact printing in a vacuum printing frame using
a carbon arc lamp at a distance of 40 inches. The developing time used was 3 minutes with Kodak Photo Resist Developer, after which Kodak Photo Resist Dye (a black dye) was applied. The sheets were then dried.

This process was found to provide a satisfactory grid both on the light surface of cold reduced sheets and the dark surface of hot rolled sheets.

Sixteen gage CRR sheets with photogridded surfaces were braked into corners of various radii. One of these corners was formed on a small hand operated bend brake (not a press brake) in the Civil Engineering Shop at Cornell University, and the rest were air press braked at the Champion Sheet Metal Company at Cortland, N. Y. Measurement of the maximum plastic strains on the inside and outside surfaces was accomplished by means of a vernier microscope. Grids were also applied to the edges of 10 gage sheet so that the distribution of plastic strains over cross sections could be studied as well as on the inside and outside surfaces of sheets bent into corners, Figs. 2 and 3. The length of specimens (i.e. in the z or longitudinal direction of a corner as shown on Fig. 4) treated in this manner was 1/4 inch. This was the maximum thickness of material which could be accommodated by the vacuum frame in exposing.

3. Discussion of Results

The plastic strains after relaxation or springback measured by the photo grid method in the tangential direction of the inside and outside fibers of corners as shown on Table 2 vary
from 0.13 to 0.32 in./in. for a/t ratios of 3.26 and 1.32, respectively. Strains in the longitudinal direction of these specimens were negligible. Consequently, a plane strain condition may be considered to exist during and after the plastic condition of cold forming.

In the curves for yield strength of corners versus a/t ratio after cold working as given in the Third Progress Report, there is less variation between curves for a given material formed into corners by coining, by air press braking, and by roll forming than between curves for different materials. This may also be seen from the experimental points on Figs. 20-27 of this report. Air press braking with a die does not produce a uniform curvature and tangential strain. The curvature tends to be somewhat sharper in the center portion of a corner than in the regions next to the flats, Fig. 1. A certain amount of radial pressure is present in die bending in addition to bending moment. In coin press braking and in roll forming, the metal in the corner is even more highly compressed in the radial direction as well as being subjected to bending. In order to attempt an analysis of strains in the corner during cold work it is helpful to choose a model with a somewhat simpler force system acting on it than actually exists in any of the common methods of cold forming. Application of a pure bending moment would produce a uniform curvature and uniform tangential strain.²

Using such a model in pure bending with an inner radius of a and an outer radius of b, as shown on Fig. 4, allows one
to make the assumption that sections in the radial direction which are plane before plastic bending remain plane after bending. When a wide flat plate or sheet is bent by the application of equal bending moments to two opposite edges, distortions occur at the two edges where no moment is applied. Thus the application of photogrids to the unrestrained edges of such sheets or plates will not give precise values of the plastic strains which have occurred in the locations in which restraint is present. In spite of such edge distortions, however, the photogrided specimens of Figs. 2 and 3 appear to roughly corroborate the assumption that plane sections before plastic bending remain plane after bending. By reason of symmetry it can be seen that the principal directions for stress and strain will be the radial or $r$, the tangential or $\theta$, and the longitudinal or $z$ directions. The Lévy-Mises theory of plastic flow\(^3\), in which it is assumed that elastic strains are negligible in comparison to plastic strains, relates the deviator stress tensor to the strain-increment tensor by

$$ S' = (2\frac{\lambda}{dt})dE $$

(1)

where $S'$ = deviator stress tensor,

\( dE \) = strain increment tensor,

\( \lambda \) = a constant of proportionality, and

\( dt \) = time increment.

This may be written in expanded form in terms of principal stresses and strains as
\[
\begin{pmatrix}
\frac{2 \sigma_z - \sigma_r - \sigma_\theta}{3} & 0 & 0 \\
0 & \frac{2 \sigma_r - \sigma_\theta - \sigma_z}{3} & 0 \\
0 & 0 & \frac{2 \sigma_\theta - \sigma_z - \sigma_r}{3}
\end{pmatrix}
\]

\[
\frac{d \varepsilon'_z}{dt} = \begin{pmatrix} d \varepsilon'_r \\ d \varepsilon'_\theta \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & d \varepsilon'_r \\ 0 & d \varepsilon'_\theta \end{pmatrix}
\]

where \( \varepsilon' \) is the natural, or logarithmic strain.

However, since \( \varepsilon'_z = 0 \) and \( d \varepsilon'_z = 0 \), the first equation contained in this matrix equation is

\[
2 \sigma_z - \sigma_r - \sigma_\theta = 0 \text{ or } \sigma_z = \frac{\sigma_r + \sigma_\theta}{2} \quad (2)
\]

Substituting this in the Huber-Mises-Hencky distortion-energy yield condition

\[
(\sigma_z - \sigma_r)^2 + (\sigma_r - \sigma_\theta)^2 + (\sigma_\theta - \sigma_z)^2 = 2 \sigma_y^2 \quad (3)
\]

gives \( \sigma_r - \sigma_\theta = \pm (2/\sqrt{3}) \sigma_y = \pm 2 K^2 \)

where \( K = \sqrt{\frac{\sigma_y}{\sqrt{3}}} \)

Note that the use of the Huber-Mises-Hencky yield criterion tacitly assumes isotropy and the absence of the Bauschinger effect.

The equilibrium equation of the element of volume of Fig. 4 is

\[
\frac{d \sigma_r}{dr} = \frac{\sigma_\theta - \sigma_r}{r} = \pm \frac{2 \sigma_y}{\sqrt{3} r} = \pm \frac{2 K^2}{r} \quad (4)
\]
Separation of variables and integration using the boundary condition \( \sigma_r = 0 \) at \( r = b \) yields
\[
\frac{\sigma_r}{2K^2} = \ln \frac{r}{b} \quad \text{for} \quad r_n < r \leq b
\]
and using the boundary condition \( \sigma_r = 0 \) at \( r = a \) gives
\[
\frac{\sigma_r}{2K^2} = \ln \frac{a}{r} \quad \text{for} \quad a \leq r \leq r_n
\]
Noting that these two expressions must be equal at the neutral surface gives the location of the neutral surface
\[
\ln \frac{r_n}{b} = \ln \frac{a}{r_n}, \quad \text{and} \quad r_n = \sqrt{ab}
\]

It may also be shown that the thickness of the model does not change during the plastic deformation,\(^1,3\) i.e., if the deformation in the radial direction is \( u_r \), then \( dt = \int_a^b du_r = 0 \). This does not mean that the thickness of the volume element of Fig. 4 does not change. It simply means that the overall thickness from \( a \) to \( b \) remains constant. Hill showed that the neutral surface (i.e., the surface where \( \sigma_\theta = 0 \)) and the fiber of zero strain are not the same.\(^1\) The neutral surface is initially at the midplane of the sheet. As bending progresses, all fibers on the inside of the neutral surface are compressed and those on the outside stretched. Then, as bending progresses still further and the neutral surface moves toward the inside radius, an area that was under compression is now stretched.

It has been shown experimentally that for large plastic strains the material may be considered incompressible for most metal-forming operations. If the location of a given fiber from the mid-plane of the undeformed sheet is described by \( m t/2 \) where
- 12 -

-1 \leq m \leq 1$, the volume constancy principle may be applied to solve for the radius $r$ locating this same fiber in the plastically deformed corner.

Let $A_1 =$ area outside of radius $r$,

$A_2 =$ area inside of radius $r$, and

$L_0 =$ original length of fiber.

Then the areas before and after deformation are the same:

$A_1 = \frac{\theta}{2} (b^2 - r^2) = \left(\frac{t}{2} - m \frac{t}{2}\right)L_0$

$A_2 = \frac{\theta}{2} (r^2 - a^2) = \left(\frac{t}{2} + m \frac{t}{2}\right)L_0$

Dividing $A_2$ by $A_1$ gives

$$\frac{r^2 - a^2}{b^2 - r^2} = \frac{1 + m}{1 - m}$$

from which

$$r = \sqrt{\frac{1/2 (a^2 + b^2) + 1/2 (b^2 - a^2) m}{1 - m}} \quad (6)$$

as given by Hill.\textsuperscript{1}

The relation between the original fiber length and the inside and outside radii may be expressed by equating initial and final areas

$$L_0 t = \frac{1}{2} (b^2 - a^2) \theta \quad \text{or}$$

$$L_0 = \frac{\theta}{2} (b + a)$$

The location of the fiber of zero strain is then given by

$$L_0 = r_0 \theta = \frac{\theta}{2} (b + a), \quad \text{or}$$

$$r_0^2 = \frac{1}{4} (b + a)^2 \quad (7)$$
Substituting in Eq. (6) and simplifying gives

$$m_0 = -1/2 \left( \frac{b - a}{b + a} \right) = -1/2 \left( \frac{1}{2a/t + 1} \right)$$

(8)

The engineering strain in the tangential direction is a straight line relationship

$$\varepsilon = \frac{r - (a + b)/2}{(a + b)/2} = \frac{2r}{a + b} - 1$$

(9)

and becomes, for \( r = a \) and for \( r = b \)

$$\varepsilon_a = -\varepsilon_b = -\frac{1}{2a/t + 1} \quad (9a)$$

Engineering strains computed by this method are listed for comparison with experimental strains obtained by the photogrid method on Table 2. The observed strains appear to be close to but slightly higher than the theoretical strains on the outside of the corners, especially for low values of the \( a/t \) ratio.

The natural strain is \( \varepsilon' = \ln (1 + \varepsilon) \) or using Eqs. (9) and (6):

$$\varepsilon' = \ln \sqrt{\frac{2}{(a + b)^2} \left[ a^2 + b^2 + m(b^2 - a^2) \right]}$$

$$= \frac{1}{2} \ln \left\{ \frac{2}{(2a/t + 1)^2} \left[ ((a/t)^2 - m) + (a/t + 1)^2(1 + m) \right] \right\} \quad (9b)$$

Two main theories are used in the consideration of the strain hardening of metals. ¹ The first makes use of the concept of a quantity known variously as the generalized stress, equivalent stress, or effective stress which is determined from the Huber-Mises-Hencky distortion energy yield condition,
Eq. (3), as

\[ \bar{\sigma} = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \]  

where \( \bar{\sigma} \) is the effective stress, and \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) are the principal stresses. Note that for the condition of uniaxial tension, \( \bar{\sigma} \) is equal to \( \sigma_1 \). The second theory makes use of a somewhat analogous quantity variously called the generalized strain, equivalent total strain, or effective strain. The effective strain may be calculated from

\[ \bar{\varepsilon} = \frac{\sqrt{2}}{3} \sqrt{(\varepsilon_1' - \varepsilon_2')^2 + (\varepsilon_2' - \varepsilon_3')^2 + (\varepsilon_3' - \varepsilon_1')^2} \]

where \( \bar{\varepsilon} \) is the effective strain, and \( \varepsilon_1', \varepsilon_2', \) and \( \varepsilon_3' \) are the logarithmic principal strains. For the case of uniaxial stress in the plastic range, taking Poisson's ratio as \( \frac{1}{2} \) results in \( \varepsilon_2' = \varepsilon_3' = -\frac{1}{2} \varepsilon_1' \). Substitution of these values in Eq. (10) gives an effective strain equal to \( \varepsilon_1' \).

In the volume constancy concept it is assumed that for plastic strain the change in volume is negligible. The volume strain \( \Delta \) is given by

\[ \Delta = (1 + \varepsilon_1')(1 + \varepsilon_2')(1 + \varepsilon_3') - 1 \]

and the logarithmic volume strain \( \Delta' \) is given by

\[ \Delta' = \ln (1 + \Delta) = \varepsilon_1' + \varepsilon_2' + \varepsilon_3' \]

where \( \varepsilon_1' = \ln (1 + \varepsilon) \)

Since \( \Delta = 0 \) for volume constancy

\[ \Delta' = \varepsilon_1' + \varepsilon_2' + \varepsilon_3' = 0 \]
In the case of the pure flexural model which is in a condition of plane strain $\varepsilon'_z = 0$ and, consequently, $\varepsilon'_r = -\varepsilon'_\theta$. (11) Using this in Eq. (10) results in

$$e = \frac{2}{\sqrt{3}} \varepsilon'_\theta,$$

and

$$e = \frac{1}{\sqrt{3}} \ln \left\{ \frac{2((a/t)^2(1-m)+(a/t+1)^2(1+m))}{(2a/t+1)^2} \right\}$$

(12)

Eq. (12) will be used in Section VI.B in the derivation of an equation for the prediction of the tensile yield strength of cold formed corners.

V. YIELD STRENGTH VS. PLASTIC STRAIN RELATIONSHIPS OF UNIDIRECTIONALLY PRESTRAINED FLAT SHEETS AND OF VIRGIN TENSILE SPECIMENS

By utilizing the true stress and true strain concepts it is sometimes possible to establish a relatively simple expression for true stress versus true strain in the plastic domain in the form

$$\sigma' = k(\bar{e})^n$$

(13)

where $\sigma'$ = true stress = load / instantaneous area,

$\bar{e}$ = effective strain,

$k$ is called the strength coefficient, and

$n$ is called the strain hardening exponent.

This formulation is possible when a plot of the logarithm of $\sigma'$ versus the logarithm of $\bar{e}$ in the plastic domain appears as a straight line which is the case for many steels and some other metals. For uniaxial tension Eq. (13) reduces to $\sigma' = k(\varepsilon')^n$ by use of Eq. (10). To utilize this equation, it is first
necessary to investigate $k$ and $n$ experimentally.

The yield strengths obtained for the five materials (as reported fully in the Second Progress Report and partially in reference 4) uniaxially stretched to permanent prestrains of 10, 25, 50, and 100 mils and subsequently aged were based on the area of specimens after prestraining. Consequently, these yield strengths may be looked upon as an approximation of the true yield strengths. These natural yield strengths for the five materials are replotted versus the natural strain of $\varepsilon' = \ln (1 + \varepsilon)$ on Figs. 5-9 on log log paper. As these figures show, the extension of this technique to prestretched materials which have been allowed to age gives the hoped for straight lines (in most cases) from which empirical relationships can be established with true yield strength expressed as a function of true plastic strain. No correction was made for elastic recovery since such corrections would be quite small compared to the plastic strains occurring. With Eq. (13) extended in this way the influences of aging and of the Bauschinger effect are included.

Values for the material constants $k$ and $n$ are given on Table 3a for four cases for each of the first five materials as determined from Figs. 5-9. The four cases are for specimens tested in (1) tension in the direction of tensile prestrain, (2) tension transverse to the direction of tensile prestrain, (3) compression in the direction of tensile prestrain, and (4) compression transverse to the direction of tensile prestrain.
Further values of k and n were also obtained from true stress strain curves (Fig. 10) of single virgin tensile specimens tested well into the plastic range for each of the first five materials; they are listed on Table 3b with an asterisk. The tests from which these data were obtained were conducted prior to February, 1962. Recently, three additional tensile tests for each of the eight materials were conducted well into the plastic range. Values of k, which vary from 70 to 115 ksi, and values of n, which vary from 0.13 to 0.24, obtained from these tests are tabulated on Table 3b.

From the non-dimensional plot of $\frac{\sigma_{yc}}{k}$ versus $\frac{\sigma_u}{\sigma_y}$ of Fig. 11 it can be seen that the empirical formula

$$k = 2.62 \sigma_u - 1.33 \sigma_y$$

(13a)

gives a good approximation for k where

$\sigma_u$ = the virgin ultimate strength in ksi. and
$\sigma_y$ = the virgin tensile yield strength in ksi.

From the plot of Fig. 12 where values of n are plotted versus $\frac{\sigma_u}{\sigma_y}$, it can be seen that values of n tend to increase in a general way with increase in the $\frac{\sigma_u}{\sigma_y}$ ratio. Fitting a curve

$$n = 0.30 \frac{\sigma_u}{\sigma_y} - 0.22$$

(13b)

to these experimental values will prove to be useful in Section VI.B in the derivation of an equation for predicting the tensile yield strength of cold formed corners. Eqs. (13) and (13a) will also be used in the derivation of Section VI.B.
VI. CORNER TESTS AND CORRELATION OF CORNER TEST RESULTS WITH YIELD STRENGTH-PLASTIC STRAIN RELATIONSHIPS

A. Test Procedure

Tensile and compressive test specimens for corners, as well as flat specimens are shown on Fig. 13. Special methods for cutting and testing corner specimens were devised.

Tension tests on corner specimens were conducted using self-aligning grips and a standard microformer gage of 2 inch gage length to measure strains. The specimens were made extra long: 16 inches and 18 inches rather than the standard 9 inches ordinarily used for flat sheet specimens, as shown on Figs. 13 (a) and (b). This was considered necessary in order to minimize bending and flattening out of the corner in the central portion of the specimen during testing.

Compression tests were somewhat more difficult because of the requirement of measuring strains while preventing buckling in the specimen. Compressive tests such as shown on Figs. 13 (g) through (k) were accomplished by two main methods. In the first, the specimen was greased, wrapped in aluminum foil and enclosed in hydrostone in a pipe tube as on Figs. 13 (g) and (h). Hydrostone is a proprietary material of white color containing gypsum which hydrates and hardens much more rapidly than portland cement and has ultimate compressive strengths of the order of 9000 psi. In the second method the specimen was greased and inserted into a special metal jig for corners, Fig. 13 (l). For the ten gage specimen shown on Fig. 13 (i), which had an inside radius of 7/16
inch, no jig or hydrostone was necessary since the specimen had an L/r ratio of less than 15 so that buckling was not a problem. For a number of tests, strains were obtained by means of two dial gages placed so as to record the movement of the head of the subpress with respect to the table of the testing machine. One of these gages is shown in place on the left side of the subpress on Fig. 15. This method gave moduli of elasticity considerably below 29,500,000 psi., which is taken as a representative value. Therefore, for most of the compressive tests on corners, electric SR-4 foil type strain gages were mounted on one side of the specimen. It was observed that values for proportional limit and yield point found on the same specimen by these two methods were quite close even though the modulus of elasticity was much better by the latter method.

One test was conducted with strain gages on both sides of the corner specimen. The stress strain curves obtained from the two gages were close enough that it was determined unnecessary to mount two gages on each specimen.

Measurement of the inside radii of the corners was accomplished visually by use of Lufkin radius gages.

Corners for the first five materials listed on Table 1 were taken from the sections shown on Fig. 14. These corners were made by three forming methods: air press braking, coin press braking, and roll forming. The corners from the last three materials were taken from air press braked angles.
The appropriate material properties (such as proportional limit, yield strength, tensile strength, and percent elongation in 2 inches) of each tensile and compressive corner specimen tested since the Third Progress Report are tabulated on Table 10.

B. Discussion of Results

An empirical equation

$$\sigma_{yc} = \sigma_y [1 + b/(a/t)^m]$$

where $\sigma_{yc}$ = the corner yield strength after cold working, $\sigma_y$ = the virgin yield strength, and $b$ and $m$ are constants fitted to the experimental data by the method of least squares was given in the Third Progress Report. The constants $b$ and $m$ were not related to basic properties of the material. In this section an equation will be established to relate $\sigma_{yc}$ directly to the fundamental material properties $k$ and $n$.

Because of the condition of plane strain it is assumed that the Bauschinger effect does not occur in the model of Fig. 4. A typical volume element located outside the surface of zero strain will have a tensile logarithmic prestrain in the tangential or $\theta$ direction and a compressive logarithmic prestrain of equal magnitude in the radial or $r$ direction (as was shown by Eq. (11).) Similarly, a volume element located inside the surface of zero strain will have a compressive logarithmic prestrain in the tangential direction and a tensile logarithmic prestrain of equal magnitude in the radial direction. In each of these two typical
elements the \( \varepsilon'_\theta \) and \( \varepsilon'_r \) prestrains of equal size and opposite sign are oriented at right angles to the final direction of testing or loading, the longitudinal z-direction. Thus, considering for the purpose of discussion one prestrain at a time and superimposing the two effects, there would be no net effect on the yield strength in the longitudinal direction from the "inverse Bauschinger effect", i.e. the increase in yield strength in the longitudinal direction from a compressive prestrain would be offset by the reduction from the equal tensile prestrain. However, there is evidently an increase in both tensile and compressive yield strength due to strain hardening.\(^5\)

While no tests were made on unidirectionally precompressed sheets, it is assumed that a curve for the tensile prestrain of a material as given by Eq. (13) is also valid when applied to the same material subjected to compressive prestrains, using the values of \( k \) and \( n \) determined from tensile tests. Using the relation between the yield strength in terms of true stress and effective strain given by equation (13) for a volume element and integrating this over the area of a corner yields

\[
\ell_0 t \sigma_{yc'} = k \int_A |\bar{\varepsilon}|^n \, dA = k \int_{-t/2}^{t/2} |\bar{\varepsilon}|^n \ell_0 \, dy
\]

With the change of variable \( dy = t/2 \, dm \)

\[
\sigma_{yc'} / k = 1/2 \int_{-1}^{1} |\bar{\varepsilon}|^n \, dm
\]

is obtained where \( \bar{\varepsilon} \) is given by Eq. (12). Eq. (16) was evaluated
numerically by means of Simpson's Rule for a number of values of n and plotted as Fig. 16. To accomplish this the integral was separated into two parts

$$\sigma_{yc}'/k = 1/2 \int_{m_0}^{1} \xi^n \, dm + 1/2 \int_{-1}^{m_0} /\xi^n \, dm$$  \hspace{1cm} (17)$$

where m_0 is given by Eq. (8).

By a succession of variable changes Eq. (15) may also be written in the form

$$\sigma_{yc}'/k = 1/2(2a/t + 1) \left[ \int_{1}^{2a/t + 2} \frac{2a/t + 2}{(2/\sqrt{3}\ln x)^n} \, xdx + \int_{2a/t}^{1} \frac{2a/t}{2a/t + 1} \, xdx \right]$$

While the integrands in this equation appear somewhat simpler than in Eq. (17) these integrals are also best evaluated by numerical means.

The final result is that $\sigma_{yc}'$ is a product of the strength coefficient k and a coefficient determined from Fig. 16 as a function of the a/t ratio and the strain hardening exponent n. This value of $\sigma_{yc}'$ needs to be reduced by an area reduction coefficient to get $\sigma_{yc}$ in terms of engineering stress. This can be approximated by

$$\sigma_{yc} = \frac{A}{A_o} \sigma_{yc}' = \frac{E_0}{E} \sigma_{yc}' = \left( \frac{1}{1 + \xi_y} \right) \sigma_{yc}'$$  \hspace{1cm} (19)$$

Since for $\sigma_{yc}' = 60$ ksi, the value of $\xi_y$ is 0.002, this correction factor was neglected in computation of the curves of Figs. 20-27.

Since the effect of the correction factor changing true stress...
to engineering stress is negligible at low plastic strains, the values of the ordinate of Fig. 16 may be considered as the tensile yield strength of corners expressed either in terms of engineering stress or in terms of true stress.

For values of a/t less than 10.0 Eq. (17) may be closely approximated by the empirical formula

$$\frac{\sigma_{yc}}{k} = \frac{\sigma_{yc}'}{k} = \frac{b}{(a/t)^m}, \quad \text{or} \quad \sigma_{yc} = \frac{kb}{(a/t)^m}$$

(18)

This is true because a plot (Fig. 18) of Eq. (17) on log log paper, holding n constant, approximates a straight line quite closely. Furthermore, using Eq. (18), it was found that the relationships between the constants b and n and between m and n are linear (as shown by the curves for b and m on Fig. (19). The empirical equations for b and m are

$$b = 0.945 - 1.315n \quad \text{(18a)}$$
$$m = 0.803n \quad \text{(18b)}$$

With the values of k and n available for a given sheet material, Eqs. (18), (18a), and (18b), or the curves of Fig. 16, may be used to establish a curve of the calculated $\sigma_{yc}$ versus the a/t ratio of the corner. This was attempted with values of the constants k and n established in three different ways, the resulting curves being compared with experimentally determined values of $\sigma_{yc}$ for varying a/t ratios. The methods used to
establish values for the material constants \( k \) and \( n \) were:

1. empirical Eqs. (13a) and (13b) which require that representative values of \( \bar{\sigma}_u \) and \( \bar{\sigma}_y \) be available from standard tension tests,
2. establishment of values for the constants \( k \) and \( n \) from true stress strain curves of virgin tensile specimens, carried well into the plastic range such as on Fig. 10, and
3. establishment of values of \( k \) and \( n \) from the yield strength curves of Figs. 5-9 for uniaxially prestrained and aged sheets.

The curves of \( \sigma_{yc} \) versus \( \alpha / t \) ratio calculated using \( k \) and \( n \) from Eqs. (13a) and (13b) are the solid curves on Figs. 20-27 on which the experimental results are also shown. As can be seen from these curves the correlation is quite good, the curves giving for most of the eight materials conservative, yet reasonable values of \( \sigma_{yc} \). Note that the curves established for the tensile \( \sigma_{yc} \) are also plotted with compressive experimental points for comparative purposes. The curves for \( \sigma_{yc} \) are, in general, more conservative when compared to experimental compressive corner yield strengths than when applied to tensile yield strengths.

Curves of \( \sigma_{yc} \) versus \( \alpha / t \) established using constants \( k \) and \( n \) taken directly from true stress strain curves of tensile specimens are not shown, but have the same general shape and appearance as the curves shown. However, the natural variation in virgin properties which occurs from location to location in any rolled sheet steel causes variation from specimen to specimen in the values of \( k \) and \( n \) as well as in \( \sigma_y \) and \( \bar{\sigma}_u \). Thus many of these curves based on the \( k \) and \( n \)
values from individual specimens would fall below and a few would fall above the experimental points. In order to obtain the best correlation using k and n values determined in this way, it would be necessary to take enough specimens from the appropriate locations in a sheet to insure that the averaged values of k and n were truly representative for that sheet.

Curves of tensile $\sigma_{yc}$ versus a/t ratio for corners as determined by using k and n values from uniaxially prestrained tensile specimens did not correlate at all well with experimental values and are not shown on the curves of Figs. 20-27. This is not surprising since uniaxially prestrained specimens exhibited Bauschinger effects and specimens from corners have been demonstrated to be free of the Bauschinger effect.

Since it is known that radial pressures are present during the plastic bending of corners by air press braking, coin press braking, or by roll forming, the effect of radial pressure on the curves of Figs. 20-27 was explored. Hill has shown that the effect of tension with bending is for the neutral surface to displace inward and for the thickness of the sheet to decrease. This assumes an equally distributed outward radial pressure on the inside surface of the corner to equalize the tensile membrane forces and so would be tantamount to inside radial pressure with bending. Integration of Eq. (4) using the boundary conditions $\sigma_r = -p$ at $r = a$ and $\sigma_r = 0$ at $r = b$ gives the following equations for stresses:

$$\sigma_r = -2K \ln b/r, \quad \sigma_\theta = 2k(1 - \ln b/r) \quad \text{for } r_n \leq r \leq b$$

$$\sigma_r = -p - 2K \ln r/a, \quad \sigma_\theta = -p - 2K(1 + \ln r/a)$$
for \( a \leq r \leq r_n \). Equating the equations for \( \sigma_r \) at the neutral surface gives the radius to the neutral surface

\[
r_n^2 = abe^{-p/2K}
\]

which shows that the neutral surface is closer to the inside radius than for the model subjected to pure flexure only.

Now, if the neutral surface is displaced inward, so will be the fiber of zero strain. Larger strains will be expected on the outside fiber and smaller strains on the inside fiber. In this case cylindrical surfaces will remain cylindrical, but the thickness \( t = b - a \) will be decreased.\(^1\)

The exact amount of radial pressure present for any of the three forming methods is not known. Therefore, a second model will be considered in which it will be arbitrarily assumed that the axis of zero strain is at \( r_o = \sqrt{ab} \).

From Table 2 it appears that this assumption tends to give theoretical strains which agree more closely with experimental strains than the assumption of pure flexural plastic bending. If it is further assumed that the thinning effect can be ignored, and that the strain distribution remains linear, the effective strain becomes

\[
\bar{\varepsilon} = 2/\sqrt{3}\varepsilon' = 2/\sqrt{3}\ln (1 + \xi) = 2/\sqrt{3}\ln \frac{l/l_o}{r/r_o}
\]

\[= 2/\sqrt{3}\ln r/r_o\]  

(21)

From the volume constancy relation it may be assumed that an area after deformation is equal to the same area before deformation. Thus

\[dA = l_o \, dy = \Theta r_o \, dy = \Theta r \, dr, \text{ from which } dy = r/r_o \, dr\]
\[
\sigma_{yc}' = \frac{1}{t} \int_{A} \sigma' \, dA = \frac{1}{t} \int_{A} k \xi^n \left( \frac{\ell_0}{\ell_0} \right) d\ell = \frac{k}{t} \int_{a}^{b} \xi^n \left( \frac{r}{r_o} \right) dr
\]

and for the change of variable \( x = \frac{r}{r_o} \)

\[
\sigma_{yc}' / k = \frac{r_o}{t} \int_{a/r_o}^{b/r_o} \xi^n \, dx = \frac{r_o}{t} \int_{a/r_o}^{b/r_o} \left( \frac{2}{\sqrt{3}} \ln x \right)^n \, dx
\]

Eq. (22) was evaluated numerically as shown on Fig. 17 and can be closely approximated by

\[
\frac{\sigma_{yc}}{k} = \frac{\sigma_{yc}'}{k} = \frac{b_1}{(a/t)^{m_1}}, \text{ or } \frac{\sigma_{yc}}{k} = \frac{kb_1}{(a/t)^{m_1}}
\]

in the same way that Eq. (17) was approximated by Eq. (18).

The relationships between \( b_1 \) and \( n \) and between \( m_1 \) and \( n \) are the linear equations

\[
b_1 = 1.0 - 1.3n \tag{23a}
\]

and \( m_1 = 0.855n + 0.035 \tag{23b} \)

as shown on Fig. 19.

Evaluating Eq. (23) for the values of \( n \) and \( k \) previously found by Eqs. (13a) and (13b) results in the dashed curves on Figs. 20-27. For \( a/t \) ratios greater than about 5 there is very little difference between the dashed curves and the solid curves, the latter being based on the pure flexurally loaded model. For smaller \( a/t \) ratios, however, the yield strengths predicted by the second model were up to 9% larger than those predicted by the pure flexural model. The theoretical \( \sigma_{yc} \) versus \( a/t \) curves of the second model correlated
better than those of the pure flexural model for some, but not for all of the eight materials tested. Consequently, the tensile yield strength of a cold formed corner should be based upon Eq. (18) rather than Eq. (23). The majority of experimental points lie above these theoretical curves, however. Whether this is due to aging, to the existence of still higher inside radial pressure, to a different strain distribution than that assumed, or to a combination of causes is uncertain. Other possible sources of difference between the theoretical model curves and the experimentally obtained points are:

1. lack of uniform curvature and possible deviation from the assumption that plane surfaces remain plane,
2. anisotropy, which is present in virgin steel and is also caused by the cold forming operations themselves, tends to render the "effective strain" concept somewhat inaccurate,
3. no definite experimental curves are available for the compressive stress strain curve characteristics,
4. variation in virgin properties of individual specimens,
5. ignoring the effects of residual stresses, and
6. the fact that prestraining in the corners was at right angles to the grain whereas k and n values were established for specimens tested in the direction of the grain.

However, the total influence of these factors must be relatively small or the differences between the theoretical curves and the
experimental values would be larger than they are. The described effort to relate curves of $\sigma_{yc}$ versus $a/t$ ratios (as given by Eq. (18)) to fundamental material properties has resulted in achieving curves which should be useful in predicting the effects of cold work upon the yield strength of corners within reasonable limits.

It should be noted that Fig. 16 and Eq. (18) should not be used for $a/t$ ratios in excess of about 6.0 without further verification, since no corner specimens were tested above that range.

VII. EXTENSION OF CORNER PLASTIC STRAIN EFFECTS INTO THE ADJACENT FLATS

A. Test Procedure

It is evident that a transition zone must exist between the high plastic deformations present in a corner cold formed by press braking and the undeformed material several sheet thicknesses from the edge of the corner. However, since the plastic deformations and, consequently, the increase in yield strength in this transition zone fall off rapidly with the distance from the edge of the corner, it was surmised that the usual variation in the virgin yield strength would tend to obscure any trends that may exist in the zone. Unfortunately, the same specimen cannot be tested both before cold working and afterward. Therefore, this investigation was divided into two parts: (1) an investigation to determine the virgin yield strength distribution in a given sheet of steel and (2) an investigation to determine the extent of the effects of plastic deformation from the corner into the
adjacent flats from materials press braked from portions of the same sheet. The information gained from (1) was utilized to evaluate the increases in yield strength.

A 14" by 60" piece of the HRSK10-37.0 steel was selected for this purpose, Fig. 28. Virgin tensile and compressive specimens were taken from three longitudinal 1" wide strips (marked 1, 2, and 3.) Virgin tensile specimens were taken from three transverse strips (A, E, and J). See Fig. 29 for a typical layout of these specimens. This left 4 portions of the sheet (CX, CXX, GX, and GXX) to be coin press braked into channel sections. The inside radius of the corners in these channels was 1/8" giving an a/t ratio of 0.89. These portions were surrounded by virgin tensile specimens. The four channels were allowed to age for 2 1/2 months after being cold formed and were then cut into thin rectangular specimens without shoulders as shown on Fig. 30. The 1/4" wide specimens were considered to be the same as virgin specimens. Note that scribe marks were accurately made before these specimens were cut out so that the distance from the edge of the specimens to the edge of the corner could be accurately determined in the final milled specimen. The specimens from locations marked 2, 3, 6, and 7 were made with widths which were purposely varied by 0.0300" with the edge farthest from the corner being a constant distance from the corner. Thus the increase in yield strength for that portion of two specimens in common (i.e. the same distance from the corner) could be considered to be the same. The increase in
tensile yield strength after cold working for the area which is the difference in area between the two specimens was calculated from

\[ \sigma_y \text{ incr.} = \frac{(\sigma_{y1} - \sigma_y)A_1 - (\sigma_{y2} - \sigma_y)A_2}{A_1 - A_2} \]  
(24)

and the yield strength by

\[ \sigma_{yf} = \sigma_y \text{ incr.} + \sigma_y \]  
(25)

where the subscripts 1 and 2 denote two specimens of different area,

- \( \sigma_{yf} \) = the tensile yield strength after cold working of the area represented by the difference in areas \((A_1 - A_2)\)
- \( \sigma_y \) = the virgin tensile yield strength of the sheet as determined from the contours of Fig. 30,
- \( \sigma_y \text{ incr.} \) = increase in yield strength above actual virgin yield strength, and
- \( A \) = the cross sectional area of a specimen.

These computations are shown on Table 4 with the specimens of approximately the same cross sectional area averaged together.

B. Discussion of Results

Fig. 31 shows the distribution of virgin tensile yield strengths using the 73 specimens laid out as on Fig. 30. These yield strengths within one 14 x 60 in. sheet varied from 37.1 ksi to 43.8 ksi, a total variation of 18%.

Assuming a normal or Gaussian distribution of these values, the standard deviation from the arithmetic mean value of
39.9 ksi was 1.2 ksi or 3%. The probable error, defined as the error such that the probability of occurrence of an error whose absolute value is less than this value is 1/2, is 0.6745 x the standard deviation, which is in this case 0.8 ksi or 2%.

Values of tensile strength for these same 73 specimens varied from 57.7 ksi to 62.6 ksi, a variation of 8%. The arithmetic mean was 60.1 ksi, the standard deviation 1.4 ksi, and the probable error 0.9 ksi.

The yield strength of 15 compressive specimens varied from 39.2 ksi to 46.3 ksi, a variation of 18%. The corresponding arithmetic mean, standard deviation, and probable error are 42.1, 2.0, and 1.4 ksi, respectively. These values serve to illustrate just how much the mechanical properties may be expected to vary from point to point in any modest-size sheet prior to cold forming operations.

The results of the computations of Table 4 are shown on Fig. 32 where the increase in yield strength is plotted as the ordinate and distance from the edge of the corner is plotted as the abscissa. The curves on this figure show that the increase in yield strength has become negligible at a distance of one sheet thickness from the edge of the corner. The increase in the force required to yield a 90° corner with inside radius of 1/8" and t = 0.14" would be 0.043 sq. in. times 34 ksi = 1.46 kips. The average values of increase in the yield strength from a corner edge to a distance one thickness away is 11.1 ksi, giving for two adjacent flat areas an increase in
the force required to cause yielding of $2 \times 0.14 \times 0.14 \times 11.1 = 0.44$ kips, which is 30% of the increase attributable to the corner alone. Put another way, the "effective corner area" in this case could be considered to be 1.3 times the actual corner area or a distance of 0.46 times the sheet thickness on each side of the corner.

It will be shown in the next section that in some press braked sections this transition range is extremely small. For roll formed sections, however, there are substantial increases in flat specimens from locations immediately adjacent to the corners. Consequently, it may be concluded that the main increase in yield strength in flat specimens taken from locations immediately adjacent to cold formed corners is attributable to the normal pressure of the rolls or dies on these flats rather than to the extension of plastic strains from the corners into the flats.

VIII. VARIATION OF TENSILE YIELD STRENGTH AND TENSILE ULTIMATE STRENGTH IN FLATS OF COLD FORMED SECTIONS

The following tests were conducted to determine how cold forming changes the tensile mechanical properties of the flats of members made from three of the test steels. Not only was it desired to investigate the general magnitude of such changes, but also to investigate the magnitude of the changes at varying locations in the flat portions of the cold formed members.

A. Test Procedure

Flat rectangular tensile specimens 1/4" by 10" were cut from the cross section of the three cold formed sections
indicated on Fig. 37. These specimens were made narrow and without shoulders in order to obtain the desired test information reasonably close to the corners and to get more points in the flats between the corners than would have been possible with standard width tensile coupons. The specimens were tested with the middle three inches of length exposed between the grips. Very few of these non-standard tensile specimens failed in the jaws of the self-aligning tension grips, the majority breaking in the desired middle portion of the specimen.

Strains were measured with an autographic microformer gage. Final elongation in 2 inches was taken.

B. Discussion of Results

Figs. 41, 45, 51, and 58 show the distribution of tensile mechanical properties in the corners as well as the flat portions of the cross sections. The yield and ultimate strengths are plotted as ordinates, and the locations of the elemental strip specimens are shown on the abscissa. For the location of these specimens with respect to the cross section see Fig. 37. The virgin tensile yield and ultimate strengths of the material as given in the First Progress Report are indicated as solid horizontal lines.

The values for corner strengths were taken from the Third Progress Report and are plotted as equal for all of the corners shown for each particular type of member. In each case the values of yield and ultimate strength of the corners can easily be identified because they are so much higher than the values for the flat material. In fact, the yield strength
values for the cold worked corners are significantly above the
virgin ultimate strength of the material in all cases.

From the average values for flats shown on Table 5 the follow­
ing conclusions may be drawn. First, if it is assumed that the
virgin values of yield and ultimate strengths taken from the
First and Second Progress Reports are reasonably representative,
then it may be concluded that changes in the yield and ultimate
strengths of the flats of the CRK-16-38.3 press braked section,
Fig. 41, are negligible. Second, the increase in yield strength
of the HRSK16-37.5 press braked hat flats, Fig. 45, is measurable,
being on the order of 6%. Third, roll forming as conducted upon
the HRSK sections of Figs. 51 and 58 increases the yield strength
in the flats in the most significant amounts, i.e. averaging 17
and 22%, respectively. Fourth, roll forming seems to raise the
average ultimate strength of the flats a significant amount, where­
as press braking does not.

It has been pointed out that the virgin properties of the
sheet are by no means constant. The non-uniformity of the
original flat sheet material is reflected in the variations in
the yield strength values for the flats of Fig. 45. However,
since the yield strength of the flats of press braked sections
are consistently above the virgin yield strength, it can scarcely
be concluded that such increases are caused entirely by the
random variation in virgin properties. The increases in yield
strength of flats appear to be attributable to strain hardening
and aging from several factors:

(1) the strain hardening and aging which occurs after
uncoiling (i.e. stretcher-straightening) of stored sheet
(2) the normal pressure of the rolls in roll forming or of the dies in coin press braking upon the flat portions of the sections being formed,

(3) the extension of the plastic deformations which occur in corners into the flats adjacent to the corners,

(4) the warping of flats with accompanying shearing strains that occurs in roll forming, and

(5) the presence of elastic strains in the flats.

These factors will be discussed in some detail in the following paragraphs.

That the stretcher straightening of sheets (i.e. flattening of the sheet from the coils in which it is stored) may increase the yield strength seems to be substantiated by the fact that the average tensile strength of the 73 virgin specimens of the (HRSK10-37.0) 10 gage sheet described earlier in this report was 39.9 ksi while it was reported to be 37.0 ksi in the Second Progress Report. The stretcher-straightening of the 10 gage sheet (HRSK10-37.0) took place about October 1, 1961. Testing of this material for the Second Progress Report occurred prior to January 23, 1962. The 73 virgin specimen tests described herein were conducted on the same material during August, 1963, a period of at least 18 and probably more than 20 months later. If stretcher straightening is responsible for the higher values occurring in later tests, then the increase from 37.0 to 39.9 ksi must be attributed to aging. Note also that no increase
occurred in the flats of the non-aging (CRK16-38.3) 16 gage press braked hat, Fig. 41, while increases occurred in the flats of all of the materials which exhibit the property of aging. The curves for yield strength versus prestrain of the unidirectionally pre-strained flats given in the First and Second Progress Reports showed larger increases due to aging for low values of prestrain than for high values of prestrain. The plastic prestrain caused by stretcher-straightening is low compared to that occurring in a corner and thus is probably the cause of large amounts of aging in those materials which age.

The behavior of the flat tension strip specimens from the roll formed track sections was markedly different from those from press braked hat sections from the moment they were cut from the members. Specimens cut from roll formed track sections at the A, G, K, and Q locations, Fig. 37, developed pronounced curvatures (with respect to the length of the specimens) which were concave toward the outside surface of the cross section. For example, specimen K-2 had a radius of curvature of 20.2 inches. Specimens from the H and J locations were curved, but not quite so much as the A, G, K, and Q specimens. Curvatures for the remaining specimens were negligible. Inspection of the outside surface of specimens from the A, G, K and Q locations showed a narrow band lengthwise along each specimen were the mill scale was partially removed by the rolls as the forming took place. No decrease in thickness as measured by means of a micrometer was observed in these locations. The shape of the stress strain curves for the A, G, H, J,
K, and Q specimens was unusual, as if each of these specimens were made from two sharp yielding materials, one of which had a higher yield strength than the other. In other words, these stress strain curves could easily be idealized (up to the strain hardening region) by three straight lines, the first line having a normal modulus of elasticity for steel (i.e., about 29.5 x 10^6 psi) up to a point somewhat less than the virgin yield strength, the second line having a considerably smaller slope or modulus, and, finally, a third (horizontal) line with a zero modulus, Fig. 57. It can be seen from Fig. 51 that the yield strength of the H and J specimens was not much larger than the virgin yield strength of the material, but that the yield strengths of the A, G, K, and Q specimens were significantly larger. This indicates that the pressure of the rolls on the material may change the shape of the stress strain curve of the material in addition to increasing the yield strength, or it may simply change the shape of the stress strain curve without increasing the yield strength. While some of the thin strip specimens taken from the 10 gage roll formed channel did exhibit curvatures (in the direction of the length of the specimens), none of them had stress strain curves with the peculiar shape shown on Fig. 57.

The third factor does not appear to have a significant influence in the case of the press braked hat sections. The tensile specimens taken without a scarf from right next to the corners (a/t = 1.06) of the press braked hat sections of Figs. 41 and 45 were evidently not affected by any such extension of
plastic strains. Compare the yield strength values of the flat specimens from locations next to corners for the roll formed track section of Fig. 51 and for the roll formed channel of Fig. 58. The increases in yield strength in these specimens are significantly above those of specimens located farther from the corners. Thus it may be inferred that the transition zone for extension of plastic strains into the adjacent flats is not appreciable for any of the three forming methods under consideration. Rather, the increases in yield strength observed in the adjacent flats of coin press braked corners and of roll formed corners is more likely due to the higher normal pressure present in these processes than in the air press braking process. Figs. 33 and 34, typical tensile and compressive stress strain curves for flat specimens taken from locations adjacent to corners were repeated from the Third Progress Report because they show a tendency for the yield strength of flats fairly distant from the corner to continue increasing with decreasing a/t ratio. This tendency surely cannot be attributed to the extension of corner plastic strain effects this far from the corner, because in the making of these specimens a scarf distance of approximately 1/8" (see Fig. 14) was left between the corner edge and the edge of the flat specimen. An additional 0.095 inch was cut out on the tensile specimens to allow for the standard shoulder (wider area at the grips).

It seems evident that as the flat portions of a cold formed member pass from station to station in a rolling mill, some of
them will be warped and plastic shearing strains will be present. For example, in the roll formed track section of Fig. 35, the two longest sides were probably subjected to shearing strains, and the 1 7/8 inches side probably was not, because of symmetry. The yield strength values of specimens C, D, E, M, N, and O would tend to indicate that these shearing strains do not contribute large increases in yield strength, since these values are about the same as those for the flats of the press braked hat section of Fig. 45.

The Levy-Mises Eqs. (1) used previously in the model for plastic deformation of a corner are valid only in cases where plastic deformations are so large that elastic deformations are negligible. The more general equations of Prandtl and Reuss include the effects of elastic and plastic strain components. Thus in the flats where plastic strains are much smaller than in the corners, any elastic strains present must be considered in an analysis of strain hardening.

Of the five factors listed above as possibly contributing to strain hardening and aging in the flats of cold formed members the first two are probably the most significant. The increase in yield strength due to factor (1), stretcher-straightening of stored materials, is assumed to be fairly uniform throughout the flats, both for roll formed and for press braked members. To determine the magnitude of such increases is a simple matter requiring only a few representative standard tensile tests from the central regions of flat portions of cold formed members. Factor (2), normal pressure on the flats, as caused by roll forming
may be the cause of increases in yield strength at locations immediately adjacent to corners or at random locations remote from corners. However, since increases in yield strength due to this factor are dependent on roll design, adjustments made by the rolling mill operator, wear on the rolls, etc., there is little likelihood that accurate predictions of them can be made prior to the rolling of a particular member.

IX. VARIATION OF COMPRESSIVE YIELD STRENGTH IN FLATS OF COLD FORMED SECTIONS

These tests were conducted to determine how cold forming changes the compressive mechanical properties of the flats of members made from three of the test steels. The approach was similar to that used in investigating the changes in tensile mechanical properties (Section VIII).

A. Test Procedure

Flat rectangular compressive specimens 0.57" x 3.57" were cut from the cross section of the cold formed hat sections and specimens 0.50" x 3.00" from the 10 gage channel and 16 gage track sections, Fig. 40.

These flat specimens were tested in a steel jig to keep the specimen from buckling in the weak direction. The jig was long enough so that a microformer gage could be mounted on the protruding edges of the specimen. See Fig. 13(e) and (f) for illustration of these specimens and a jig. The assembled jig, specimen, and microformer gage were placed into the subpress shown on Fig. 15 in order to ensure maximum axiality of loading.
B. Discussion of Results

Figs. 42 and 46 show, respectively, the distribution of the compressive yield strength in the CRK16-38.3 and HRSK16-37.5 press braked hat sections. Figs. 52 and 59 show the distribution of the compressive yield strength in the roll formed track and channel sections. See Fig. 40 for location of the specimens in the cross sections. The general appearance of these curves is quite similar to that of their respective tensile counterparts. As is seen from Table 5, in the CRK16-38.3 hat section the average value of the compressive yield strength of flats is lower than the average tensile yield strength while in all other sections tested the average compressive yield strength was higher than average tensile yield strength of flats.

X. FULL SECTION TENSION TESTS

A. Test Procedure

Full section tension tests were performed by welding 1/4" plates to the sections in the neutral plane of the member, Figs. 35 and 36. In two tests (T1 and T3) the hat section was slotted and welded to the plate which made welding of the thin 16 gage material to the relatively heavy 1/4 inch plate a difficult process. In the second specimen for each of these two hat section materials and for all other specimens, the two end plates were slotted rather than the specimen. This made the welding easier and more reliable since the tendency to burn through a thin sheet is greater when welding along a cut edge than in an uncut location. It also had the advantage that welding across the ends of the 1/4
inch plates was unnecessary.

SR-4 electric wire type strain gages were mounted on each of these full section tensile specimens, Figs. 35 and 36. Strains were recorded by these gages as long as they could be read. Thereafter, strains were taken visually by means of a scale reading to the nearest hundredth of an inch in a six inch gage length.

B. Discussion of Results

With the arrangement of Fig. 35 it has been possible to carry tension tests of all of the full section tensile specimens to stresses beyond the yield point; in fact, most specimens could be taken to their ultimate load with necking down and fracture occurring near mid-length of the specimen. Specimens which did not fail in the central portion of the specimen (see Tables 6 and 7) were: hat specimens T1 and T3, Figs. 43 and 48, respectively, in which the specimens were slotted to fit around the pull plates rather than visa versa; track specimen T5, Fig. 53, in which interior welding to the pull plates was omitted since the interior lips of the track section interfered; and track specimen T6, Fig. 53 in which portions of the inside lip were cut away in order to complete the interior welding to the pull plates. Specimen T1 was rewelded and retested with success in attaining a failure in the central portion of the specimen length. The maximum stress (42.5 ksi.) obtained in specimen T1 in the first test when it tore at a weld was less than the ultimate strength (49.0 ksi.) obtained in the retest, when it failed near the mid-height of the specimen. The maximum stress (47.6 ksi.) obtained in specimen T3, which
failed by tearing at a weld, was less than the ultimate strength (51.1 ksi.) of specimen T4, which had a central failure. In specimen T5 testing was stopped shortly after the yielding process began because the pull plate sections bent out from the specimen and distorted it. The discontinuity which occurs between strains of 2 and 3 mils in specimen T6, Fig. 53 was probably caused by a similar distortion. However, the full section curve follows very closely the calculated composite curve (see below) up to a strain of 2.5 mils, indicating that the composite curve is a valid representation of the properties of the section.

To illustrate the performance of the various gages during a typical full section tension test (from HRSK16-37.5 gage hat specimen T4) the strains of gages #1 and #4 were plotted versus stress on Fig. 47. All five of the gages performed in a manner reasonably similar to each other up to approximately the point of virgin tensile yield strength. At this point gage 1 began to depart from the straight line of proportionality, i.e. gave a less steep curve, while gage 4 continued in a nearly straight line up to just below the yield point of the full section. The curve of gage 4 went up in a vertical line until it yielded, dropped back about one ksi. and then rose with a slightly decreasing strain until it reached a new high point at 43.0 ksi. At that stress the strain increased rapidly and began to catch up with that of gage 1. This indicates that the section behaved essentially in the manner to be expected of an axially loaded tensile specimen up to the point where yielding in some elements began. At this
point, because the local yielding evidently started first near the gage 1 side of the specimen, there existed an axial load and a superimposed bending moment on the remaining elastic section. Yielding then progressed across the section until, finally, all elements had yielded. At this time the section was again essentially completely in axial tension so that the strains quickly equalized. The magnitude of the differences in strains was quite large at some stages, e.g.

- At 42.8 ksi #1 was 10.7 mils and #4 was 1.3 mils
- 43.0 ksi #1 was 13.2 mils and #4 was 1.28 mils
- 43.0 ksi #1 was 16.1 mils and #4 was 2.5 mils
- 43.4 ksi #1 was 24.3 mils and #4 was 9.5 mils.

Composite stress strain curves (calculated from data from 112 thin strip tensile specimens) compared to full section tension test curves are shown on Figs. 44, 48, 53, 54, 60, and 61 for the CRK16-38.3 hat, HRSK16-37.5 hat, HRSK16-37.5 track and 10 gage HRSK16-37.0 channel sections. Composite stress strain curves were calculated by selecting convenient values of strain and calculating corresponding mean stresses from the stress strain curves of all the component corner and flat test specimens. This is rather a tedious procedure and would not be practical for routine use, but it did serve to give an excellent check on full section test values.

The experimental stress strain curves from the full section tests appear to be within a scatter range from the calculated composite stress strain curves defined by the variation which can be expected from specimen to specimen. It may, therefore, be said that this method of full section testing is satisfactory in
obtaining the shape of the stress strain curve and the tensile yield point of the section. The small accidental eccentricities which are present in the elastic range will have no serious effect on determining the correct overall yield point since the material being used is ductile. There is no guarantee that any given specimen will not fail prematurely at the end zones which may have been weakened by the welding. The more cold worked material a specimen has, the more liable it is to be weakened by the welding of the end plates. However, the ultimate strength will be attainable for quite a variety of cold formed shapes by this or similar full section testing methods.

The full section tension stress strain curves for specimens T3 and T4, 16 gage HRSK16-37.5 hat sections, Fig. 48, were more sharp yielding than the calculated composite curves, even though the latter could be considered sharp yielding in and of themselves. This phenomenon of sharp yielding and even of an upper yield point in the full section may at first appear somewhat surprising when one considers that the member consists of elements of widely varying yield strengths. Inasmuch as these full section tension stress strain curves were definitely of the sharp yielding type, it may be concluded that the combined effect of the variation of yield strength of the cold worked material and of residual stresses on the shape of the full section stress strain curve is negligible in press braked hat sections of the type used in this investigation. This does not mean that the resulting curve is simply a virgin curve because the yield plateau is 5.0 ksi or 13.3% above the
virgin yield plateau at 37.5 ksi. For the 16 gage roll formed track section, Figs. 53 and 54, and the 10 gage roll formed channel sections, Figs. 60 - 62, both the calculated composite and the full section stress strain curves are more gradual yielding than those of the above discussed press braked hat sections. Since this is the same sheet subjected to a different forming process, it is evident that the combined effect of the variation of the yield strength of the cold worked material and of residual stresses does affect the shape of the stress strain curve in this roll formed section.

For the CRK16-38.3 press braked hat the percent elongation was 50%, and for the HRSK10-37.0 roll formed channel it was 26%, showing that the section having the largest increase in yield strength had less ductility.

XI. FULL SECTION COMPRESSION TESTS

A. Test Procedure

The first series of full section compression tests was accomplished by casting approximately 8 inch lengths (except as noted differently in Tables 6 and 7) of the sections in hydrostone within 7 1/2" lengths of 4 inch diameter pipes, Fig. 38. The purpose of the hydrostone was to limit local bending of flat portions of the section and to prevent local buckling. SR-4 wire type electric strain gages were mounted on each specimen as shown by the short dark lines next to the cross sections of Fig. 39(a).

Before casting these specimens in the hydrostone, the gages were coated with "Petrosene" wax for waterproofing. To protect
them from damage, the waterproofed gages were covered with 7 1/2" long sections of metal tubing split longitudinally. This assembly was again waterproofed with "Fetrosene" wax. The specimens were then greased and wrapped in aluminum foil so that they could slide longitudinally within the hydrostone.

The ends of the specimens were milled to a plane surface after the hydrostone had hardened. The milled ends of the specimens were placed against 1 1/2" thick milled bearing plates which were, in turn, seated against the head and table of the testing machine with hydrostone, Fig. 38. The hydrostone was allowed to harden for approximately one hour before each test. The spherical-seated compression head was fixed with three shims to insure that it did not rotate during testing. In the second series of full section compression tests two tests without lateral support were performed for each of the sections shown on Fig. 39(b). These tests were conducted in the same manner as shown on Fig. 38, except that the hydrostone surrounding the specimen and the 4" diameter tubes were omitted. Lengths of these specimens are shown on Table 8.

In addition, specimen C9A, cast in hydrostone, had plates welded across both ends to check the influence of welding in the full section compression test procedure.

When the described test procedure is carefully followed, strain increments in the elastic domain as given by the various strain gages are nearly equalized from the beginning of the test, which is very desirable even if not always attainable.

B. Discussion of Results

Results of full section compressive stress strain curves
compared to calculated composite stress strain curves are shown on Figs. 44, 49, 50, 55, 56, 63 and 64 for sections shown on Fig. 39(a). These sections were tested with hydrostone lateral support. Full section compression stress strain curves for the press braked lipped angle and hat sections (tested with hydrostone lateral support) are shown on Figs. 67 and 70.

The full section compression stress strain curves for the HRSK16-37.5 hat section, Fig. 49, show that the same general shape characteristics are obtained in compression as in tension. This is true, in general, for all of the sections tested. Specimen C4 even exhibits an upper and lower yield point. From data tabulated in Tables 6, 7, and 8 it is seen that in the inelastic range the compressive full section stress strain curves were above the tensile curves for all the sections tested except the CRK16-38.3 hat sections. The full section yield strengths for the CRK16-38.3 press braked hat sections of Fig. 35 averaged only 4.5% lower in compression than in tension, and those of Fig. 36 averaged 3.1% lower in compression than in tension.

Specimen C9, Fig. 66, which was from the same roll formed 10 gage channel member as specimens C7 and C8 and was tested without the usual hydrostone lateral support, had an L/r ratio of 9.2 and a Q of 1 as computed in accordance with Section 3.6.1 of the AISI Specification for the Design of Light Gage Cold-Formed Steel Structural Members, 1962 Edition. This unsupported specimen yielded at a value which was 11 percent below the average for the supported specimens C7 and C8. The two simple lips
appeared to have buckled locally during the testing. It was felt that additional tests of this type should be conducted to determine if this lower compressive yield strength represented a general trend or simply an isolated case. Therefore, similar full section compressive tests without lateral support were performed on one identical 10 gage roll formed channel section (specimen C16, Fig. 66) and two tests each on three different 16 gage press braked sections, a hot rolled lipped angle section (C10 and C11, Fig. 68), a hot rolled channel section (C12 and C13, Fig. 69), and a cold reduced hat section (C14 and C15, Fig. 71). All the sections chosen for these tests were picked so that Q for each section was equal or very close to one.

The results of these tests are compared to the results of laterally supported compressive full section tests on Table 8 for all of the sections shown on Fig. 39(b) except the 16 gage channel. Both unsupported HRSK10-37.0 roll formed channel specimens C9 and C16 yielded at a stress of 49.1 ksi or 11.5% below supported specimens C7 and C8. Both unsupported hot rolled 16 gage lipped angle specimens C10 and C11 yielded at 44.7 ksi or 6.1% below supported specimens C19 and C20. On the other hand, unsupported CRK16-38.3 hat section specimens C14 and C15 yielded at an average stress of 1.3% above supported specimens C17 and C18. The compressive yield strengths of the laterally unsupported compression specimens are all above the full section tensile yield strengths for specimens made from hot rolled, or aging sheet steels, and slightly below for specimens made from the cold
reduced killed material.

Local buckling was observed in all of the laterally unsupported compressive specimens C9 through C16. This local buckling became visible at or slightly before yielding occurred in each of these specimens. The most severe waving was in the simple lips and was roughly symmetrical about the axis of symmetry for all of the sections except the lipped angle sections C10 and C11. These latter specimens had the appearance of a torsional failure, i.e. both flanges buckled in the same direction rather than in opposing directions as in the hat and channel sections.

By a close inspection of Figs. 68, 69, and 71 it may be seen that the stress strain curves of all of the 16 gage unsupported full section compression specimens reached a maximum load at a much smaller strain (i.e. at a strain of between 3 and $5 \times 10^{-3}$ in./in.) than the unsupported 10 gage channel specimen C16 which reached its maximum stress at a strain of approximately $30 \times 10^{-3}$ in./in. Thus the stress strain curves for the 16 gage unsupported specimens exhibit instability at low plastic strains while the curves for the unsupported channel specimens demonstrate stability at low values of plastic strain. This instability is apparently due to the occurrence of local plastic buckling in the elements of these unsupported specimens.

From Table 7 it may be seen that welding plates across the ends of compressive specimen C9A reduced its yield strength by about 7%. This is due to the annealing effect of the welding process in reducing the increases in strength which were caused
by the cold work of forming the section and possibly in reducing residual stresses.

XII. PREDICTION OF THE EFFECTS OF COLD WORKING

Significant increases in both the compressive and tensile yield strengths may occur due to cold working in both the corners and the flat portions of light gage cold formed steel members. The cumulative effects of these yield strength increases may be as high as 40% above the virgin yield strength of the as-rolled sheet steel. While the yield strength of cold formed corners will always be higher than that of any other portion of a cold formed member because of the extremely large plastic deformations which occur in these corners, it should be pointed out that for members with a relatively low ratio of corner area to total cross sectional area the total contribution to the increased yield strength of the member may be higher in the flat portions of the cross section than in the corners. The percentage of corner area is usually less than 25% and seldom, if ever, more than 50% of the total cross sectional area.

In this section a method for predicting full section tensile yield strength will be discussed which might be added in the AISI Specification as an alternative to full section testing as presently stipulated. Predictions of full section properties will be made for a selection of cold formed cross sections in which the cross sectional area of the corners varies from approximately 5 to 50%. This will illustrate the relative increases in the tensile yield strength which may be expected in some representative types of
cold formed members subjected to axial loading. No attempt is made to predict full section compressive properties because: (1) the method of predicting the yield strength of corners used earlier in this report, i.e. by Eq. (18), was based on basic material properties obtained from tensile tests and (2) the full section yield strength in compression is generally above that in tension. The only exceptions to this which were encountered in the testing described herein were for sections cold formed from the cold reduced killed or "non-aging" steel. The full section yield strengths for the CRK16-38.3 press braked hats averaged not more than 4.5% lower in compression than in tension. Consequently, it appears that the use of the tensile in lieu of the compressive full section yield strength would be conservative in most cases and very close in those cases where the compressive is smaller than the tensile yield strength. By this it is not intended that the use of either compressive or tensile full section tests as presently allowed by the AISI Specification be ruled out; it is simply intended that in the absence of full section tests the tensile full section yield strength may be predicted by the method restated below.

In attempting to make predictions of the mechanical properties of cold formed light gage members, the properties of the corner will first be calculated by the method of Eq. (18). This will be followed by a treatment of the properties of the flats.

The tensile yield strength of corners can be conservatively and adequately predicted by

\[ \sigma_{yc} = \frac{kb}{(a/t)^m} \]  

(18)
or graphically by Fig. 16 where

\[ \sigma_{yc} = \text{the predicted corner tensile yield strength in ksi}, \]
\[ k = \text{the strength coefficient of the material in ksi}, \]
\[ \alpha/t = \text{the inside radius to thickness ratio of the corner}, \]

where \( b \) and \( m \) are linear functions of \( n \), the strain hardening exponent, as given by

\[ b = 0.945 - 1.315n \tag{18a} \]
\[ m = 0.803n \tag{18b} \]

The values of \( n \) and \( k \) may be determined experimentally from true stress strain curves of representative tension specimens tested in the plastic range. To establish these constants for a coil of material at least 8 tension specimens should be taken from the sheet, half of these from the first and half from the last end of the sheet or strip. These specimens should be taken from locations distributed across the full width of the sheet and not all along one edge. Alternatively, the constants \( k \) and \( n \) may be approximated by

\[ k = 2.62 \sigma_u - 1.33 \sigma_y \tag{13a} \]
\[ n = 0.30 \sigma_u / \sigma_y - 0.22 \tag{13b} \]

if representative values of the virgin tensile yield strength \( \sigma_y \) and of the virgin ultimate strength \( \sigma_u \) are used.

It was stated earlier in this report that the two factors which are probably most significant in increasing the yield strength of the flat portions of cold formed members are: (1) the strain hardening and aging resulting from the stretcher straightening of stored coiled sheet stock and (2) the normal pressure of
the rolls on the flats which occurs during roll forming operations. If no tests are made on flats taken from members then any increase from these factors should be neglected and the virgin yield strength value used for the flats. Should it be desired to utilize increases in yield strength in the flats as well as in the corners, then \( \sigma_{yf} \), the representative value of tensile yield strength of the flats, may be determined from standard tensile specimens (Fig. 13(c)) taken from the flats of a length of the cold formed member. The exact number of such specimens will depend on the shape of the cross section of the member, i.e. on the number of flats in the cross section. No less than one tension coupon should be taken from each flat, and if only one is taken from each flat it shall be taken from the middle of the flat. More coupons may be taken from each flat if desired. This may be of some advantage in roll formed sections where the yield strength of flats is not as uniform as in press braked sections. \( \sigma_{yf} \) may be obtained from the coupon yield strengths by summing the product for each flat of the average yield strength for that flat by the ratio of the area in that flat to the total area of flats in the cross section. In other words, \( \sigma_{yf} \) is the weighted average of the coupon yield strengths. With \( \sigma_{yf} \) computed, the full section tensile yield strength of the section is given by

\[
\sigma_{ys} = C \sigma_{yc} + (1-C) \sigma_{yf}
\]  

(26)

where \( C \) is the ratio of corner area to total cross section area.

The simple weighted averaging of yield strengths in Eq. 26 is not an exact procedure, but for sharp yielding materials the error
introduced will be practically nil and for gradual yielding materials the error from this source will be quite small. A simple computation illustrates that the tensile yield strength of the full section can be approximated in a member made from a sharp yielding material such as the HRSK16-37.5 press braked hat from the weighted arithmetic mean of the yield strength of its components:

\[
\begin{align*}
39.7 \times 0.92 &= 36.5 \\
65.8 \times 0.08 &= 5.3 \\
&= 41.8 \text{ ksi}
\end{align*}
\]

where .92 and .08 are the ratios of flat and corner areas to total cross sectional area, respectively. This compares well with the average tensile yield strength, 42.5 ksi, of the two full section tests performed on this member. A similar computation for ultimate strength of this member is:

\[
\begin{align*}
49.5 \times 0.92 &= 46.0 \\
69.5 \times 0.08 &= 5.0 \\
&= 51.0 \text{ ksi}
\end{align*}
\]

This compares favorably with that of 51.1 ksi obtained for one of the HRSK16-37.5 press braked hat full section tension tests. These results serve to demonstrate the accuracy of this approximate method.

The nine sections which have been chosen for illustrative purposes are: (1) the sections which have been tested in full section tension and compression tests as shown on Figs. 35 and 39(a), (2) a 16 gage roll formed channel in HRSK16-37.5 steel,
(3) a 16 gage press braked C-section in HRSK16-37.5 steel,
(4) an Armco roll formed joist chord, (all on Fig. 72) and (5) two commercial sections with an unusual number of corners and an intricately roll formed cross section, Fig. 73.

Section (2) above is on hand at Cornell, but no full section tests have been performed on it. The Armco Joist Chord was tested both in full section tension and compression and reported upon in reference 6. The report listed the following chemical analysis of the steel: Carbon 0.21%, Manganese 0.62%, Phosphorus 0.016%, Sulphur 0.020%, and Silicon 0.04%. On the commercial sections, (5) above, full section compression and tension tests were made at Cornell. Thus values obtained from full section tests and composite stress strain curves are available for comparison with the predicted values for a good number of these sections.

Predicted values (along with test values, where available) of the tensile full section yield strength for each of the nine sections are tabulated on Table 9. Column (6) is the ratio of corner area to the total cross sectional area of the member. Column (7), the "Calculated Tensile Corner Yield Strength $\sigma_{yc}$," was computed using Eqs. (18), (18a), and (18b). The material constants k and n for use in these equations were calculated from equations (13a) and (13b). Column (8), the "Average Flat Tensile Yield Strength $\sigma_{yt}$," is the weighted average from tensile test specimens taken from the flats of the cold formed members unless noted otherwise. Column (9), the "Calculated Tensile Full Section Yield Strength $\sigma_{ys}$," was computed from Eq. (26). The predicted values of Column (9) agree quite well with those obtained from the
full section tension tests of Column (10). By comparing the compressive (Column (11)) with the tensile (Column (10)) full section test yield strengths it can be seen that assuming the compressive yield strength to be equal to the tensile yield strength for full sections is conservative and reasonable for all materials except the non-aging CRK16-38.3 steel. Even in this case the compressive yield strength is not significantly smaller than the tensile yield strength.

XIII. SUMMARY AND CONCLUSIONS

A. Gains in both the compressive and tensile yield strengths due to the cold work of forming in light gage steel members are impressive, being as much as 40% in some members. The largest increases in yield strength occur in the corners of the cross section, the yield strength after cold working being considerably higher than the original ultimate strength of the material for corners with low a/t ratios. The increase in yield strength in the flat portions of cross section is much smaller; e.g. the largest tensile increase for flats found in this investigation was 22% for the flats of the roll formed HRSK10-37.0 channel section. The smallest increase in the tensile yield strength of flats of a hot rolled material was 6% for the press braked HRSK16-37.5 hat section. The tensile yield strength in the flats of the press braked CRK16-38.3 hat section was 1% below the virgin value. Thus, the so called compact sections or sections with a large ratio of corner area to total cross sectional area will have the largest increases in yield strength. However, in members with a
low ratio of corner area to total cross sectional area the total contribution to the increased yield strength of the member may be higher in the flat portions of the cross section than in the corners. The percentage of corner area is usually less than 25% and seldom, if ever, more than 50% of the total cross sectional area.

B. Results from specimens which were prestrained in uniaxial tension to permanent prestrains of 10, 25, 50, and 100 mils, aged, and tested transverse to and in the direction of prestrain were given in the First and Second Progress Reports. By plotting the logarithm of the yield strength expressed as true stress versus the logarithm of the permanent prestrain expressed as true plastic strain for these specimens, it was found that a straight line could be fitted to the data, establishing the relationship

\[ \sigma' = k (\bar{\varepsilon})^n \]  

where

\( \sigma' \) = the true stress in the inelastic range,
\( \bar{\varepsilon} \) = the effective strain = the natural strain for a simple tension specimen in the inelastic range,
\( k \) = the strength coefficient, and
\( n \) = the strain hardening exponent.

Values of k and n were established from the tests of the First and Second Progress Reports and also for single virgin tensile specimens carried into the plastic range. Values of n varied from 0.13 to 0.24 and values of k varied from 70 to 115 ksi for these virgin specimens.
C. The tensile corner yield strength can be conservatively and adequately predicted from the equation
\[ C_{yc} = \frac{kb}{(a/t)^m} \]  
(18)
or graphically by Fig. 16 where
\[ C_{yc} = \text{the predicted corner tensile yield strength in ksi,} \]
\[ k = \text{the strength coefficient of the material in ksi,} \]
\[ a/t = \text{the inside radius to thickness ratio of the corner,} \]
and where \( b \) and \( m \) are linear functions of \( n \), the strain hardening exponent, as given by
\[ b = 0.945 - 1.315n \]  
(18a)
and
\[ m = 0.803n \]  
(18b)
The values of \( n \) and \( k \) may be determined experimentally from true stress strain curves (such as Fig. 10) of representative tension specimens tested in the plastic range. To establish these constants for a coil of material at least 8 tension specimens should be taken from the sheet, half of these from the first and half from the last end of the sheet or strip. These specimens should be taken from locations distributed across the full width of the sheet and not all from along one edge. Alternatively, the material constants \( k \) and \( n \) may be approximated by
\[ k = 2.62 \sqrt[3]{u} - 1.33 \sqrt[y]{y} \]  
(13a)
and
\[ n = 0.30 \sqrt[3]{u} / \sqrt[y]{y} - 0.22 \]  
(13b)
if representative values of the virgin tensile yield strength \( \sqrt[y]{y} \) and of the virgin ultimate strength \( \sqrt[3]{u} \) are used.

Eq. (18) is an empirical equation closely approximating Eq. (17) which was evaluated numerically by Simpson's rule, since a
closed form of the integral in Eq. (17) was not found. Eq. (17) was based upon the use of a model which consists of a wide plate subject to purely flexural loads as shown on Fig. 4. In this purely flexurally loaded model it was assumed that a condition of plane strain exists when a corner is formed, i.e. that the strain in the corner in the longitudinal or z direction is negligible because of the restraint imposed on the corner by the adjacent undeformed flats. It was further assumed, using this plane strain condition and the volume constancy concept for large plastic deformations, that the natural strain in the circumferential direction is equal in magnitude and opposite in sign to the natural strain in the radial direction. From this assumption it was concluded that there will be no Bauschinger effect in volume elements taken from such a corner and tested in the longitudinal direction. This conclusion is verified by tests. Using the concept of "effective strain" given by Eq. (10), Eq. (13) was applied to a volume element and integrated over the area of the corner model to obtain Eq. (17). (No correlation was achieved by using values of k and n obtained from the data from uniaxially prestrained specimens. It would be somewhat surprising if such a correlation had been obtained, since uniaxially prestrained specimens exhibited Bauschinger effects and specimens from corners have been demonstrated to be free of the Bauschinger effect.)

D. In order to study the plastic distortions occurring during the various kinds of cold forming operations photogrids
of 200 lines per inch were applied to the surfaces of sheets before cold forming them into corners. From this study it was found that:

(1) Plane sections (in the radial direction) before bending do appear to remain plane.

(2) There is apparently more strain on the outside of a corner than would be predicted from the pure flexural model. There is an inside radial pressure present in all three types of cold forming operations studied; air press braking, coin press braking, and roll forming. Therefore, the second finding above indicates that the presence of an inside radial pressure does tend to shift the axis of zero strain toward the inside of the corner as theory would predict.

E. The exact amount of radial pressure present for any of the three forming methods is not known. Therefore, a second model was considered in which it was arbitrarily assumed that the axis of zero strain is at $r_o = \sqrt{ab}$. This was done to see, qualitatively rather than quantitatively, what the effect of an outward radial pressure (on the inside radius of a corner) in combination with plastic bending would be. Eq. (23) was derived for this model in a similar way to the development of Eq. (18) for the pure flexural model. It was found that for $a/t$ ratios greater than about 5 there was very little difference in the results obtained by the two methods. However, for smaller $a/t$ ratios, the yield strengths predicted by the second model were up to 9% larger than those predicted by the pure flexural model. The theoretical $\sigma_{yc}$ versus
a/t curves of the second model correlated better than those of the pure flexural model for less than about half of the eight materials tested. Therefore, to be on the conservative side it is recommended that Eq. (18), based on the pure flexural model, be used rather than Eq. (23), based on the model including the effect of an arbitrary radial pressure.

F. In regard to flats press braking produced small percentage increases in the average tensile and compressive yield strengths, the maximum average value being 6%, Table 5, for the tensile yield strength of the 16 gage HRSK hat. The roll forming process brought about considerably higher percentage increases in average tensile yield strength of flats, up to 22% for the 10 gage roll-formed HRSK channel. Increases above virgin ultimate strengths of flats due to cold forming by either process were smaller than the increases in the yield strength of flats. The main increases in yield strengths in the flats were attributed to:

(1) the strain hardening and aging resulting from stretcher straightening of sheets stored as coils and
(2) the normal pressures present in the coin press braking and roll forming operations.

For practical purposes, the only factor which contributes significantly to the increase in yield strength of the flats of either air or coin press braked members is the first factor stated above. No increase in yield strength was observed in the flats next to air press braked corners. It was found that the increase in yield strength drops off very close to a coin press braked corner, i.e. within less than a thickness on each side of the
corner. Both factors (1) and (2) contribute to the increase in yield strength of flats of rolled formed members. In either case, if it is desired to utilize the increases in yield strength occurring in the flats, the uncertainties connected with predicting such increases dictate that they be determined experimentally by specimens taken from cold formed members.

G. The average full section test results are summarized from Tables 6 and 7, using the 0.2% offset method for determination of yield strength values, as follows:

<table>
<thead>
<tr>
<th></th>
<th>Press Braked ksi</th>
<th>%</th>
<th>Roll Formed ksi</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Tensile yield strength</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. 16 gage CRK16-38.3 hat</td>
<td>39.5</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. 16 gage HRSK16-37.5 hat</td>
<td>42.1</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. 16 gage HRSK16-37.5 track</td>
<td>46.6</td>
<td>24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d. 10 gage HRSK10-37.0 channel</td>
<td>48.3</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2. Compressive yield strength (laterally supported)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. 16 gage CRK16-38.3 hat</td>
<td>37.5</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. 16 gage HRSK16-37.5 hat</td>
<td>44.9</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. 16 gage HRSK16-37.5 track</td>
<td>51.0</td>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d. 10 gage HRSK10-37.0 channel</td>
<td>55.4</td>
<td>44</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>3. Ultimate strength</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. 16 gage CRK16-38.3 hat</td>
<td>48.8</td>
<td>-5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. 16 gage HRSK16-37.5 hat</td>
<td>51.1</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. 16 gage HRSK16-37.5 track</td>
<td>-----</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d. 10 gage HRSK10-37.0 channel</td>
<td>59.2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: % indicates percentage change from the virgin yield or ultimate strength, as appropriate.

Thus it can be seen that the full section compressive yield strengths were higher than the full section tensile yield strengths for all the sections except the press braked CRK16-38.3 gage hat section. Increases above virgin values in both the full section tensile and
full section compressive yield strengths were higher for the roll formed sections than for the press braked sections tested. Percentage increases in the full section ultimate strength values above virgin values were much smaller than percentage increases in either the tensile or the compressive yield strengths.

For the CRK16-38.3 press braked hat the percent elongation was 50%, and for the HRSK10-37.0 roll formed channel it was 26%, showing that the section having the largest increase in yield strength had less ductility.

H. Full section compression tests without lateral support were conducted on a HRSK10-37.0 roll formed channel section, and on four press braked 16 gage sections: a cold reduced killed hat, a hot rolled channel, and a hot rolled lipped angle, Fig. 39(b). The value of Q (as defined by the AISI Specification) for each of these sections was 1.0 or nearly so. The yield strengths obtained from laterally unsupported full section compression tests varied from practically the same as the yield strength for the full section compression tests laterally supported with hydrostone for the CRK16-38.3 press braked hat to 11.5% below for the HRSK10-37.0 roll formed channel. The compressive yield strength for each such specimen tested was greater (except for the cold reduced killed material in the press braked hat section) than the yield strength of companion full section tensile specimens. Local plastic buckling which began at about the load at which yielding occurred was observed in all of the laterally unsupported specimens. The stress strain curves of the 16 gage unsupported speci-
mens reached a maximum load at a plastic strain of from 3 to $5 \times 10^{-3}$ in./in., while a 10 gage unsupported channel specimen did not attain the maximum stress until a strain of $30 \times 10^{-3}$ in./in. had been reached. Thus the 16 gage unsupported specimens exhibited instability at small plastic strains while the 10 gage unsupported specimens demonstrated instability at large plastic strains. This instability is evidently due to the occurrence of local plastic buckling in the elements of these unsupported specimens.

I. Welding decreased the full section compressive yield strength of specimen C9A to 51.7 ksi, 7% below the average yield strength of specimens C7 and C8 on which no welding was done.

J. It was found that composite stress-strain curves calculated from the stress-strain curves of strip specimens from the flats plus those of corner specimens matched the stress strain curves of full section test specimens quite well, both for tension and compression. From such calculated composite stress-strain curves, yield strengths, proportional limits and other mechanical properties may be determined without testing a full section, should this prove necessary or advantageous. It was found that simple weighted averages (as illustrated by examples on page 56) of the yield strengths of component parts will give the yield strength of a full section with sufficient accuracy for most purposes. (The fact that the stress-strain curves for full section testing were in close agreement with the calculated composite stress strain curves implies that the longitudinal residual shearing stresses which are released by the cutting of strip specimens are not of sufficient
net value to have a significant direct effect upon the mechanical properties of the full section.)

K. For sections with a low percentage of corner area, the full section stress strain curves may be sharp yielding even though the yield strength of corners is significantly greater than that of the flats. For example, see Figs. 48 and 49, the full section stress strain curves for the 16 gage HRSK16-37.5 hat. However, both the tensile and compressive full section stress strain curves for the roll formed sections were gradual yielding.

L. It is proposed that an alternate procedure to full section tension testing as presently required by the AISI Specification be provided. The proposed procedure consists in (1) predicting the corner yield strength by means of Eq. (18) with values for k, the strength coefficient, and n, the strain hardening exponent, being determined from simple tension tests on virgin specimens in one of the two ways described above in Conclusion C (Section XIII.C). (2) If desired, the virgin yield strength may be used for the flat portions of the cross section. However, should it be desired to utilize increases in yield strength in the flats as well as in the corners, then the value of $\sigma_{yf}$, the representative yield strength of the flats, is to be determined from standard tensile specimens taken from the flats of a length of the cold formed member. The exact number of such specimens will depend on the shape of the cross section of the member, i.e. on the number of flats in the cross section. No less than one tension coupon should be taken from each flat, and if only one is taken from each flat is shall
be taken from the middle of the flat. More coupons may be taken from each flat if desired. This may be of advantage in roll formed sections where the yield strength of flats is not as uniform as in press braked sections. $\bar{\sigma}_{yf}$ is the weighted average of the coupon yield strengths. (3) With $\bar{\sigma}_{yf}$ and $\bar{\sigma}_{yc}$ computed, the full section tensile yield strength of the section is calculated from

$$\bar{\sigma}_{ys} = C \bar{\sigma}_{yc} + (1-C) \bar{\sigma}_{yf} \quad (26)$$

where $C$ is the ratio of corner area to total cross sectional area. Percentage increases by the full section test method and by this method are tabulated for comparison on Table 9 for a variety of cross sectional shapes.

M. For all materials except the CRK16-38.3 steel it was found that the compressive yield strength was somewhat higher than the tensile yield strength in corners, in flats, and in laterally supported full sections. Since this was also true for laterally unsupported full section compression tests, it is proposed that the tensile yield strength be adopted for design purposes. By this it is not intended that the use of either compressive or tensile full section tests as presently allowed by the AISI Specification be ruled out; it is simply intended that in the absence of full section tests the tensile full section yield strength may be predicted by the method outlined above, and that the use of this tensile strength for all design purposes is reasonable.
REFERENCES


<table>
<thead>
<tr>
<th>Material Description</th>
<th>Gage</th>
<th>Chemical Composition by Random Check Analysis</th>
<th>Compr. Yield Strength ksi</th>
<th>Tensile Properties</th>
<th>Ultimate Strength ksi</th>
<th>% Elong. in 2&quot; gage length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C Mn S P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Cold Reduced</td>
<td>16</td>
<td>.15 .40 .024 .008</td>
<td>34.6</td>
<td>38.3</td>
<td>51.1</td>
<td>40</td>
</tr>
<tr>
<td>Annealed, Tempered</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rolled, Killed, Sheet Coil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Cold Reduced</td>
<td>16</td>
<td>.09 .39 .028 .008</td>
<td>33.0</td>
<td>36.4</td>
<td>50.7</td>
<td>35</td>
</tr>
<tr>
<td>Annealed, Tempered</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rolled, Rimmed, Sheet Coil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Hot Rolled</td>
<td>16</td>
<td>.04 .32 .025 .008</td>
<td>40.5</td>
<td>37.5</td>
<td>49.0</td>
<td>37</td>
</tr>
<tr>
<td>Semi-Killed Sheet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Hot Rolled</td>
<td>16</td>
<td>.08 .32 .045 .008</td>
<td>40.3</td>
<td>40.5</td>
<td>50.7</td>
<td>35</td>
</tr>
<tr>
<td>Rimmed, Sheet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Hot Rolled</td>
<td>10</td>
<td>.18 .50 .029 .008</td>
<td>38.5</td>
<td>37.0</td>
<td>57.5</td>
<td>36</td>
</tr>
<tr>
<td>Semi-Killed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheet Coil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Hot Rolled</td>
<td>16</td>
<td>.16 .46 .024 .009</td>
<td>37.6</td>
<td>39.7</td>
<td>55.9</td>
<td>35</td>
</tr>
<tr>
<td>Semi-Killed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheet Coil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Hot Rolled</td>
<td>10</td>
<td>.22 .43 .024 .008</td>
<td>43.2</td>
<td>42.8</td>
<td>66.6</td>
<td>31</td>
</tr>
<tr>
<td>Semi-Killed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheet Coil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Hot Rolled</td>
<td>16</td>
<td>.23 .45 .025 .012</td>
<td>39.1</td>
<td>40.7</td>
<td>61.4</td>
<td>31</td>
</tr>
<tr>
<td>Semi-Killed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheet Coil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specimen Formed By</td>
<td>a</td>
<td>t</td>
<td>a/t</td>
<td>Strain Measured By Photogrid in./in.</td>
<td>Theoretical Strain in./in.</td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td>------</td>
<td>------</td>
<td>-----</td>
<td>-------------------------------------</td>
<td>---------------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>in.</td>
<td>in.</td>
<td></td>
<td>Inside Surface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bend Brake</td>
<td>.0782</td>
<td>.0575</td>
<td>1.32</td>
<td>.324</td>
<td>.275 .32</td>
<td></td>
</tr>
<tr>
<td>Air Press Brake</td>
<td>.125</td>
<td>.0575</td>
<td>2.18</td>
<td>.224</td>
<td>.187 .21</td>
<td></td>
</tr>
<tr>
<td>Air Press Brake</td>
<td>.125</td>
<td>.0575</td>
<td>2.18</td>
<td>.18</td>
<td>.187 .172</td>
<td></td>
</tr>
<tr>
<td>Air Press Brake</td>
<td>.1875</td>
<td>.0575</td>
<td>3.26</td>
<td>.133</td>
<td>.133 .125</td>
<td></td>
</tr>
</tbody>
</table>

Notes: Theoretical strain (1) is for axis of zero strain given by \( r_0 = \frac{1}{2} (a + b) \) where \( a \) = inside corner radius, \( b \) = outside corner radius, and \( r_0 \) = radius of axis of zero strain. Theoretical strain (2) is for the axis of zero strain arbitrarily assumed at \( r_0 = \sqrt{ab} \).
TABLE 3a

VALUES FOR THE STRENGTH COEFFICIENT k AND STRAIN HARDENING EXponent n FROM UNIAXIALLY PRESTRAINED TENSILE SPECIMENS

<table>
<thead>
<tr>
<th>Material</th>
<th>k</th>
<th>n</th>
<th>Type of Specimens*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ksi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. CRK16-38.3</td>
<td>68.6</td>
<td>.121</td>
<td>LT</td>
</tr>
<tr>
<td></td>
<td>55.2</td>
<td>.100</td>
<td>TT</td>
</tr>
<tr>
<td></td>
<td>42.7</td>
<td>.085</td>
<td>LC</td>
</tr>
<tr>
<td></td>
<td>84.5</td>
<td>.163</td>
<td>TC</td>
</tr>
<tr>
<td>2. CRR16-36.4</td>
<td>81.9</td>
<td>.133</td>
<td>LT</td>
</tr>
<tr>
<td></td>
<td>85.6</td>
<td>.173</td>
<td>TT</td>
</tr>
<tr>
<td></td>
<td>75.8</td>
<td>.164</td>
<td>LC</td>
</tr>
<tr>
<td></td>
<td>98.5</td>
<td>.192</td>
<td>TC</td>
</tr>
<tr>
<td>3. HRSK16-37.5</td>
<td>86.1</td>
<td>.152</td>
<td>LT</td>
</tr>
<tr>
<td></td>
<td>77.6</td>
<td>.135</td>
<td>TT</td>
</tr>
<tr>
<td></td>
<td>66.5</td>
<td>.102</td>
<td>LC</td>
</tr>
<tr>
<td></td>
<td>98.0</td>
<td>.198</td>
<td>TC</td>
</tr>
<tr>
<td>4. HRR16-40.5</td>
<td>64.8</td>
<td>.121</td>
<td>LT</td>
</tr>
<tr>
<td></td>
<td>79.5</td>
<td>.145</td>
<td>TT</td>
</tr>
<tr>
<td></td>
<td>71.6</td>
<td>.148</td>
<td>LC</td>
</tr>
<tr>
<td></td>
<td>88.1</td>
<td>.160</td>
<td>TC</td>
</tr>
<tr>
<td>5. HRSK10-37.0</td>
<td>127.5</td>
<td>.257</td>
<td>LT</td>
</tr>
<tr>
<td></td>
<td>93.1</td>
<td>.220</td>
<td>TT</td>
</tr>
<tr>
<td></td>
<td>73.7</td>
<td>.161</td>
<td>LC</td>
</tr>
<tr>
<td></td>
<td>109.5</td>
<td>.203</td>
<td>TC</td>
</tr>
</tbody>
</table>

* LT = tested in tension in direction of prestrain, TT = transverse tension, LC = longitudinal compression, and TC = transverse compression.
### TABLE 3b

VALUES FOR THE STRENGTH COEFFICIENT \( k \) AND STRAIN HARDENING EXponent \( n \) FROM VIRGIN TENSILE SPECIMENS

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Properties</th>
<th>( \sigma_u / \sigma_y )</th>
<th>( n )</th>
<th>( k )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yield Strength ( \sigma_y ) ksi</td>
<td>Ultimate Strength ( \sigma_u ) ksi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. CRK16-38.3</td>
<td>40.1 50.7</td>
<td>1.27</td>
<td>.149</td>
<td>77.7</td>
</tr>
<tr>
<td></td>
<td>40.7 51.0</td>
<td>1.25</td>
<td>.143</td>
<td>77.2</td>
</tr>
<tr>
<td></td>
<td>40.2 50.8</td>
<td>1.27</td>
<td>.155</td>
<td>78.8</td>
</tr>
<tr>
<td></td>
<td>37.0 45.7</td>
<td>1.24</td>
<td>.149</td>
<td>69.6*</td>
</tr>
<tr>
<td>2. CRR16-36.4</td>
<td>38.2 49.8</td>
<td>1.30</td>
<td>.149</td>
<td>76.3</td>
</tr>
<tr>
<td></td>
<td>38.9 50.3</td>
<td>1.29</td>
<td>.155</td>
<td>78.8</td>
</tr>
<tr>
<td></td>
<td>38.6 50.3</td>
<td>1.30</td>
<td>.143</td>
<td>76.2</td>
</tr>
<tr>
<td></td>
<td>37.8 51.4</td>
<td>1.36</td>
<td>.137</td>
<td>76.5*</td>
</tr>
<tr>
<td>3. HRSK16-37.5</td>
<td>40.3 49.8</td>
<td>1.23</td>
<td>.161</td>
<td>77.4</td>
</tr>
<tr>
<td></td>
<td>40.5 49.3</td>
<td>1.22</td>
<td>.158</td>
<td>76.8</td>
</tr>
<tr>
<td></td>
<td>41.0 50.8</td>
<td>1.24</td>
<td>.190</td>
<td>85.2*</td>
</tr>
<tr>
<td>4. HRR16-40.5</td>
<td>34.7 45.5</td>
<td>1.31</td>
<td>.195</td>
<td>75.2</td>
</tr>
<tr>
<td></td>
<td>33.7 45.3</td>
<td>1.34</td>
<td>.203</td>
<td>76.1</td>
</tr>
<tr>
<td></td>
<td>38.7 46.8</td>
<td>1.21</td>
<td>.152</td>
<td>71.7</td>
</tr>
<tr>
<td></td>
<td>41.5 51.5</td>
<td>1.24</td>
<td>.198</td>
<td>87.0*</td>
</tr>
<tr>
<td>5. HRSK10-37.0</td>
<td>39.1 58.1</td>
<td>1.49</td>
<td>.208</td>
<td>99.2</td>
</tr>
<tr>
<td></td>
<td>42.5 60.5</td>
<td>1.42</td>
<td>.197</td>
<td>101.5</td>
</tr>
<tr>
<td></td>
<td>42.7 60.2</td>
<td>1.41</td>
<td>.236</td>
<td>109.0</td>
</tr>
<tr>
<td></td>
<td>37.5 58.0</td>
<td>1.55</td>
<td>.228</td>
<td>101.7*</td>
</tr>
<tr>
<td>6. HRSK16-39.7</td>
<td>35.8 52.3</td>
<td>1.46</td>
<td>.210</td>
<td>90.1</td>
</tr>
<tr>
<td></td>
<td>35.8 52.0</td>
<td>1.45</td>
<td>.212</td>
<td>90.4</td>
</tr>
<tr>
<td></td>
<td>36.0 51.3</td>
<td>1.43</td>
<td>.201</td>
<td>86.7</td>
</tr>
<tr>
<td>7. HRSK10-42.8</td>
<td>41.4 65.0</td>
<td>1.57</td>
<td>.215</td>
<td>114.0</td>
</tr>
<tr>
<td></td>
<td>40.8 64.0</td>
<td>1.57</td>
<td>.212</td>
<td>111.0</td>
</tr>
<tr>
<td></td>
<td>45.2 66.1</td>
<td>1.46</td>
<td>.208</td>
<td>114.0</td>
</tr>
<tr>
<td>8. HRSK16-40.7</td>
<td>44.8 64.8</td>
<td>1.45</td>
<td>.208</td>
<td>111.2</td>
</tr>
<tr>
<td></td>
<td>45.3 65.5</td>
<td>1.45</td>
<td>.204</td>
<td>112.8</td>
</tr>
<tr>
<td></td>
<td>45.7 66.0</td>
<td>1.45</td>
<td>.199</td>
<td>110.9</td>
</tr>
</tbody>
</table>

*Computed from data given in the Second Progress Report, Feb. 1962, and from unpublished test data taken prior to that time.
<table>
<thead>
<tr>
<th>Specimen</th>
<th>Area (in²)</th>
<th>Cold Wkd</th>
<th>Virgin</th>
<th>Col 5</th>
<th>Increase</th>
<th>Ave. Dist.</th>
<th>σy</th>
<th>Force-</th>
</tr>
</thead>
<tbody>
<tr>
<td>CX2</td>
<td>0.0702</td>
<td>41.5</td>
<td>40.3</td>
<td>2.9</td>
<td>203</td>
<td>25.7</td>
<td>0.0228</td>
<td>65.2</td>
</tr>
<tr>
<td>CX6</td>
<td>0.0703</td>
<td>41.5</td>
<td>38.7</td>
<td>2.8</td>
<td>197</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CX3</td>
<td>0.0663</td>
<td>41.5</td>
<td>39.9</td>
<td>1.6</td>
<td>106</td>
<td>8.5</td>
<td>0.0621</td>
<td>47.9</td>
</tr>
<tr>
<td>CX7</td>
<td>0.0658</td>
<td>40.0</td>
<td>38.8</td>
<td>1.2</td>
<td>79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CX2</td>
<td>0.0613</td>
<td>40.4</td>
<td>39.2</td>
<td>1.2</td>
<td>74</td>
<td>6.6</td>
<td>0.0628</td>
<td>46.4</td>
</tr>
<tr>
<td>CX6</td>
<td>0.0613</td>
<td>40.8</td>
<td>40.3</td>
<td>0.5</td>
<td>31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CX3</td>
<td>0.0572</td>
<td>39.6</td>
<td>39.4</td>
<td>0.2</td>
<td>11</td>
<td>2.4</td>
<td>0.1111</td>
<td>42.5</td>
</tr>
<tr>
<td>CX7</td>
<td>0.0572</td>
<td>41.5</td>
<td>40.8</td>
<td>0.7</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CX2</td>
<td>0.0535</td>
<td>40.2</td>
<td>39.6</td>
<td>0.6</td>
<td>32</td>
<td>2.6</td>
<td>0.1397</td>
<td>42.0</td>
</tr>
<tr>
<td>CX6</td>
<td>0.0534</td>
<td>39.2</td>
<td>39.2</td>
<td>0.0</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CX3</td>
<td>0.0492</td>
<td>39.7</td>
<td>39.3</td>
<td>0.4</td>
<td>20</td>
<td>2.6</td>
<td>0.1709</td>
<td>41.8</td>
</tr>
<tr>
<td>CX7</td>
<td>0.0492</td>
<td>38.9</td>
<td>39.2</td>
<td>-0.3</td>
<td>-15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CX2</td>
<td>0.0448</td>
<td>38.8</td>
<td>39.0</td>
<td>-0.2</td>
<td>-9</td>
<td>1.3</td>
<td>0.1798</td>
<td>40.9</td>
</tr>
<tr>
<td>CX6</td>
<td>0.0447</td>
<td>40.1</td>
<td>40.2</td>
<td>-0.1</td>
<td>-4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CX3</td>
<td>0.0407</td>
<td>38.7</td>
<td>39.0</td>
<td>-0.3</td>
<td>-12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CX7</td>
<td>0.0405</td>
<td>40.3</td>
<td>40.3</td>
<td>-0.3</td>
<td>-12</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### TABLE 5

**AVERAGE TEST RESULTS IN FLAT PORTIONS OF SECTIONS**

<table>
<thead>
<tr>
<th>Gage</th>
<th>Mat'l</th>
<th>Forming</th>
<th>Shape</th>
<th>0.2% offset Yield Strength</th>
<th>Tensile Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Compressive</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Virgin (ksi)</td>
<td>Ave Flats (ksi)</td>
</tr>
<tr>
<td>16</td>
<td>CRK</td>
<td>Press Braked</td>
<td>Hat</td>
<td>34.6</td>
<td>36.0**</td>
</tr>
<tr>
<td>16</td>
<td>HRSK</td>
<td>Press Braked</td>
<td>Hat</td>
<td>40.5</td>
<td>42.2**</td>
</tr>
<tr>
<td>16</td>
<td>HRSK</td>
<td>Roll Formed</td>
<td>Track</td>
<td>40.5</td>
<td>47.3</td>
</tr>
<tr>
<td>10</td>
<td>HRSK</td>
<td>Roll Formed</td>
<td>Channel</td>
<td>38.5</td>
<td>47.4</td>
</tr>
</tbody>
</table>

* Does not include specimens H and C.

** Does not include specimens 1 and 9.
# TABLE 6

Test Results for Press Braked Sections

<table>
<thead>
<tr>
<th>Section Type</th>
<th>Spec. No.</th>
<th>Length (in.)</th>
<th>P/A @.5% Strain (ksi.)</th>
<th>P/A @ .2% Offset (ksi.)</th>
<th>Ave. % incr. above virgin y.s.</th>
<th>Tensile Strength (ksi.)</th>
<th>Ave. % incr. above virgin t.s.</th>
<th>Failure Location or Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 gage CRK hat</td>
<td>Tens. strips*</td>
<td>T3</td>
<td>30</td>
<td>41.0</td>
<td>39.6</td>
<td>3</td>
<td>49.0</td>
<td>Center failure in retest</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T2</td>
<td>30</td>
<td>40.5</td>
<td>39.3</td>
<td>5</td>
<td>48.7</td>
<td>Center failure</td>
</tr>
<tr>
<td></td>
<td>Compr. strips*</td>
<td>Cl</td>
<td>8</td>
<td>40.1</td>
<td>38.0</td>
<td>9</td>
<td></td>
<td>Used pasteboard tube rather than pipe (Cl only)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C2</td>
<td>8</td>
<td>41.4</td>
<td>38.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 gage HR/K hat</td>
<td>Tens. strips*</td>
<td>T3</td>
<td>30</td>
<td>42.5</td>
<td>42.5</td>
<td>12</td>
<td>47.6+</td>
<td>Tore at end weld</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T4</td>
<td>30</td>
<td>42.8</td>
<td>41.3**</td>
<td>4</td>
<td>51.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Compr. Strips*</td>
<td>C3A</td>
<td>4 3/8</td>
<td>45.6</td>
<td>45.1</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>C3B</td>
<td>4</td>
<td>44.2</td>
<td>44.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>C3</td>
<td>8</td>
<td>45.5</td>
<td>45.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>C4</td>
<td>8</td>
<td>45.0</td>
<td>44.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: T specimens are tensile.  
C specimens are laterally supported compressive  
* Calculated composite stress strain curve properties  
** Lower yield point rather than 0.2% offset point  
+ Maximum load < tensile strength
<table>
<thead>
<tr>
<th>Section Type</th>
<th>Spec. No.</th>
<th>Length (in.)</th>
<th>P/A @ .5% Strain (ksi.)</th>
<th>P/A @ .2% Offset (ksi.)</th>
<th>% incr. above virgin</th>
<th>Tensile Strength (ksi.)</th>
<th>% incr. above virgin</th>
<th>Failure Location or Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tens. Strips*</td>
<td>T5</td>
<td>30</td>
<td>46.1</td>
<td>46.0</td>
<td>24</td>
<td>45.3</td>
<td>48.8</td>
<td>48.5</td>
</tr>
<tr>
<td>T6</td>
<td>30</td>
<td>44.8</td>
<td>45.9</td>
<td>48.5</td>
<td></td>
<td>50.9</td>
<td>51.2</td>
<td>26</td>
</tr>
<tr>
<td>C5</td>
<td>8</td>
<td>51.2</td>
<td>50.9</td>
<td></td>
<td></td>
<td>26c6</td>
<td></td>
<td>26</td>
</tr>
<tr>
<td>C6</td>
<td>8</td>
<td>52.0</td>
<td>51.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>26</td>
</tr>
<tr>
<td>C7</td>
<td>8</td>
<td>56.3</td>
<td>55.2</td>
<td></td>
<td></td>
<td>54.6</td>
<td>52.0</td>
<td>51.2</td>
</tr>
<tr>
<td>C9</td>
<td>3.5</td>
<td>49.4</td>
<td>49.1</td>
<td>28</td>
<td></td>
<td>34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C9A</td>
<td>3.5</td>
<td>52.0</td>
<td>51.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: T specimens are tensile C specimens are laterally supported compressive * Calculated composite stress strain curve properties
<table>
<thead>
<tr>
<th>Section Type</th>
<th>Spec. No.</th>
<th>Length (in.)</th>
<th>Laterally Unsupported Compress.</th>
<th>Laterally Supported Compress.</th>
<th>Tensile Yield Str. (ksi)</th>
<th>Ultimate Strength (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 gage</td>
<td>C9</td>
<td>3.50</td>
<td>49.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HR SK-</td>
<td>C16</td>
<td>3.52</td>
<td>49.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-37.0</td>
<td>C7</td>
<td>8</td>
<td>56.3</td>
<td>54.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roll-formed</td>
<td>T7*</td>
<td>30</td>
<td></td>
<td>47.9</td>
<td>59.4</td>
<td></td>
</tr>
<tr>
<td>Channel</td>
<td>T6*</td>
<td>30</td>
<td></td>
<td>47.7</td>
<td>59.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T9*</td>
<td>30</td>
<td></td>
<td>47.8</td>
<td>50.0</td>
<td></td>
</tr>
<tr>
<td>15 gage</td>
<td>C10</td>
<td>4.38</td>
<td>44.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HR press</td>
<td>C11</td>
<td>4.38</td>
<td>44.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C19</td>
<td>8</td>
<td>44.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C20</td>
<td>8</td>
<td>44.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lipped angle</td>
<td>T13*</td>
<td>24</td>
<td>42.8</td>
<td>49.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 gage</td>
<td>C12</td>
<td>3.76</td>
<td>41.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HR press</td>
<td>C13</td>
<td>3.76</td>
<td>42.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T11*</td>
<td>24</td>
<td>42.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 gage</td>
<td>C14</td>
<td>6.76</td>
<td>41.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRK-</td>
<td>C15</td>
<td>6.77</td>
<td>41.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-38.3</td>
<td>C17</td>
<td>8</td>
<td>41.3</td>
<td>40.9</td>
<td>49.5</td>
<td></td>
</tr>
<tr>
<td>Press</td>
<td>C18</td>
<td>8</td>
<td>41.3</td>
<td></td>
<td>50.2</td>
<td></td>
</tr>
<tr>
<td>Braked hat</td>
<td>T12*</td>
<td>24</td>
<td>42.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Specimen failed by necking rather than tearing at a weld.
<table>
<thead>
<tr>
<th>Specimen Description</th>
<th>Virgin Yield Strength</th>
<th>Virgin Ultimate Strength</th>
<th>Inside Radius of Div. by Corner</th>
<th>Inside Area</th>
<th>Calc. Tensile Compr. Str.</th>
<th>Average Corner</th>
<th>Tensile Corner Yield</th>
<th>Tensile Full Section Yield</th>
<th>Tensile Full Section Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(ksi)</td>
<td>(ksi)</td>
<td>(ksi)</td>
<td>(ksi)</td>
<td>(ksi)</td>
<td>(ksi)</td>
<td>(ksi)</td>
<td>(ksi)</td>
<td>(ksi)</td>
</tr>
<tr>
<td>CRK16-38.3 Press Braked Hat.</td>
<td>38.3</td>
<td>34.6</td>
<td>51.1</td>
<td>1.05</td>
<td>.08</td>
<td>58.3</td>
<td>37.9</td>
<td>39.5</td>
<td>39.4</td>
</tr>
<tr>
<td>HRSK16-37.5 Press Braked Hat.</td>
<td>37.5</td>
<td>40.5</td>
<td>49.0</td>
<td>1.00</td>
<td>.08</td>
<td>56.4</td>
<td>39.7</td>
<td>41.0</td>
<td>42.5</td>
</tr>
<tr>
<td>HRSK16-37.5 Roll Formed Track.</td>
<td>37.5</td>
<td>40.5</td>
<td>49.0</td>
<td>1.49</td>
<td>.17</td>
<td>53.4</td>
<td>39.2</td>
<td>41.6</td>
<td>45.6</td>
</tr>
<tr>
<td>HRSK16-37.0 Roll Formed Channel.</td>
<td>37.0</td>
<td>38.5</td>
<td>57.5</td>
<td>.89</td>
<td>.184</td>
<td>64.5</td>
<td>43.5</td>
<td>47.4</td>
<td>47.8</td>
</tr>
<tr>
<td>HRSK16-37.5 Roll Formed Channel.</td>
<td>37.5</td>
<td>40.5</td>
<td>49.0</td>
<td>3.02</td>
<td>.064</td>
<td>48.4</td>
<td>41.9</td>
<td>42.3</td>
<td></td>
</tr>
<tr>
<td>HRSK16-37.5 Press Braked C-Section.</td>
<td>37.5</td>
<td>40.5</td>
<td>49.0</td>
<td>2.50</td>
<td>.049</td>
<td>49.7</td>
<td>37.5*</td>
<td>38.1</td>
<td></td>
</tr>
</tbody>
</table>

*Estimated at the virgin yield strength in the absence of tests on flats of press braked section
## TABLE 9b
CALCULATED TENSILE FULL SECTION YIELD STRENGTH

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Armco Roll Formed Joist Chord.</td>
<td>44.8</td>
<td>72.3</td>
<td>1.028</td>
<td>.46</td>
<td>77.1</td>
<td>49.2</td>
<td>62.1</td>
<td>64.4</td>
<td>71.9</td>
</tr>
<tr>
<td>Roll Formed Commercial Section A</td>
<td>46.4</td>
<td>55.6</td>
<td>.08</td>
<td>.21</td>
<td>65.6</td>
<td>50.0**</td>
<td>53.3</td>
<td>57.3</td>
<td>56.9</td>
</tr>
<tr>
<td>Roll Formed Commercial Section B</td>
<td>42.7</td>
<td>50.8</td>
<td>.80</td>
<td>.23</td>
<td>59.8</td>
<td>48.0**</td>
<td>50.7</td>
<td>55.8</td>
<td>55.7</td>
</tr>
</tbody>
</table>

**Estimated at approximately 10% above virgin yield strength in the absence of tests of flats of the roll formed section.
<table>
<thead>
<tr>
<th>a/t</th>
<th>$\sigma_p$ (ksi)</th>
<th>$\sigma_y$ (ksi)</th>
<th>$\sigma_u$ (ksi)</th>
<th>% Elong.</th>
<th>% Red. in 2''</th>
<th>$\sigma_p / \sigma_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>.955</td>
<td>55.0</td>
<td>59.0</td>
<td>30.5</td>
<td>5</td>
<td>83</td>
<td>.80</td>
</tr>
<tr>
<td>.955</td>
<td>52.5</td>
<td>58.0</td>
<td>2.9</td>
<td>5</td>
<td>86</td>
<td>.75</td>
</tr>
<tr>
<td>.955</td>
<td>52.0</td>
<td>58.0</td>
<td>2.9</td>
<td>5</td>
<td>86</td>
<td>.75</td>
</tr>
<tr>
<td>1.96</td>
<td>44.0</td>
<td>44.2</td>
<td>2.9</td>
<td>5</td>
<td>83</td>
<td>.79</td>
</tr>
<tr>
<td>1.96</td>
<td>51.2</td>
<td>55.2</td>
<td>2.9</td>
<td>5</td>
<td>83</td>
<td>.79</td>
</tr>
<tr>
<td>1.96</td>
<td>42.3</td>
<td>52.4</td>
<td>2.9</td>
<td>5</td>
<td>83</td>
<td>.78</td>
</tr>
<tr>
<td>1.97</td>
<td>39.3</td>
<td>53.3</td>
<td>2.9</td>
<td>5</td>
<td>83</td>
<td>.78</td>
</tr>
<tr>
<td>1.97</td>
<td>43.3</td>
<td>53.0</td>
<td>2.9</td>
<td>5</td>
<td>83</td>
<td>.78</td>
</tr>
<tr>
<td>1.97</td>
<td>40.3</td>
<td>53.5</td>
<td>2.9</td>
<td>5</td>
<td>83</td>
<td>.78</td>
</tr>
<tr>
<td>5.83</td>
<td>45.2</td>
<td>47.2</td>
<td>2.9</td>
<td>5</td>
<td>83</td>
<td>.78</td>
</tr>
<tr>
<td>5.83</td>
<td>43.2</td>
<td>53.3</td>
<td>2.9</td>
<td>5</td>
<td>83</td>
<td>.78</td>
</tr>
<tr>
<td>5.32</td>
<td>37.9</td>
<td>43.4</td>
<td>2.9</td>
<td>5</td>
<td>83</td>
<td>.78</td>
</tr>
</tbody>
</table>

**TENSION SPECIMENS**

<table>
<thead>
<tr>
<th>a/t</th>
<th>$\sigma_p$ (ksi)</th>
<th>$\sigma_y$ (ksi)</th>
<th>$\sigma_u$ (ksi)</th>
<th>% Elong.</th>
<th>% Red. in 2''</th>
<th>$\sigma_p / \sigma_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>.96</td>
<td>52.0</td>
<td>65.5</td>
<td>0.5</td>
<td>5</td>
<td>83</td>
<td>.79</td>
</tr>
<tr>
<td>.96</td>
<td>50.5</td>
<td>64.5</td>
<td>0.3</td>
<td>5</td>
<td>83</td>
<td>.78</td>
</tr>
<tr>
<td>1.74</td>
<td>43.3</td>
<td>59.8</td>
<td>68.8</td>
<td>8</td>
<td>80</td>
<td>.72</td>
</tr>
<tr>
<td>1.75</td>
<td>43.3</td>
<td>59.7</td>
<td>68.0</td>
<td>8</td>
<td>77</td>
<td>.72</td>
</tr>
<tr>
<td>1.73</td>
<td>47.2</td>
<td>59.6</td>
<td>68.4</td>
<td>8</td>
<td>77</td>
<td>.72</td>
</tr>
<tr>
<td>4.53</td>
<td>35.9</td>
<td>48.3</td>
<td>50.1</td>
<td>25</td>
<td>23</td>
<td>.82</td>
</tr>
<tr>
<td>4.53</td>
<td>39.5</td>
<td>47.9</td>
<td>59.1</td>
<td>24</td>
<td>23</td>
<td>.82</td>
</tr>
<tr>
<td>4.51</td>
<td>42.1</td>
<td>49.4</td>
<td>50.1</td>
<td>22</td>
<td>23</td>
<td>.82</td>
</tr>
<tr>
<td>5.93</td>
<td>40.4</td>
<td>47.2</td>
<td>59.0</td>
<td>30</td>
<td>15</td>
<td>.86</td>
</tr>
<tr>
<td>5.94</td>
<td>41.1</td>
<td>48.7</td>
<td>51.1</td>
<td>29</td>
<td>18</td>
<td>.85</td>
</tr>
<tr>
<td>5.92</td>
<td>41.1</td>
<td>48.7</td>
<td>59.2</td>
<td>33</td>
<td>6</td>
<td>.81</td>
</tr>
</tbody>
</table>

$\sigma_p$ = proportional limit
$\sigma_y$ = yield strength
$\sigma_u$ = ultimate strength
a/t = inside radius to thickness ratio.
<table>
<thead>
<tr>
<th>a/t</th>
<th>$\sigma_p$ (ksi)</th>
<th>$\sigma_y$ (ksi)</th>
<th>$\sigma_u$ (ksi)</th>
<th>% Elong.</th>
<th>% Red.</th>
<th>$\sigma_p/\sigma_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>.713</td>
<td>66.5</td>
<td>87.0</td>
<td></td>
<td>10</td>
<td></td>
<td>.76</td>
</tr>
<tr>
<td>.713</td>
<td>64.5</td>
<td>82.0</td>
<td></td>
<td>11</td>
<td></td>
<td>.79</td>
</tr>
<tr>
<td>.713</td>
<td>62.8</td>
<td>81.0</td>
<td></td>
<td>10</td>
<td></td>
<td>.78</td>
</tr>
<tr>
<td>1.78</td>
<td>57.5</td>
<td>75.4</td>
<td></td>
<td>17</td>
<td>46</td>
<td>.76</td>
</tr>
<tr>
<td>1.78</td>
<td>55.7</td>
<td>75.5</td>
<td></td>
<td>15</td>
<td>52</td>
<td>.89</td>
</tr>
<tr>
<td>1.78</td>
<td>57.0</td>
<td>74.6</td>
<td></td>
<td>14</td>
<td>55</td>
<td>.88</td>
</tr>
<tr>
<td>2.85</td>
<td>53.7</td>
<td>64.2</td>
<td></td>
<td>17</td>
<td>17</td>
<td>.84</td>
</tr>
<tr>
<td>2.85</td>
<td>51.2</td>
<td>57.8</td>
<td></td>
<td>14</td>
<td>55</td>
<td>.89</td>
</tr>
<tr>
<td>2.85</td>
<td>57.7</td>
<td>65.6</td>
<td></td>
<td>14</td>
<td>55</td>
<td>.88</td>
</tr>
<tr>
<td>5.71</td>
<td>48.2</td>
<td>56.9</td>
<td></td>
<td>10</td>
<td>68</td>
<td>.85</td>
</tr>
<tr>
<td>5.71</td>
<td>48.4</td>
<td>54.8</td>
<td></td>
<td>10</td>
<td>68</td>
<td>.88</td>
</tr>
<tr>
<td>5.71</td>
<td>51.1</td>
<td>57.3</td>
<td></td>
<td>10</td>
<td>68</td>
<td>.89</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>a/t</th>
<th>$\sigma_p$ (ksi)</th>
<th>$\sigma_y$ (ksi)</th>
<th>$\sigma_u$ (ksi)</th>
<th>% Elong.</th>
<th>% Red.</th>
<th>$\sigma_p/\sigma_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>.96</td>
<td>67.3</td>
<td>79.7</td>
<td>88.2</td>
<td>10</td>
<td>68</td>
<td>.85</td>
</tr>
<tr>
<td>.96</td>
<td>58.2</td>
<td>76.3</td>
<td>87.0</td>
<td>11</td>
<td>65</td>
<td>.76</td>
</tr>
<tr>
<td>.96</td>
<td>58.2</td>
<td>75.0</td>
<td>86.3</td>
<td>10</td>
<td>68</td>
<td>.78</td>
</tr>
<tr>
<td>1.92</td>
<td>49.1</td>
<td>69.0</td>
<td>80.2</td>
<td>17</td>
<td>46</td>
<td>.71</td>
</tr>
<tr>
<td>1.92</td>
<td>51.3</td>
<td>69.3</td>
<td>80.8</td>
<td>15</td>
<td>52</td>
<td>.74</td>
</tr>
<tr>
<td>1.92</td>
<td>50.8</td>
<td>69.2</td>
<td>80.1</td>
<td>14</td>
<td>55</td>
<td>.74</td>
</tr>
<tr>
<td>2.99</td>
<td>45.8</td>
<td>57.0</td>
<td>71.5</td>
<td>26</td>
<td>17</td>
<td>.80</td>
</tr>
<tr>
<td>2.99</td>
<td>46.7</td>
<td>57.9</td>
<td>72.4</td>
<td>25</td>
<td>21</td>
<td>.81</td>
</tr>
<tr>
<td>2.99</td>
<td>46.7</td>
<td>58.0</td>
<td>72.0</td>
<td>25</td>
<td>21</td>
<td>.80</td>
</tr>
<tr>
<td>5.73</td>
<td>39.1</td>
<td>53.3</td>
<td>70.0</td>
<td>32</td>
<td></td>
<td>.73</td>
</tr>
<tr>
<td>5.73</td>
<td>42.2</td>
<td>53.7</td>
<td>69.5</td>
<td>32</td>
<td></td>
<td>.67</td>
</tr>
<tr>
<td>5.73</td>
<td>44.8</td>
<td>54.7</td>
<td>70.5</td>
<td>32</td>
<td></td>
<td>.82</td>
</tr>
</tbody>
</table>

$\sigma_p$ = proportional limit  
$\sigma_y$ = yield strength  
$\sigma_u$ = ultimate strength  
a/t = inside radius to thickness ratio.
### TABLE 10c

**HRSK16-40.7 CORNER SPECIMENS**

**COLD FORMED BY AIR PRESS BRAKE**

#### COMPRESSION TESTS

<table>
<thead>
<tr>
<th>a/t</th>
<th>$\sigma_p$ (ksi)</th>
<th>$\sigma_y$ (ksi)</th>
<th>$\sigma_p / \sigma_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.03</td>
<td>68.3</td>
<td>77.9</td>
<td>.88</td>
</tr>
<tr>
<td>1.03</td>
<td>52.9</td>
<td>68.8</td>
<td>.73</td>
</tr>
<tr>
<td>1.03</td>
<td>58.8</td>
<td>72.7</td>
<td>.81</td>
</tr>
<tr>
<td>2.10</td>
<td>53.5</td>
<td>67.5</td>
<td>.79</td>
</tr>
<tr>
<td>2.10</td>
<td>47.5</td>
<td>67.5</td>
<td>.70</td>
</tr>
<tr>
<td>2.10</td>
<td>45.5</td>
<td>66.2</td>
<td>.69</td>
</tr>
<tr>
<td>4.21</td>
<td>40.5</td>
<td>60.1</td>
<td>.67</td>
</tr>
<tr>
<td>4.21</td>
<td>46.0</td>
<td>62.3</td>
<td>.74</td>
</tr>
<tr>
<td>4.21</td>
<td>40.7</td>
<td>58.0</td>
<td>.70</td>
</tr>
<tr>
<td>6.30</td>
<td>30.5</td>
<td>48.3</td>
<td>.63</td>
</tr>
<tr>
<td>6.30</td>
<td>37.2</td>
<td>45.4</td>
<td>.82</td>
</tr>
<tr>
<td>6.30</td>
<td>37.7</td>
<td>47.7</td>
<td>.79</td>
</tr>
</tbody>
</table>

#### TENSION SPECIMENS

<table>
<thead>
<tr>
<th>a/t</th>
<th>$\sigma_p$ (ksi)</th>
<th>$\sigma_y$ (ksi)</th>
<th>$\sigma_u$ (ksi)</th>
<th>$%$ Elong. in 2&quot;</th>
<th>$%$ Red. in Elong.</th>
<th>$\sigma_p / \sigma_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.06</td>
<td>67.2</td>
<td>75.3</td>
<td>8.5</td>
<td>73</td>
<td>.76</td>
<td></td>
</tr>
<tr>
<td>1.06</td>
<td>50.5</td>
<td>66.3</td>
<td>73.5</td>
<td>7.5</td>
<td>76</td>
<td>.69</td>
</tr>
<tr>
<td>1.04</td>
<td>45.1</td>
<td>65.7</td>
<td>71.0</td>
<td>8.0</td>
<td>75</td>
<td>.69</td>
</tr>
<tr>
<td>1.83</td>
<td>48.8</td>
<td>61.3</td>
<td>68.6</td>
<td>14</td>
<td>55</td>
<td>.80</td>
</tr>
<tr>
<td>1.83</td>
<td>52.6</td>
<td>62.3</td>
<td>69.2</td>
<td>14</td>
<td>55</td>
<td>.84</td>
</tr>
<tr>
<td>1.84</td>
<td>44.7</td>
<td>61.8</td>
<td>69.8</td>
<td>12</td>
<td>62</td>
<td>.72</td>
</tr>
<tr>
<td>4.18</td>
<td>38.2</td>
<td>53.9</td>
<td>65.3</td>
<td>28</td>
<td>11</td>
<td>.71</td>
</tr>
<tr>
<td>4.18</td>
<td>38.5</td>
<td>54.5</td>
<td>65.6</td>
<td>27</td>
<td>14</td>
<td>.70</td>
</tr>
<tr>
<td>4.21</td>
<td>39.7</td>
<td>55.2</td>
<td>65.7</td>
<td>32</td>
<td>5</td>
<td>.72</td>
</tr>
<tr>
<td>6.33</td>
<td>39.3</td>
<td>50.4</td>
<td>63.7</td>
<td>30</td>
<td>5</td>
<td>.78</td>
</tr>
<tr>
<td>6.33</td>
<td>38.3</td>
<td>49.3</td>
<td>62.8</td>
<td>30</td>
<td>5</td>
<td>.78</td>
</tr>
<tr>
<td>6.32</td>
<td>37.9</td>
<td>49.7</td>
<td>63.7</td>
<td>31</td>
<td>1.6</td>
<td>.76</td>
</tr>
</tbody>
</table>

- $\sigma_p$ = proportional limit
- $\sigma_y$ = yield strength
- $\sigma_u$ = ultimate strength
- a/t = inside radius to thickness ratio
FIGURE 1

(b)

(c)

FIG. 1. AIR PRESS BRAKING
FIG. 2. PHOTOGRID ON EDGE OF 10 GAGE AIR PRESS BRAKED CORNERS
(Magnified 7.5 times)
FIGURE 3
PHOTOGRID ON EDGE OF LO CAGE
(Magnified 17.5 times)
FIG. 4. WIDE PLATE PLASTICALLY DEFORMED BY PURE PLASTIC loads.

(a) Stresses on Volume Element of Plastically Deformed Plate

(b) Location of Planar Surface Before Plastic Deformation

(c) Radius to Surface After Deformation
FIG. 5. YIELD STRENGTH VERSUS PERMANENT TENSILE PRESTRAIN FOR 16 GAGE COLD REDUCED SEMI-KILLED SHEET STEEL (CRK 16 - 38.3)
LEGEND: Specimens tested in
○ Tension in dir. of prestrain
□ Tension perpendicular to prestrain dir.
△ Compression in dir. of prestrain
+ Compression perpendicular to prestrain dir.

FIG. 6. YIELD STRENGTH VERSUS PERMANENT TENSILE PRESTRAIN FOR 16 GAGE COLD REDUCED RIMMED SHEET STEEL

(CRR 16 - 36.4)
FIG. 7. YIELD STRENGTH VERSUS PERMANENT TENSILE PRESTRAIN FOR 16 GAUGE HOT ROLLED SEKI-KILLEO SHEET STEEL (HRSK 16 - 37.5)

LEGEND: Specimens tested in
○ Tension in dir. of prestrain
□ Tension perpendicular to prestrain dir.
△ Compression in dir. of prestrain
+ Compression perpendicular to prestrain dir.

YIELD STRENGTH AFTER AGING
(expresses as true stress $\sigma'$ in ksi)

PERMANENT TENSILE PRESTRAIN
(expresses as true strain $\varepsilon$' in in./in. $\times 10^{-3}$)
FIG. 8. YIELD STRENGTH VERSUS PERMANENT TENSILE PRESTRAIN FOR 16 GAGE HOT ROLLED RIBBED SHEET STEEL (HRR 16 - 40.5°)

LEGEND: Specimens tested in
○ Tension in dir. of prestrain
□ Tension perpendicular to prestrain dir.
△ Compression in dir. of prestrain
+ Compression perpendicular to prestrain dir.

PERMANENT TENSILE PRESTRAIN
(expressed as true strain $\varepsilon'$ in in./in. x $10^{-3}$)
FIG. 9. YIELD STRENGTH VERSUS PERMANENT TENSILE PRESTRAIN FOR 10 GAGE HOT ROLLED SEMI-KILLED SHEET STEEL

( HRK 10 - 37.0 )
FIGURE 10

LEGEND:
- HRSK 16 - 37.5
- HRR 16 - .40.5
- HRSK 10 - 37.0

TENSILE STRESS-STRAIN CURVES OF VIRGIN MATERIALS IN TERMS OF TRUE STRESS AND TRUE STRAIN
FIGURE 11

NON-DIMENSIONAL PLOT OF STRENGTH COEFFICIENT \( k \) AND RATIO OF ULTIMATE TO TENSILE YIELD STRENGTH \( \sigma_c / \sigma_y \)

\[ x = 2.62 \sigma_c - 2.33 \sigma_y \]

LEGEND: MATERIAL

- O CHL 16-36.4
- X BRN 16-36.4
- O BRK 16-37.2
- X BRK 16-42.0
- T BRK 16-35.0
- < BRK 16-35.0
- * BRK 16-42.0
- * BRK 16-40.7

RATIO OF ULTIMATE TO TENSILE YIELD STRENGTH \( \sigma_c / \sigma_y \)
TEST SPECIMENS. (a) Tensile specimen inside radius of 1/4"., (b) Tensile spec. rad. of 1/8", (c) Standard flat tens. spec., (d) Flat tens. spec. after testing, (e) Flat compr. spec., (f) Jig for compr. spec., (g) and (h) Compr. corner spec. cast in hydrostone, (i), (j) and (k) Compr. spec. (corners) of 7/16", 1/8" and 1/4", respectively, with foil type electric SR 4 strain gages, (l) Steel jig for compr. corner specimens.
Upper corners used for test specimens for Hat and for Track.

**Figure 14**

16 GA. HAT

- Inner radius: 5/8" 
- Outer radius: 1 1/2"
- Height: 5/8" 
- Width: 2 5/8"

4/16" nominal r

**16 GA. TRACK**

- Inner radius: 5/8" 
- Outer radius: 2 7/8"
- Height: 5/8" 
- Width: 2 1/8"

1/8" nominal r

**16 GA. CHANNEL**

- 1 3/4"
- 1 3/16"

1/4" nominal r

10 & 16 GA. ANGLE

- Inner radius: 1 1/4"
- Outer radius: 1 1/8"
- Height: 4 1/4" 
- Width: 1 5/8"

4/16", 5/16", 1/4", 1/2
nominal r

10 GA. CHANNEL

- 2 3/16"
- 1 3/16"

3/16" nominal r

**Cross Sectional Dimensions of Specimens**

- +t Not more
- r* = nominal inside radius

**Notes:**

1. Hat section press braked in HRSK, HRR, CRK & CRR mater'ls.
2. Track and 16 ga. channel roll formed in HRSK, HRR, CRK & CRR.
3. 10 ga. HRSK channel roll formed.
4. Angles were press & bend braked in all 5 materials.

**Figure 14. Sections from Which Corner Specimens Were Taken for the First Five Materials**
FIGURE 15

COMPRESSIVE TEST SET-UP for CORNERS
TRUE CORNER YIELD STRENGTH/STRENGTH COEFFICIENT VERSUS
\(a/t\) RATIO FOR MODEL SUBJECTED TO PURE FLEXURAL LOADS
TRUE CORNER YIELD STRENGTH DIVIDED BY STRENGTH COEFFICIENT \( \sigma_{y}/\sigma \) VERSUS \( a/t \) RATIO FOR MODEL SUBJECTED TO RADIAL PRESSURE AND FLEXURAL LOADS
FIG. 18. TRUE CORNER YIELD STRENGTH/STRENGTH COEFFICIENT VERSUS a/t RATIO FOR MODEL SUBJECTED TO PURE FLEXURAL LOADS
RELATIONSHIPS BETWEEN THE CONSTANTS $b$ AND $m$ AND THE STRAIN HARDENING EXPONENT $n$
FIGURE 20

YIELD STRENGTH OF CORNERS VS. a/t RATIO  
( CRK 16-38.3 )
FIGURE 21

YIELD STRENGTH OF CORNERS VS. a/t RATIO

(CHR16-36.4)

LEGEND:
- ○ ROLL FORMED
- △ AIR PRESS BRAKED
- □ COIN PRESS BRAKED
--- --- PURE FLEXURAL MODEL
- --- FLEXURE PLUS RADIAL PRESSURE
LEGEND:
- O ROLL FORMED
- △ AIR PRESS BRAKED
- ○ COIN PRESS BRAKED
--- PURE FLEXURAL MODEL
--- FLEXURE PLUS RADIAL PRESSURE

YIELD STRENGTH OF CORNERS VS. a/t RATIO
(HESK16-37.5)
FIGURE 2.3

LEGEND:

○ ROLL FORMED
△ AIR PRESS BRAKED
□ COIN PRESS BRAKED

— PURE FLEXURAL MODEL
— FLEXURE PLUS RADIAL PRESSURE

YIELD STRENGTH OF CORNERS VS. a/t RATIO
(HRR 16-40, 1.5)
YIELD STRENGTH OF CORNERS VERSUS a/t RATIO
(HRSK 10-37.0)
YIELD STRENGTH OF CORNERS VS. a/t RATIO

( BRSK 16-39.7 )
FIGURE 26

YIELD STRENGTH OF CORNERS VS. a/t RATIO

( HRSK 10-42-8 )
FIGURE 27

YIELD STRENGTH OF CORNERS VS. a/t RATIO

(ERSK 16-40.7)
### NOTES:

1. Shearing done on lines marked ①.
2. Letters & numerals used to identify specimens & channels.
3. 4 channels coin press braked in direction of rolling (i.e. corners run in direction of rolling.)
4. All 1” wide strips for virgin specimens.
5. See Fig. for further layout info.

**FIG. 28. LOCATIONS ON 10 GAUGE SHEET FROM WHICH VIRGIN SPECIMENS AND PRESS BRAKED CHANNELS WERE TAKEN.**
Fig. 29. Typical Layout for Virgin Tensile and Compressive Specimens from 5½" x 11¾" Pieces Sheared from 1/4" x 60" 10 ga. Sheet. (See Fig. )
### Dimensions Requested

<table>
<thead>
<tr>
<th>CHANNEL MARK</th>
<th>SPEC. MARKS</th>
<th>DIMENSION (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CX</td>
<td>CXI thru CXB</td>
<td>A: 0.2812, B: 0.5000, C: 0.3112, D: 0.4700, E: 0.2812, F: 0.5000, G: 0.3112, H: 0.4700</td>
</tr>
<tr>
<td>CXX</td>
<td>CXXI thru CXXB</td>
<td>A: 0.3412, B: 0.4400, C: 0.3712, D: 0.4100, E: 0.3412, F: 0.4400, G: 0.3712, H: 0.4100</td>
</tr>
<tr>
<td>GX</td>
<td>GXI thru GXB</td>
<td>A: 0.4012, B: 0.3800, C: 0.4312, D: 0.3500, E: 0.4012, F: 0.3800, G: 0.4312, H: 0.3500</td>
</tr>
<tr>
<td>GXX</td>
<td>GXII thru GXXB</td>
<td>A: 0.4612, B: 0.3200, C: 0.4912, D: 0.2900, E: 0.4612, F: 0.3200, G: 0.4912, H: 0.2900</td>
</tr>
</tbody>
</table>

**Dimensions Measured**

<table>
<thead>
<tr>
<th>CHANNEL MARK</th>
<th>SPECIMEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>CX</td>
<td>B: 0.5000, J: 1.688, D: 0.4713, K: 1.1618, F: 0.5000, L: 1.623, H: 0.4712, M: 1.657</td>
</tr>
<tr>
<td>CXX</td>
<td>B: 0.4402, J: 1.612, D: 0.4100, K: 1.594, F: 0.4401, L: 1.676, H: 0.4100, M: 1.684</td>
</tr>
<tr>
<td>GX</td>
<td>B: 0.3807, J: 1.563, D: 0.3493, K: 1.632, F: 0.3800, L: 1.659, H: 0.3496, M: 1.578</td>
</tr>
<tr>
<td>GXX</td>
<td>B: 0.3200, J: 1.600, D: 0.2896, K: 1.608, F: 0.3194, L: 1.659, H: 0.2894, M: 1.560</td>
</tr>
</tbody>
</table>

Specimens to have no shoulders, i.e. same cross section for complete length.

**10 GA. PRESS BRAKED CHANNEL SPECIMENS**
**Fig. 31. Contour Variation of Tensile Yield Strength (in KSI) in Virgin 14"x60" 10 Gage HRSK Sheet. (Transverse scale distorted.)**
FIGURE 32

TOTAL TENSILE YIELD STRENGTH

AVERAGE TENSILE YIELD STRENGTH OF SHEET

INCREASE IN TENSILE YIELD STRENGTH
DUE TO THE EXPANSION OF CONSER PLASTIC
SPARK EFFECTS INTO THE ADJACENT PLATE.
CORE TR. 4/8, RATIO = 0.4/3

VARIATION IN YIELD STRENGTH IN THE TRANSITION ZONE OF THE PLATE.
EFFECTIVE YIELD STRENGTH (INCHES)

DISTANCE FROM THE EDGE OF THE CORNER (INCHES)
Figure 33

Typical Tensile & Compressive Stress Strain Curves
Cold Reduced Kill Steel
16 Gage ComPress bead Flat
Tension
Compression
CRK/4-38.5

Stress (KSI)
0 60 80 100

Strain Scale (1/2/10)

Strain
Figure 34

Typical Tensile and Compressive Stress Strain Curves

Hot Rolled Semi-Killed Steel

1/4 Gage Coin Press Brake Flats

Tension

Compression

HRSHK - 37.5

Stress Scale (ksi)

300 600 900

0.001 0.002 0.003

Strain Scale (in/in)
FULL SECTION TENSION SPECIMENS
AND NOMINAL DIMENSIONS

16 GA. HAT
(roll formed)
CRK16-38.3
HRSK16-37.5

16 GA. TRACK
(press braked)
CRK16-38.3
HRSK16-37.5

---

NOTE: No.'s 
#1, #2, etc. indi- 
cate SR-4 
gage locations.

---

SRA strain 
gages located 
at mid-height 
of specimen

---

10 GA. CHANNEL
(roll formed)
HRSK10-37.0

---

Full Section Tension Specimens
and nominal dimensions

---
**16 GA. CHANNEL**
(press braked)
Spec T11
hot rolled

**16 GA. HAT SECTION**
(press braked)
Spec T12
CRX12-38.3

**16 GA. LIPPED ANGLE**
(press braked)
Spec T13
hot rolled

**Full Section Tension Specimens**
and Nominal Dimensions

**NOTE:** No.'s #1, #2, ... #5 indicate SR-4 gage locations.
16 GA. HAT SECTIONS
(press braked)
CRK 16 - 38.3
HRSK 16 - 37.5

10 GA. CHANNEL
(roll formed)
HRSK 10 - 31.0

16 GA. TRACK
(roll formed)
HRSK 16 - 37.5

NOTE: Hatched portions discarded.

TENSILE STRIP SPECIMEN LOCATIONS
Length of tubing of semi-circular cross section for protection of SR4 electric wire type strain gages. Dots indicate SR4 gage locations. Gages waterproofed with "Petrose" wax.

Hydrostone for lateral support against buckling. Specimen greased and encased in aluminum foil prior to casting in hydrostone.

See Fig. 5 for dimensions of specimens.

4" pipe sleeve.

Testing machine head fixed to prevent rotation.

Specimen ends milled plane and square after casting specimen in hydrostone.

Full Section Compression Test Set-Up
FULL SECTION COMPRESSION SPECIMENS
AND NOMINAL DIMENSIONS

(a) Specimens Tested With Hydrostone Lateral Support

- 16 GA. HAT (press brake formed)
  HRSK10-37.5
- 16 GA. TRACK (roll formed)
  HRSK10-37.5
- 10 GA. CHANNEL (roll formed)
  HRSK10-37.0

(b) Specimens Tested Without Hydrostone Lateral Support

- 10 GA. CHANNEL
  HRSK10-37.0
- 16 GA. CHANNEL (press brake)
  hot rolled
- 16 GA. LIPPED ANGLE (press brake)
  hot rolled
- 16 GA. HAT (press brake)
  CRK16-38.3

* Tested with hydrostone support
16 GA. HAT SECTION  
(press brake)  
CRK 16-38.3  
HRSK 16-37.5

10 GA. CHANNEL  
(roll formed)  
HRSK 16-37.0

16 GA. TRACK  
(roll formed)  
HRSK 16-37.5  
Note: Hatched portions discarded.

Compressive Strip Specimen Locations
Fig. 41

Variation of Tensile Yield and Ultimate Strengths in the cross section of a 16 Gage Press Braked CRK 16-383 Hat

Legend:
- Yield Strength
- Ultimate Strength
- Series 1 Flats
- Series 2 Flats
- Corners

See Fig. 37 for location of specimens in the cross section.
See Fig. 40 for location of specimens in the cross section.

**Legend:**
- + Corners
- O Flats

Variation of compressive yield strength in the cross section of a 16 gauge press brake Crk16-38.3 Hat
LEGEND:

YIELD STRENGTH

ULTIMATE STRENGTH

SERIES 1 FLA

SERIES 2 FLA

CORNERS

SEE FIG. 37 FOR LOCATION OF SPECIMENS IN THE CROSS SECTION.

VARIATION OF TENSILE YIELD AND ULTIMATE STRENGTHS IN THE CROSS SECTION OF A 16 GAUGE PRESS BRAKE HR SK16-37.5 HAT
Figure 46

Variation of compressive yield strength in the cross section of a 16 gage press brake HR SK10-37.5 hat

Legend:
+ Corners
○ Flats

Virgin yield strength

See Fig. 46 for location of specimen in the cross section.
STRESS VERSUS STRAIN FOR INDIVIDUAL GAGES OF HRSK HAT TENSILE SPECIMEN T4
COMPOSITE vs. FULL SECTION TENSION STRESS STRAIN CURVES
Figure 49

Composite vs. Full Section Compression Stress Strain Curves

Legend:
- Calculated Composite Curve
- Full Section Compression Curve

HRSA 8-36 1/2 in.
Specimen C3

HRSA 8-36 1/2 in.
Specimen C4

Stress (ksi) vs. Strain (in./in. x 10^-3)
POSITIVE VS. FULL SECTION COMPRESSION STRESS-STRAIN CURVES

FIG. 50

LEGEND:
- CALCULATED COMPOSITE CURVE
- FULL SECTION COMPRESSION

HR SK 16-935 FLAT SPECIMEN C3A

HR SK 16-975 FLAT SPECIMEN C3B

STRAIN (in./in. x 10^{-3})

STRESS (ksi)
FIG. 51

LEGEND:

YIELD STRENGTH

ULTIMATE STRENGTH

○ SERIES 1 FLATS

△ SERIES 2 FLATS

+ CORNERS

SEE FIG. 37 FOR LOCATION OF SPECIMENS IN THE CROSS SECTION.

VARIATION OF TENSILE YIELD AND ULTIMATE STRENGTHS IN THE CROSS SECTION OF A 16-GAGE ROLL FORMED HRSK16-37.5 TRACK
**Figure 52**

**Legend:**
- ○ Series 1 flats
- △ Series 2 flats
- + Corners

Variation of Compressive Yield Strength in the Cross Section of a 16 Gage Roll Formed HRSK16-37.5 Track

See Fig. 40 for location of specimens in the cross section.
LEGEND

- Calculated Composite Curve
- Full Section Tension Curve

HRSK Track
Specimen 15
(HRSK 15.375)

HRSK Track
Specimen 16
(HRSK 16.375)

Composite vs. Full Section Tension Stress Strain Curve
LEGEND:
- Calculated Composite Curve
- Full Section Tension Curve

HRSK Track
Specimen T10
(413K16-37.5)

Composite vs. Full Section Tension Stress Strain Curves
FIG. 55

LEGEND:
- Calculated Composite Curve
- Full Section Compr. Curve

HRSK Track
Specimen C5
(HRSK 16 - 37.5)

Strain (in./in. x 10^-3)

Composite vs. Full Section Compression Stress Strain Curves
LEGEND:

- CALCULATED COMPOSITE CURVE
- FULL SECTION COMPR. CURVE

STRESS (ksi)

10
20
30
40
50
60

STRAIN (in./in. x 10^-3)

1
2
3
4
5
6

HRSK TRACK
SPECIMEN C6
(HRSK 16 - 375)

COMPOSITE VS. FULL SECTION COMPRESSION STRESS STRAIN CURVES
Tensile Stress Strain Curves for 1/8" x 1/8" Strip Specimens from Flats of Roll Formed 16 Gauge Track Section.

FIG. 57

See Fig. 3 for specimen location in the cross section.
FIG. 58

NOTE: SPECIMENS C-1, H-1, AND H-2 CONTAINED SOME CORNER MATERIAL.

LEGEND:

--- YIELD STRENGTH

--- ULTIMATE STRENGTH

○ SERIES 1 FLATS

▲ SERIES 2 FLATS

+ CORNERS

SEE FIG. 37 FOR LOCATION OF SPECIMENS IN THE CROSS SECTION.

VARIATION OF TENSILE YIELD AND ULTIMATE STRENGTHS IN THE CROSS SECTION OF A 10 GAGE ROLL FORMED HRSK CHANNEL (H05X10-37K)
Variation of Compressive Yield Strength in the Cross Section of a 10 Gage Roll Formed HRSK Channel (HRSK 10-37.0)

Legend:
- Series 1 Flats
- Series 2 Flats
- Corners

See Fig. 40 for location of specimens in the cross section.
FIG. 60

**Legend:**
- Calculated Composite Curve
- Full Section Tension Curve

**HRSK Channel Specimen TT**
(HRSK 10-37.0)

**Composite vs. Full Section Tension Stress Strain Curves**
LEGEND
- Calculated Composite Curve
- Full Section Tension Curve

HRSK Channel Specimen 78
(HRSK 10 37.0)

Composite vs. Full Section Tension Stress Strain Curves
FIG. 62

LEGEND:
- CALCULATED COMPOSITE CURVE
- FULL SECTION TENSION CURVE

HRSK CHANNEL SPECIMEN 7.9
(HRSK 10-37.0)

STRAIN (in./in. x 10^-3)

COMPOSITE VS. FULL SECTION TENSION STRESS STRAIN CURVES
FIG. 63

LEGEND:

- Calculated Composite Curve
- Full Section Compr. Curve

HRSK Channel Specimen C7 (HRSK 10-37.0)

Stress (kips)

0 10 20 30 40 50

0.2% 0.5% Elong.

Strain (in./in. x 10^-3)

0 1 2 3 4 5 6

Composite vs Full Section Compression Stress Strain Curves
HRSK Channel Specimen C8
(HRSL 10-37.0)

Composite vs. Full Section Compression Stress Strain Curves
FIG. 65

**Legend:**
- Calculated Composite Curve
- Full Section Compr. Curve

**HRSK Channel Specimen CSA**
(HRSK 10-37.0)

**Stress (ksi)**

0 10 20 30 40 50 60

**Strain (in./in. x 10^-3)**

0 1 2 3 4 5 6

**Composite vs. Full Section Compression Stress Strain Curves**
FIG. 66. FULL SECTION STRESS STRAIN CURVES FOR CHANNEL SECTION
OF 10 GAGE HOT ROLLED SEMI-KILLED STEEL

HRSK 10 = 37.0

(LATERALLY UN SUPPORTED )
FIG. 67. FULL SECTION STRESS STRAIN CURVES FOR LIPPED ANGLE SECTION OF 16 GAGE HOT ROLLED STEEL (LATERALLY SUPPORTED).
FIG. 68. FULL SECTION STRESS STRAIN CURVES FOR LIPPED ANGLE SECTION OF 16 GAGE HOT ROLLED STEEL (LATERALLY UNSUPPORTED)
FIG. 69. FULL SECTION STRESS STRAIN CURVES FOR CHANNEL SECTION OF 16 GAUGE HOT ROLLED STEEL (LATERALLY SUPPORTED)
FIG. 70. FULL SECTION STRESS STRAIN CURVES FOR HAT SECTION OF 16 GAUGE COLD REDUCED KILLED STEEL (LATERALLY SUPPORTED)
FIGURE 71

LEGEND:
○ Compressive Specimen C 14
△ Compressive Specimen C 15
□ Tensile Specimen T 12

Nominal Dimensions
a = 1.250"
b = 1.850"
c = 0.525"
t = 0.058"

FIG. 71. FULL SECTION STRESS STRAIN CURVES FOR HAT SECTION OF 16 GAGE COLD REDUCED KILLED STEEL (LATERALLY UNSUPPORTED)
FIG. 72. SECTIONS USED IN PREDICTION OF FULL SECTION TENSILE STRENGTH.
FIG. 73. ROLL FORGED COMMERCIAL SECTIONS.

SECTION A

Typical welding of end plates for full section tension tests.

All Material 10.6" Galv. Steel.

SECTION B