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STRUCTURAL BEHAVIOR AND DESIGN OF THICK, COLD-FORMED STEEL MEMBERS

by

Wei-Wen Yu,[1] Victor A. S. Liu[2] and William M. McKinney[3]

INTRODUCTION

In steel design, the AISI Specification[1] has long been used for the design of structural members, cold-formed to shape from steel sheet or strip, that are intended for load-carrying purposes in buildings. The design provisions included in the Specification were developed from research in which material less than 1/4 inch in thickness[2] was used.

During recent years, cold-formed members fabricated from steel sheets and plates up to 1/2 inch thick have been successfully used in buildings, bridges, car bodies, transmission poles, and other structures.[3] In some cases, cold-formed steel plate sections up to 3/4 inch in thickness have been used for steel transmission poles.

In order to provide the needed design criteria for thick, cold-formed steel sections, the scope of the AISI Specification was extended in 1968 to include steel members up to 1/2 inch in thickness.

In 1971, a new research project on thick, cold-formed steel members was initiated at the University of Missouri-Rolla under the sponsorship of American Iron and Steel Institute. The objective of the project

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was to study the structural behavior of steel members cold-formed from thick sheets and plates and to develop additional design recommendations if necessary.

This project consisted of the following four phases:

1. Preliminary investigation
2. Analytical study
3. Experimental verification
4. Preparation of design recommendations

PRELIMINARY INVESTIGATION

It is well known that the structural behavior of cold-formed steel members depends mainly on the material properties of the steel and on the configuration of the cross section. A major task in the preliminary investigation was to review the 1968 AISI design provisions for the design of thick, cold-formed steel members up to about 1 inch in thickness. In this regard, due consideration was given to several factors, such as manufacturing process, limitation on bend radius, practical width-to-thickness ratios, material properties, and initial imperfections.

ANALYTICAL STUDY

Following the preliminary investigation, a study was conducted to determine for thicknesses up to 1 inch, the effective design width of stiffened elements and the allowable design stress for unstiffened compression elements. The effect of initial imperfection on buckling strength and effective width was also considered.

In cold-formed steel design, the effective design width of stiffened elements can be computed by the following formula which was developed by Winter:[2]

$$b = 1.9t\sqrt{\frac{E}{f_{max}}}\ [1 - \frac{0.415}{(w/t)}\ \sqrt{\frac{E}{f_{max}}}\ ] \qquad (1)$$

In this formula, b is the effective design width, w is the actual width, t is the thickness of material, E is the modulus of elasticity, and f_{max} is the maximum edge stress. The equation is based on Winter's extensive investigation on light gage, cold-formed steel sections. It reflects the cumulative effects of various imperfections, including initial deviations from flatness.

The influence of small, initial out-of-flatness on the structural behavior of simply supported square plates subjected to unidirectional edge compression has been studied analytically by Hu et al.[4], Coan,[5] Yamaki,[6] Abdel-Sayed,[7] and Yang.[8] It was found that an initial imperfection will reduce the buckling strength and the effective width of stiffened compression elements. Figure 1 shows the relationship between the b/w and δ_o/t ratios based on References 4 and 7. In the figure, δ_o represents the initial deviation from flatness. Correlations between various formulas and the test data of Winter, Johnson, Wang, Errera, Dwight, and Ractliffe are shown in Figure 2.[9-12]

Because the preliminary investigation indicated that the δ_o/t ratio decreases as the thickness of steel sheet or plate increases, it can be seen from Figures 1 and 2 that the AISI effective design width formula developed from the study of thin sheets can be conservatively used for those sections fabricated from relatively thick plates for which the δ_o/t ratios are relatively small.

For unstiffened compression elements, a literature survey indicated that no specific information is available which describes the effect of initial deviation from flatness on the buckling strength of compression elements. A finite element analysis, which uses a NASTRAN computer program,[13] provides the load deformation relationships of two arbitrarily selected unstiffened compression elements that have various degrees of initial imperfections, as shown in Figure 3. The reduction of buckling strength of a plate can be obtained by the Top-of-the-Knee Method. Based on a reason similar to one used for stiffened elements, the current AISI design formula for the allowable stress of unstiffened elements that was developed for thin, cold-formed steel sections can also be used conservatively for thick plates.

EXPERIMENTAL INVESTIGATION

It is well known that the mechanical properties of steel, such as yield point, tensile strength, and ductility, are affected by the cold-work applied to steel members during the forming operation. Usually, cold work increases the yield point and the tensile strength of steel but reduces its ductility.[2]

The current AISI design provision for determining the yield point of corners is based on a study conducted by Britvec, Chajes, Karren, Uribe, and Winter at Cornell University.[14] The constants used in the empirical equations were determined by Karren[15] on the basis of both cold-reduced and hot-rolled sheet steels. The thicknesses of the steel sheets used in the investigation range from 0.06 to 0.15 inches. The yield strengths of the virgin materials vary from 29.5 to 45.2 ksi.

The experimental study recently conducted at the University of

Missouri-Rolla (UMR) was concentrated on the change brought about in the mechanical properties of thick sheets and plates by cold-work. The primary objective of the study was to verify the applicability of the AISI design provision for steel sheets and plates thicker than 1/4 inch. The specimens used in the testing program were channel sections, as shown in Figure 4. These specimens were cold-formed from 1/2 and 1 inch steel plates by using a hydraulic press. The dimensions of the cross sections were purposely designed to cover the following variables:

(1) Thicknesses of material: 1/2 and 1 inch

(2) R/t ratios: 3, 5, and 6

(3) Types of stress: tension and compression

(4) Types of steel: A36 and A588 steels

Three types of testing were involved in the UMR program. They are:

(1) Tensile and compressive tests of virgin steels

(2) Tensile tests of corner sections

(3) Compressive tests of corner sections

(1) Tensile and Compressive Tests of Virgin Steels

Eight tension specimens, prepared from the 1/2 and 1 inch, A36 and A588 flat steel plates, were tested in a 200,000 pound, Tinius Olsen, universal testing machine. The dimensions of the specimens and the test procedures were based on ASTM Specification E8.[16] The stress-strain curves were obtained by using an autographic recording device.

Eight rectangular compression specimens, prepared from A36 and A588 flat steel plates, were also tested in the Tinius Olsen, universal testing machine. The dimensions of the specimens satisfy the requirements of the Technical Memorandum, No. 2, of the Column Research

Council[17] and of Appendix A of the AISI Specification.[1] The stress-strain relationships of the compressive tests were obtained by using a pair of 1/4 inch, foil strain gages mounted on opposite surfaces of the specimens. During the testing, the applied load and strain gage readings were recorded and printed by using a 40-channel Data Acquisition System.

The typical stress-strain curves for the 1/2 inch thick, A36 and A588 steels are shown in Figure 5. It should be noted that for A588 steel, the strain hardening begins at a much smaller strain than A36 steel. In some cases, A588 steel may have a gradual yielding type of stress-strain curve depending on the rolling history.

(2) Tensile Tests of Corner Sections

In view of the fact that the corner sections cut from the channels are excessively large for testing in the machine available at the UMR structural laboratory, five tensile coupons were cut from each 1/2 inch thick corner as shown in Figures 6 and 7 for the nominal R/t ratios equal to 3 and 6, respectively. After both ends were press flattened, the central reduced portion was machined to the typical dimensions for the 2-inch gage length specimens specified by ASTM E8. During the preparation of the tensile coupons, special care was taken to avoid the possible effect of machining on the properties at corner sections by using a proper cooling process.

A total of 40 tensile coupons were tested in the same manner as that used in the testing of virgin steels. Figures 8 and 9 show the typical stress-strain curves of A36 steel, individual coupon tests for R/t equal to 3 and 6, respectively. Also shown in the figures are the composite curves that represent the stress-strain relationship of an entire corner section. They were computed from the measured stresses for individual coupons. The typical distribution along the curved corner sections of the tensile yield points of A36 and A588 steels is shown in Figure 10.

(3) Compressive Tests of Corner Sections

For A36 steel, four corner specimens cut from 1/2 inch thick channels (Figure 11) and four corner specimens cut from 1 inch thick channels were tested under compression. The stress-strain relationships were obtained by using a pair of 1/4 inch foil strain gages mounted on opposite surfaces of the specimens.

For A588 steel, compression tests were conducted for two full corners, four half corners (Figure 12), and ten small specimens (Figure 13) cut from 1/2 inch thick channels, and 20 small compression specimens cut from the corners of 1 inch thick channels in the same manner as that used for the testing of A36 steel corners. The stress-strain relationships of all compression tests were obtained by using the 1/4 inch foil strain gages.

The typical stress-strain curves of the corner tests under compression are shown in Figures 14 and 15.

(4) Evaluation of Test Data

The results obtained from the UMR tests have been compared with the AISI design formulas.[1] For A588 steel, good agreements were found between the tested and computed corner yield points. As shown in Table 1, the ratios of $(F_{yc})_{test}/(F_{yc})_{comp}$ range from 0.94 to 1.03. For A36 steel, the test data show a slightly larger scatter; the ratios of $(F_{yc})_{test}/(F_{yc})_{comp}$ vary from 0.87 to 1.01 as indicated in Table 2.

It was realized that there is a slight difference in the stress-strain curves for two different steels, as shown in Figure 5. A study indicated that a somewhat better result of the corner yield point of A36 steel could be obtained by using the following equations derived by regression analysis[18,19] with a 95 percent probability of the corner tests for thin, hot-rolled steels as reported in Reference 15.

$$F_{yc} = B_c F_y/(R/t)^m \tag{2}$$

$$B_c = 4.03 (F_u/F_y) - 0.898 (F_u/F_y)^2 - 2.26 \tag{3}$$

$$m = 0.187 (F_u/F_y) - 0.072 \tag{4}$$

where F_{yc} = tensile yield point of corners

F_y = tensile yield point of virgin steel

F_u = ultimate tensile strength of virgin steel

R = inside bend radius

t = thickness of steel

The comparison of the tested yield points of corners and the computed values on the basis of Equations (2) to (4) is given in Table 3.

It should be noted that Equations (2) to (4) are similar to current AISI design criteria except that slight modifications have been made on the constants used in Equations (3) and (4). These equations can be conservatively used for A588 steel.

SUMMARY

A study was made on the use of the AISI Specification for the design of steel structural members cold-formed from thick sheets and plates. Experiments were conducted to study the increase in yield point caused by the cold-work. The purpose of the investigation was to verify the validity of the AISI design rules for thick, cold-formed steel members.

For stiffened and unstiffened compression elements, initial deviation from true flatness reduces the buckling strength and the effective design width of the elements. In view of the fact that thick sheets and plates usually have small δ_o/t ratios as compared with thin sheets, the AISI design formulas for determining the effective design width of stiffened elements and the allowable stress for unstiffened elements can be conservatively used for sections cold-formed from thick sheets and plates.

One hundred tests were conducted to study the increase in yield point at corners of channel sections cold-formed from 1/2 inch and 1 inch, A36 and A588 steel plates. It was found that the AISI design provisioh for the calculation of corner yield point provides good results for thick steel sheets and plates having a sharp yielding stress-strain curve with a small plateau and for cold-rolled sheets and strip. For steel sheets, strip and plates having a sharp yielding type of stress-strain curve with a large plateau, the AISI design formula can also provide reasonable results; however, modified formulas may be used to improve the accuracy of prediction of tensile yield points for corner sections.

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NOTATIONS

The following symbols are used in this paper:

b = effective design width

E = modulus of elasticity

f_{max} = maximum edge stress

F_{yc} = tensile yield point of corners

F_y = tensile yield point of virgin steel

F_u = ultimate tensile strength of virgin steel

R = inside bend radius

t = thickness of the plate

w = actual width of the plate

δ_o = initial deviation from flatness

TABLE 1

COMPARISON OF TESTED YIELD POINT OF CORNERS AND COMPUTED TENSILE YIELD POINT OF CORNERS
(A588 Steel)
(Based on the AISI Formulas[1])

Thickness t (In.)	R/t	Type of Stress	Virgin Properties				Computed F_{yc} (ksi)	Tested F_{yc} (ksi)	$\frac{(F_{yc})_{test}}{(F_{yc})_{comp}}$
			F_y (ksi)	F_u (ksi)	B_c	m			
0.488	3.07	tension	60.4	83.5	1.742	0.197	84.4	79.7	0.94
		compression	62.5	----	-----	-----	84.4*	80.1	0.95
0.490	5.98	tension	60.4	83.5	1.742	0.197	74.0	73.8	1.00
		compression	62.5	----	-----	-----	74.0*	73.5** 74.9***	0.99 1.01
0.995	3.07	tension	60.3	89.0	1.871	0.215	88.7	----	----
		compression	62.6	----	-----	-----	88.7*	84.0	0.95
0.999	5.01	tension	60.3	89.0	1.871	0.215	79.8	----	----
		compression	62.6	----	-----	-----	79.8*	81.9	1.03

* Based on the computed tensile yield point of corners

** Each 90° corner was cut into two parts for testing purposes

*** Each 90° corner was cut into five parts for testing purposes

TABLE 2

COMPARISON OF TESTED YIELD POINT OF CORNERS AND COMPUTED TENSILE YIELD POINT OF CORNERS
(A36 Steel)
(Based on the AISI Formulas[1])

Thickness t (In.)	R/t	Type of Stress	Virgin Properties				Computed F_{yc} (ksi)	Tested F_{yc} (ksi)	$\frac{(F_{yc})_{test}}{(F_{yc})_{comp}}$
			F_y (ksi)	F_u (ksi)	B_c	m			
0.534	3.18	tension	42.9	68.6	2.016	0.239	65.6	57.2	0.87
		compression	44.0	----	-----	-----	65.6*	57.7	0.88
0.543	6.08	tension	42.9	68.6	2.016	0.239	56.2	51.3	0.91
		compression	44.0	----	-----	-----	56.2*	49.6	0.88
1.001	3.05	tension	40.2	67.9	2.106	0.256	63.7	----	----
		compression	40.0	----	-----	-----	63.7*	58.9	0.93
0.993	5.04	tension	40.2	67.9	2.106	0.256	56.0	----	----
		compression	40.0	----	-----	-----	56.0*	56.3	1.01

* Based on the computed tensile yield point of corners.

TABLE 3

COMPARISON OF TESTED YIELD POINT OF CORNERS AND COMPUTED TENSILE YIELD POINT OF CORNERS
(A36 Steel)
(Based on Eqs. 2, 3 and 4)

Thickness t (In.)	R/t	Type of Stress	Virgin Properties				Computed F_{yc} (ksi)	Tested F_{yc} (ksi)	$\frac{(F_{yc})_{test}}{(F_{yc})_{comp}}$
			F_y (ksi)	F_u (ksi)	B_c	m			
0.534	3.18	tension	42.9	68.6	1.888	0.228	62.3	57.2	0.92
		compression	44.0	----	-----	-----	62.3*	57.7	0.93
0.543	6.08	tension	42.9	68.6	1.888	0.228	53.7	51.3	0.96
		compression	44.0	----	-----	-----	53.7	49.6	0.93
1.001	3.05	tension	40.2	67.9	1.985	0.244	60.8	----	----
		compression	40.0	----	-----	-----	60.8	58.9	0.97
0.993	5.04	tension	40.2	67.9	1.985	0.244	53.7	----	----
		compression	40.0	----	-----	-----	53.7	56.3	1.05

* Based on the computed tensile yield point of corners.

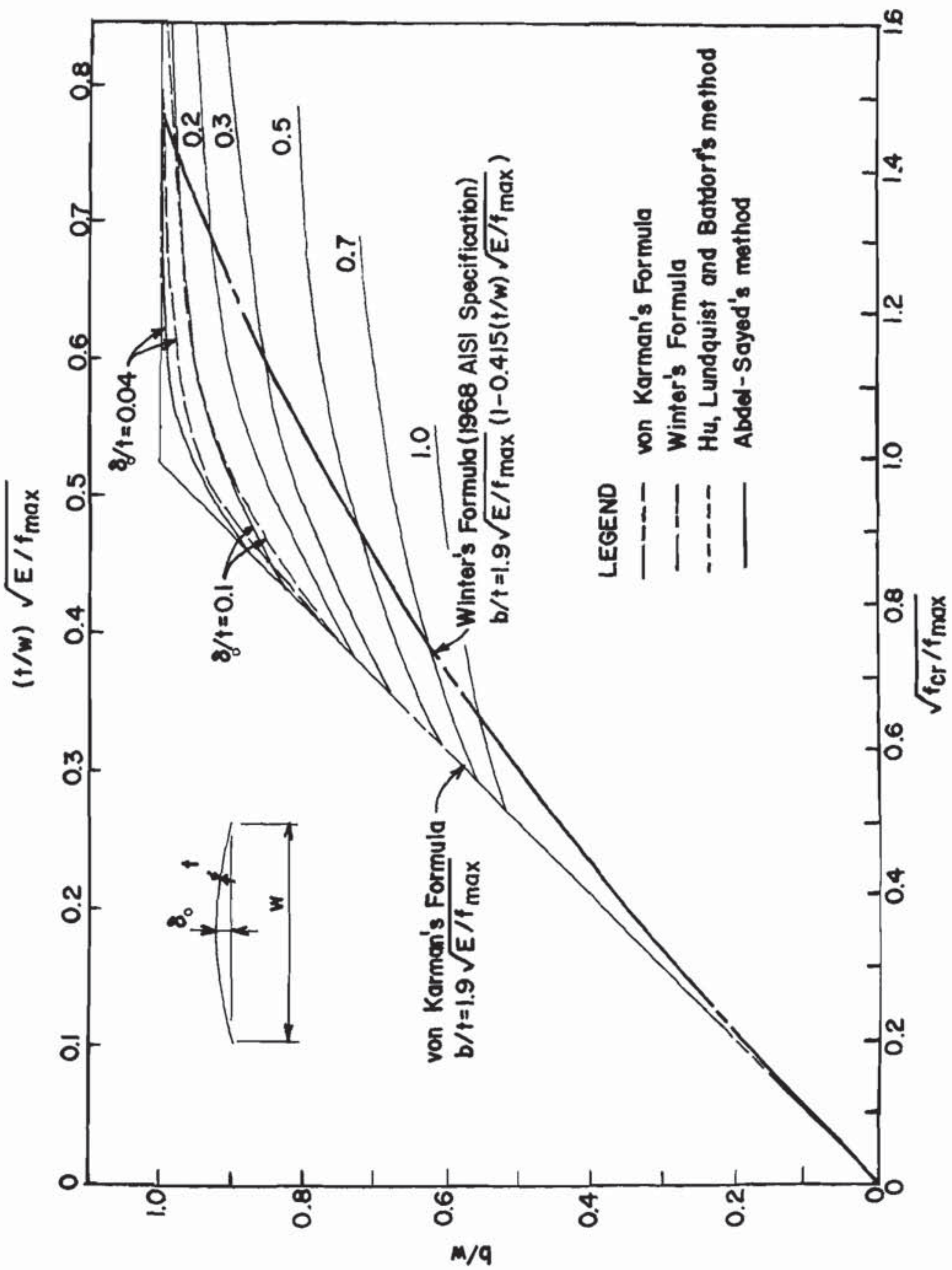

Fig. 1. Reduction of the Effective Design Width Due to Initial Deviation from Flatness

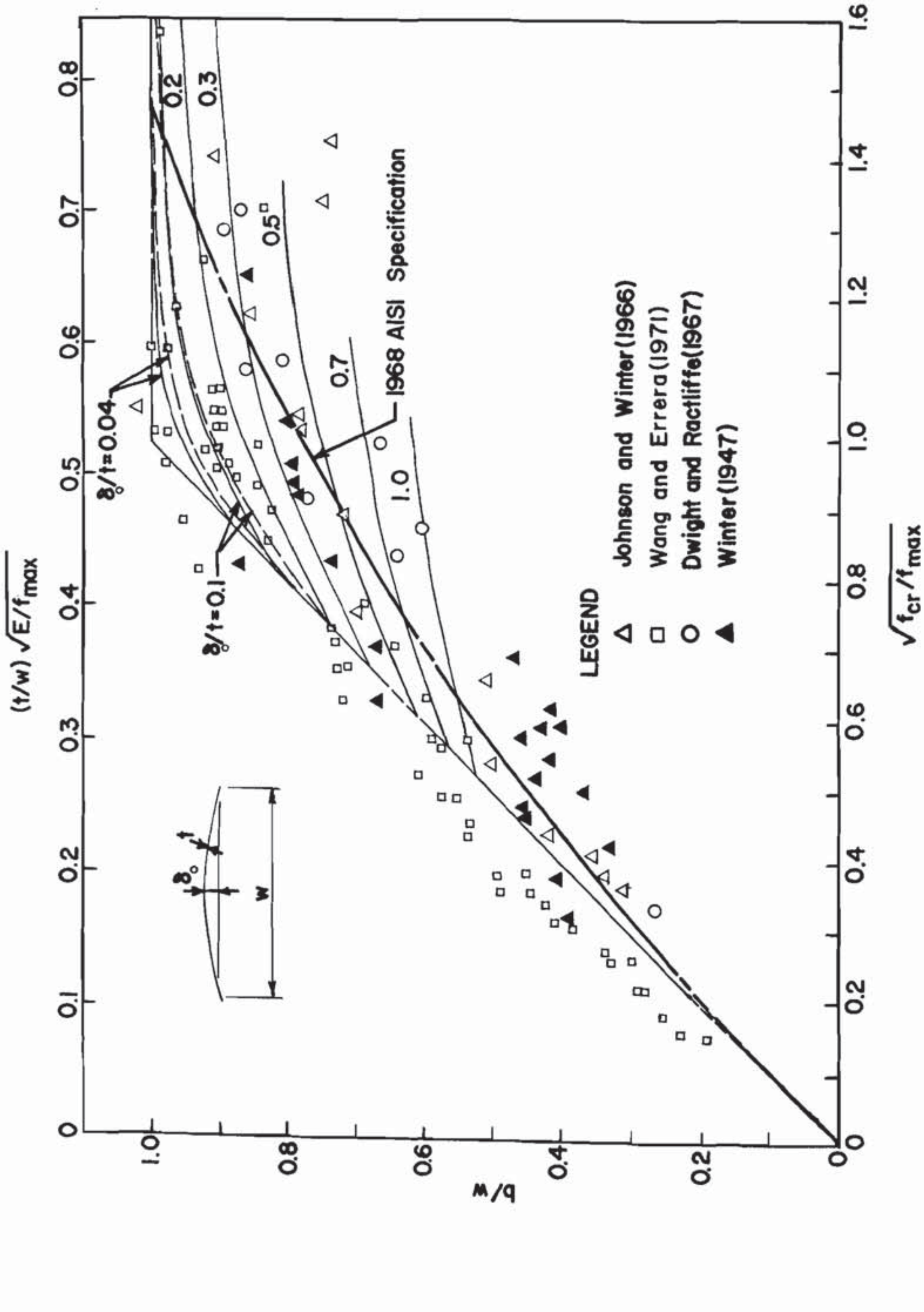

Fig. 2. Correlation Between Test Data and Various Formulas

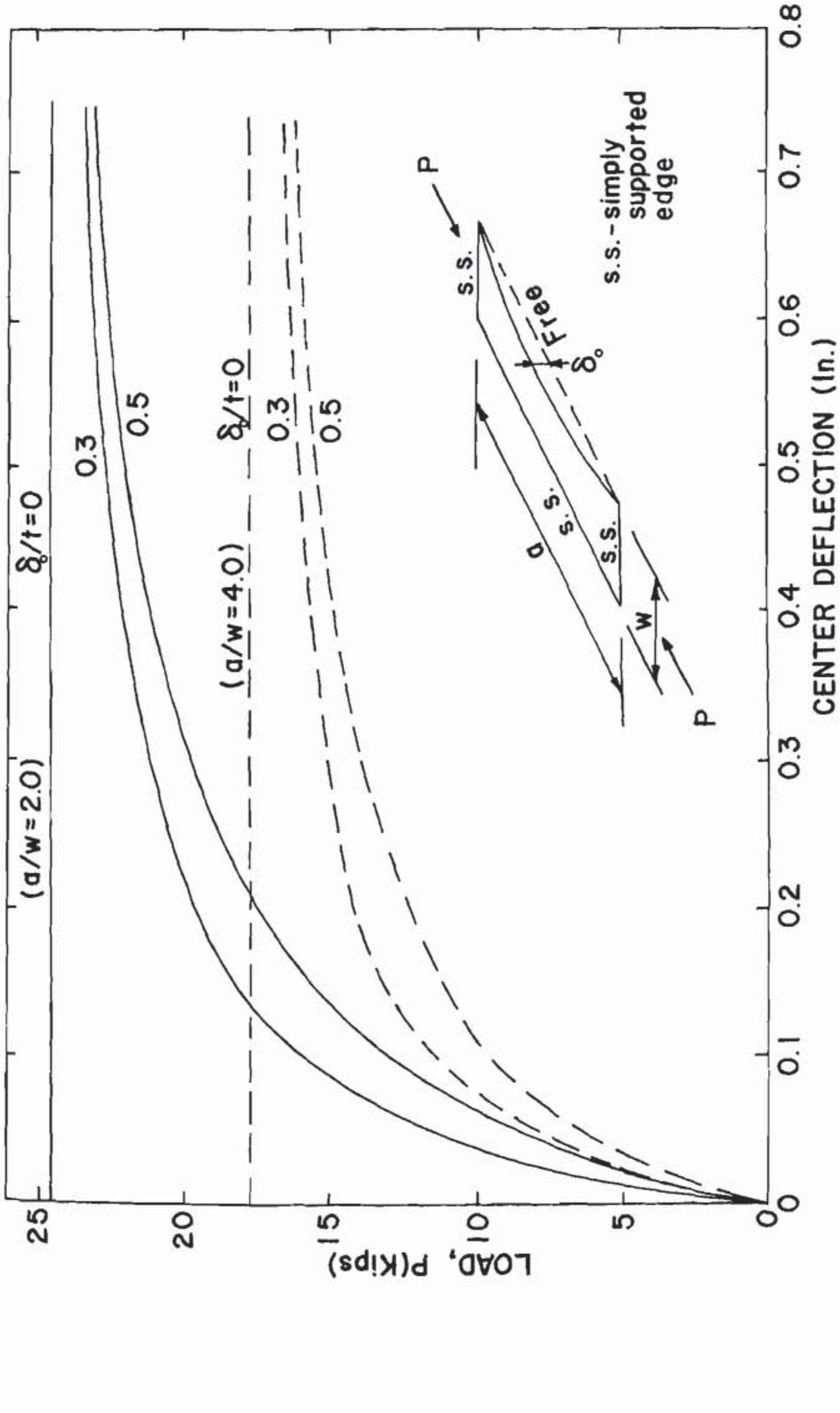

Fig. 3. Effect of Initial Imperfection on Load-Deformation of Unstiffened Compression Elements

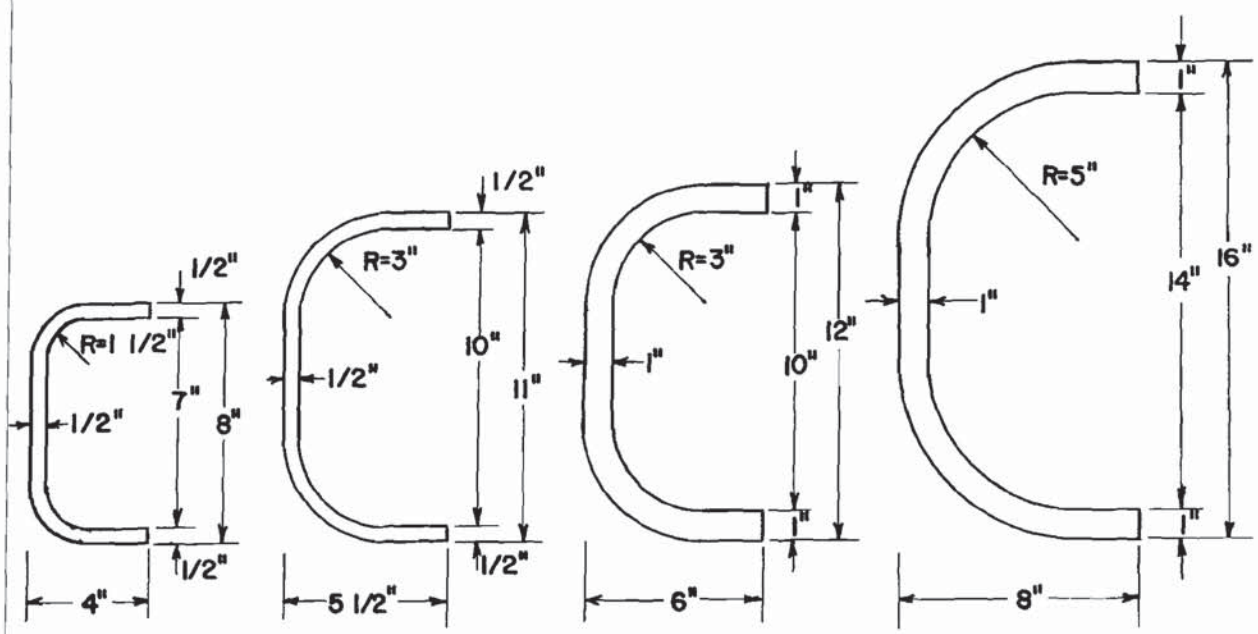

Fig. 4. Nominal Dimensions for Channel Sections Used in the UMR Experimental Investigation

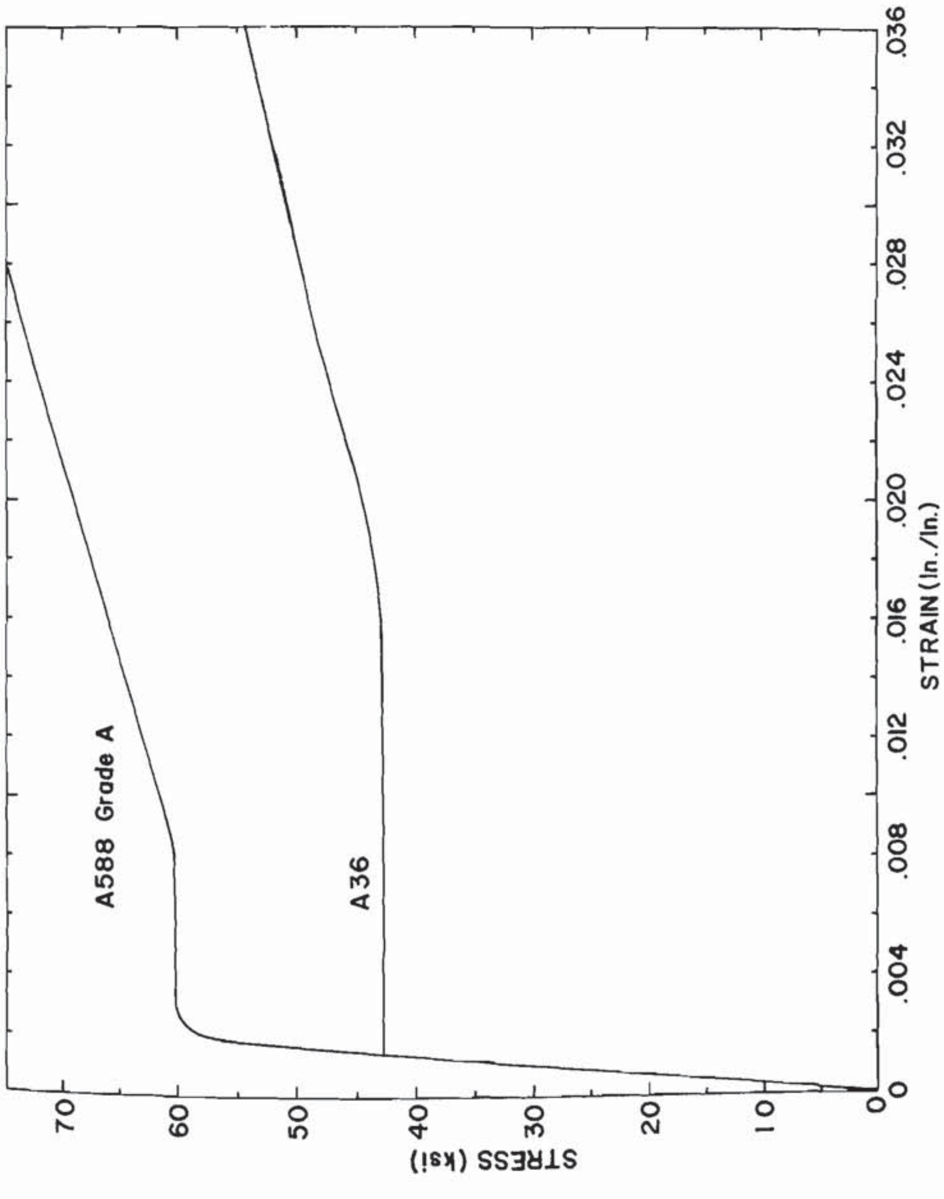

Fig. 5. Stress-Strain Curves of A36 and A588 Steels Based on Tensile Tests

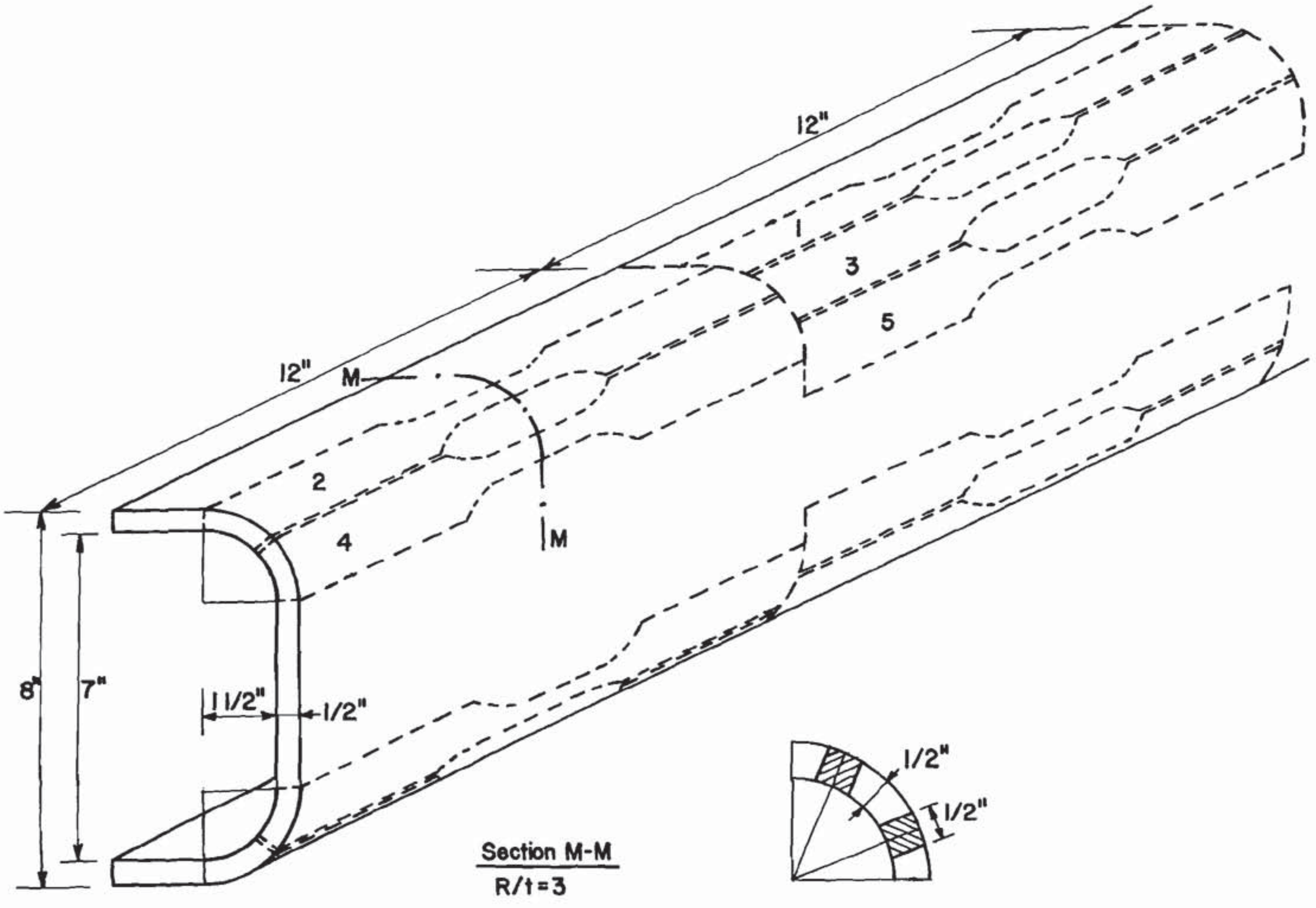

Fig. 6. Location of Tensile Coupons for R/t = 3

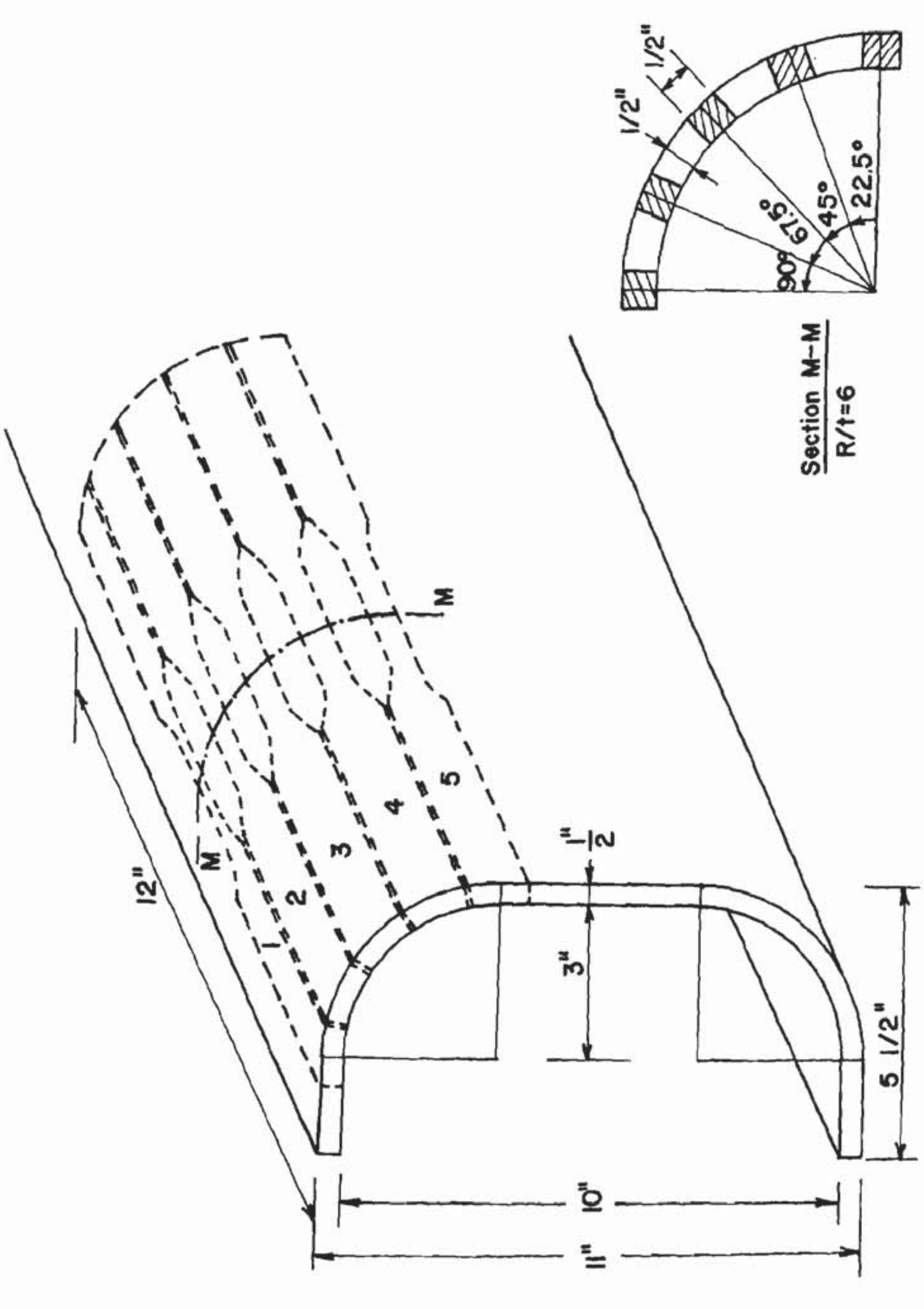

Fig. 7. Location of Tensile Coupons for R/t = 6

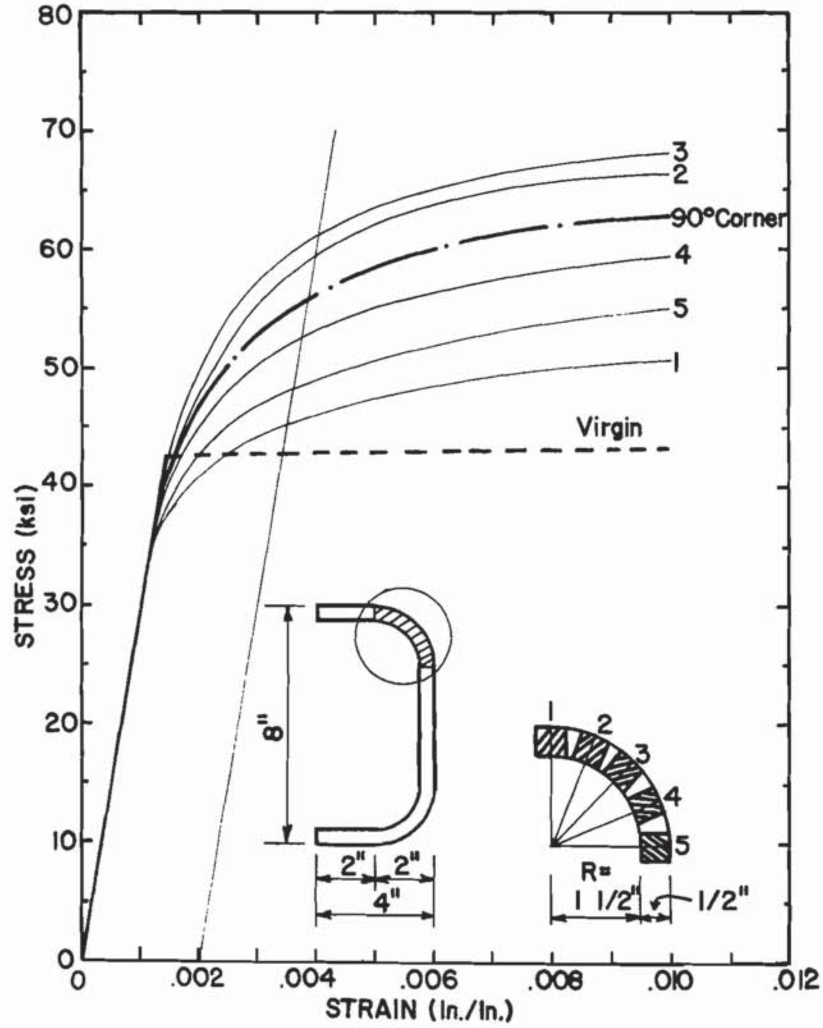

Fig. 8. Typical Stress-Strain Curves for Tensile Coupons
(R/t = 3)(A36 Steel)

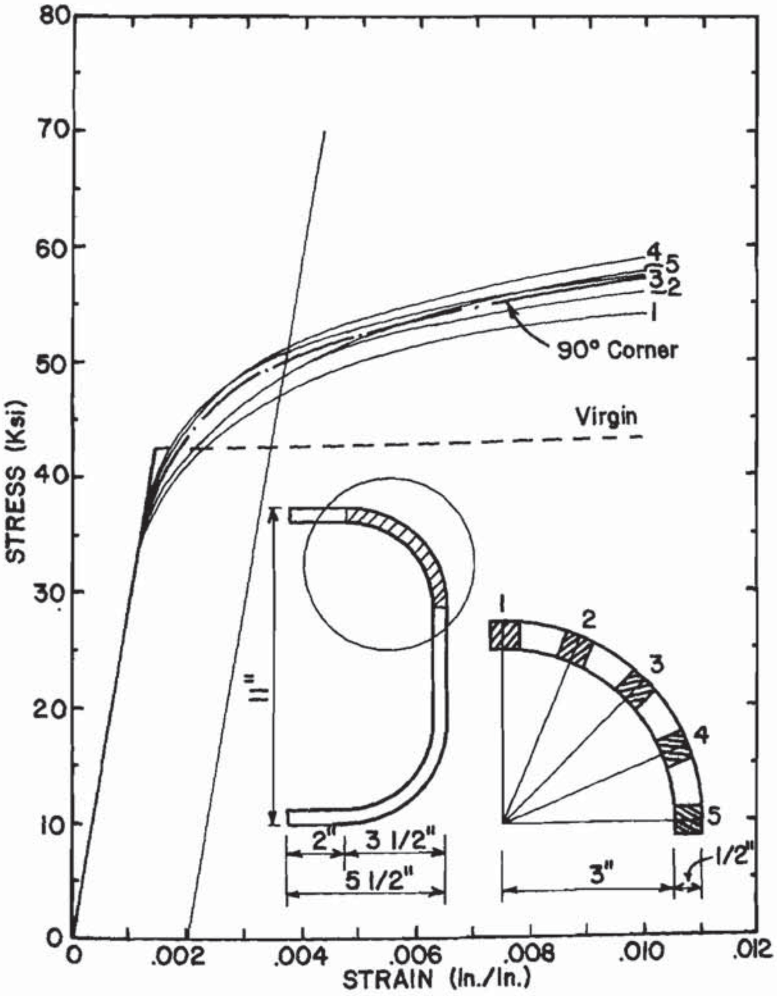

Fig. 9. Typical Stress-Strain Curves for Tensile Coupons
(R/t = 6)(A36 Steel)

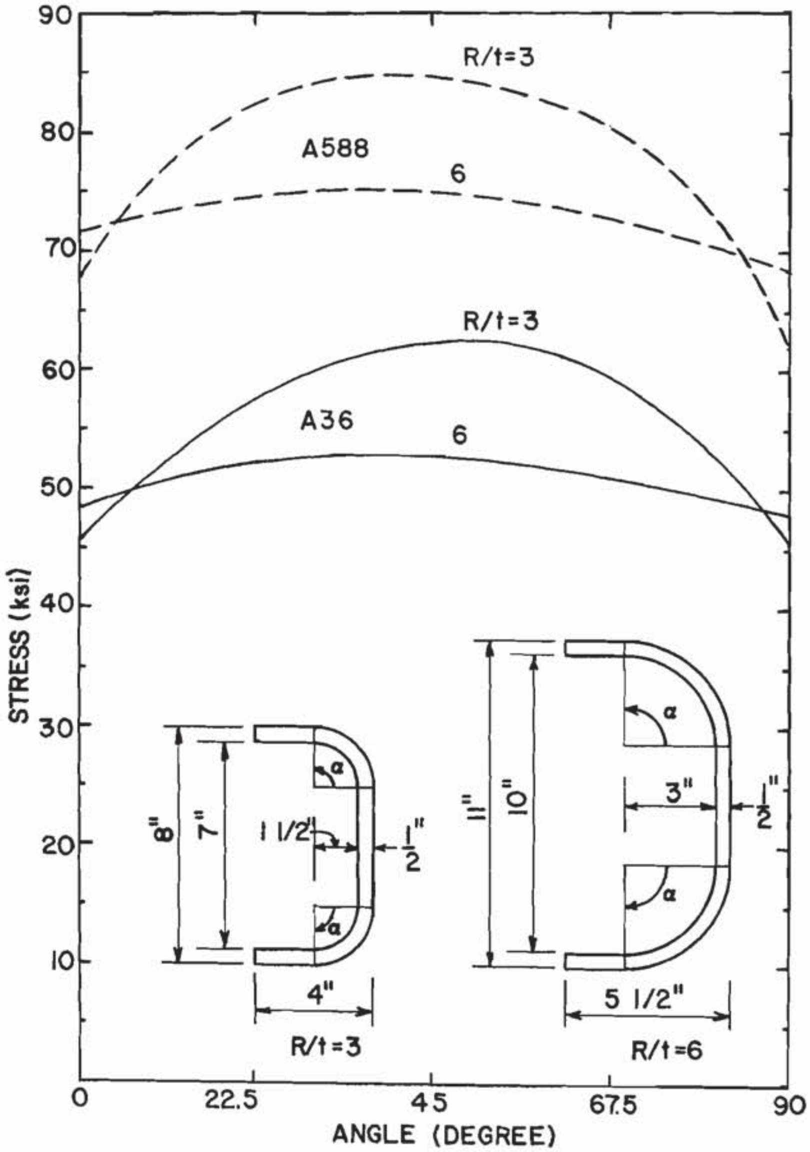

Fig. 10. Typical Distribution of the Tensile Yield Points of A36 and A588 Steels Along the Curved Corner Section (Nominal Dimensions)

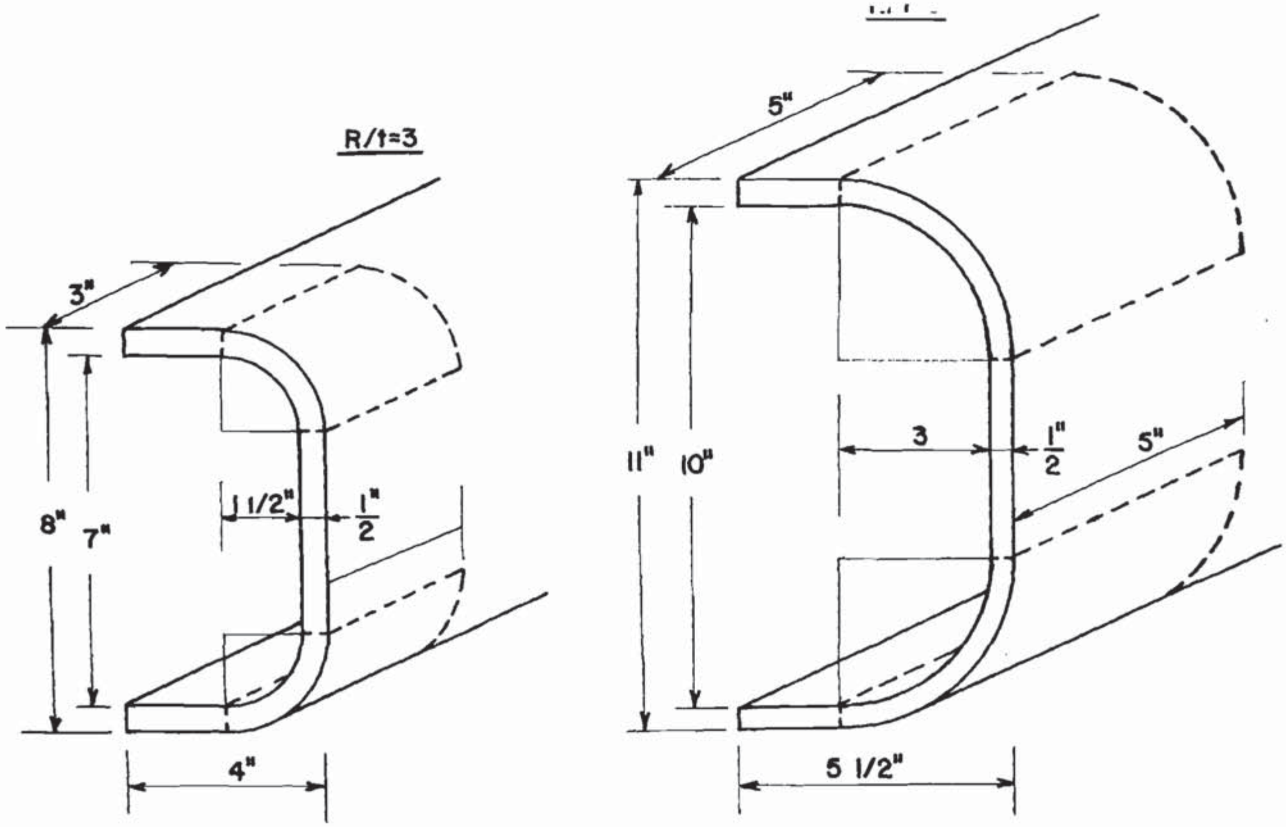

Fig. 11. Location of Compressive Coupon for Corner Test

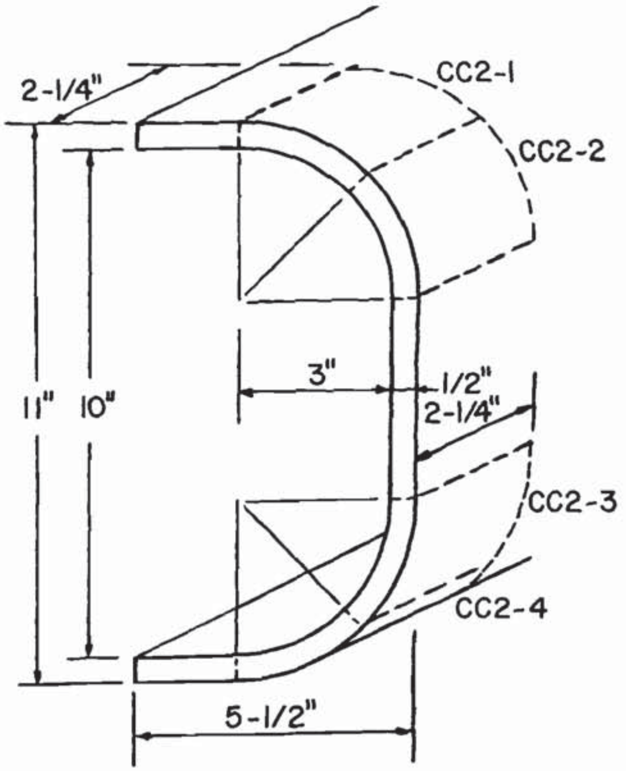

Fig. 12. Half Corner Specimens (A588 Steel) (Nominal Dimensions)

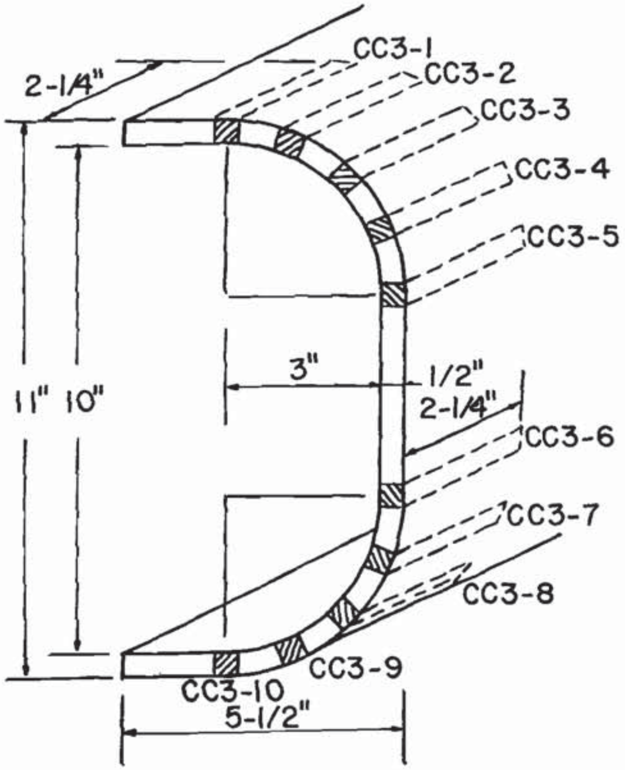

Fig. 13. Individual Coupons Used for Compression (A588 Steel) (Nominal Dimensions)

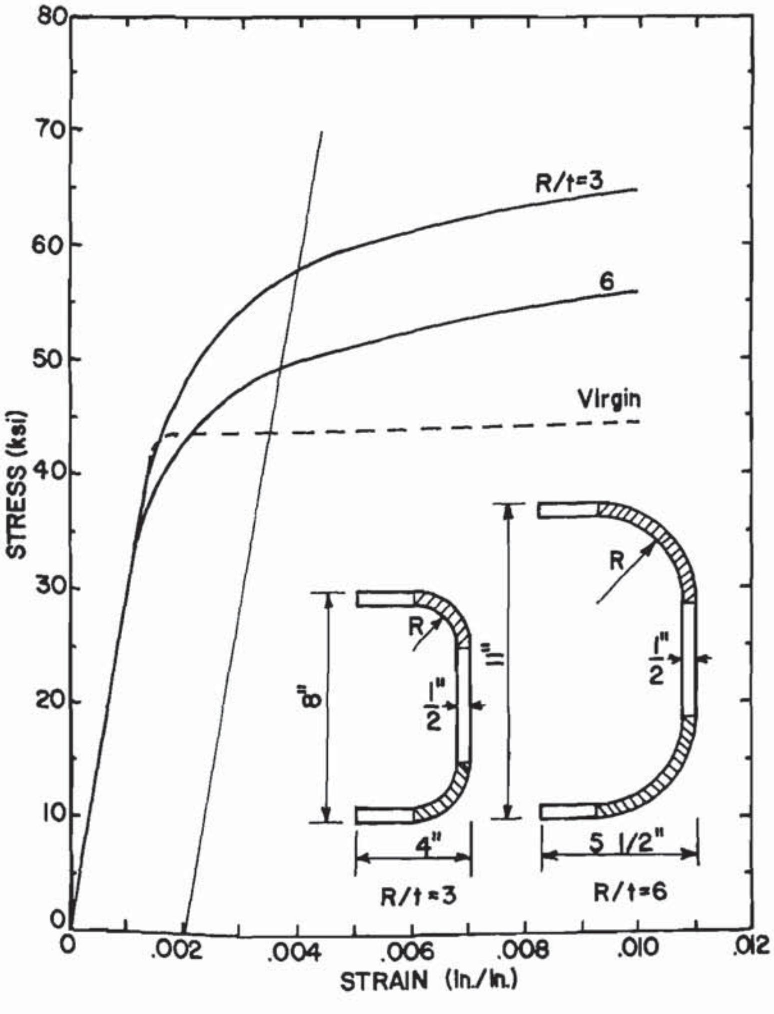

Fig. 14. Effect of R/t Ratio on Compressive Yield Point of Corners (A36 Steel)

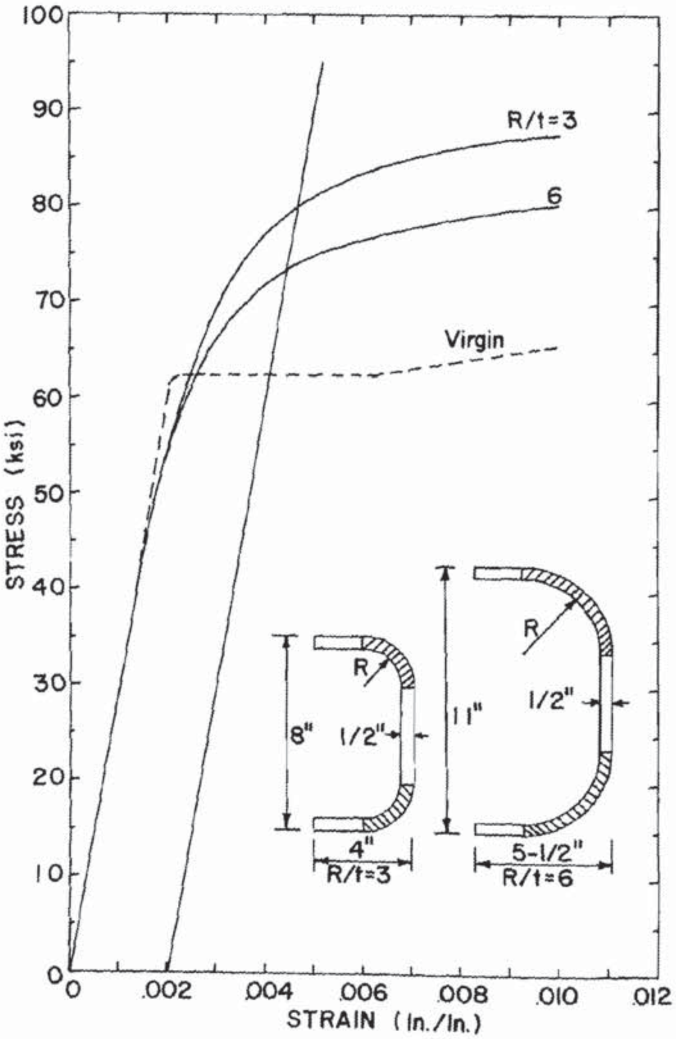

Fig. 15. Effect of R/t Ratio on Compressive Yield Point of Corners (A588 Steel)