THE ULTIMATE STRENGTH OF COLUMNS IN CONTINUOUS FRAMES

By Lynn Beedle, Joseph Ready and Bruce Johnston
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The Chairman announced that a statement of the unencumbered financial balance would be sent to the membership in addition to a revised roster of the Council. The annual meeting adjourned at 12:30 p.m.

Respectfully submitted,

Lynn S. Beedle
Acting Secretary
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LSB/ps
ABSTRACT

Test equipment has been developed in which any desired combinations of axial load and end moments of 8, 12, and may be applied to metal columns. Lengths up to 16 feet and may be accommodated in the apparatus. Axial load is applied by a universal testing machine, the end moments being applied with tension-compression hydraulic jacks mounted in series with dynamometers which measure the thrust.

A pilot test was conducted on a 4"WF member sixteen feet long under three different test conditions, calculated Good agreement was obtained with buckling load and with the carry-over factor in the elastic range. Information which can be obtained from test equipment is described.

The program of tests to be sponsored by WRC and AISC during the coming year is presented. The behavior of structural columns in the inelastic region of stress is to be emphasized.

A general understanding of the test apparatus and results may be obtained by reviewing the Figures as follows:

Apparatus: Fig. 1-19, 20, 23, 26, 27

Results: Figs

Program: Table I, II
In frame analysis by the method of Moment Distribution, unbalanced moments are distributed to the ends of members meeting at a joint in proportion to their rotational stiffness factors, and a portion of each distributed moment is "carried over" to the far end in proportion to a "carry-over factor".

If, now, the member is subjected to direct loads together with end moments, then these factors vary appreciably. If the elastic limit is passed, the factor will vary for columns of any length.

This is---the system of forces under which continuous columns act in existing frames and their real behaviour is not understood. There is---understood---even---less---the---action of such members when subjected to "Plastic-Design"-loads. There is increasing evidence that such design procedures should be adopted to more effectively use steel.---Note the work by Baker and his associates in England and that theoretically proposed by Van den Broek in this country.

In 1946, with two objectives, then, the American Institute of Steel Construction sponsored this project with two objectives:

(a) to determine the carry-over and stiffness factors of steel columns in the elastic and plastic range, and,

(b) to determine the influence of compressive load on these two factors when combined with various end moments.

Numerous tests have been conducted on small specimens, but none of this size have come to the attention of the authors in which a constant axial load could be maintained while the applied moment was varied.

INTRODUCTION
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The program is coordinated with an investigation on ultimate strength of Welded Continuous Frames sponsored by the Welding Research Council. These tests are being conducted concurrently with the column investigations, each program eventually to contribute to the other.

(Continued on next page)
Due to this size it was necessary to develop elaborate test apparatus to allow for application of accurately known direct loads and end moments and for the measurement of these loads on deflections, strain, and end rotations of the effect on the test column. This equipment has now been designed and a single pilot test conducted to determine adequacy of apparatus.

This report is a description of the testing apparatus. Herein is described the method of applying loads and moments, the details of end fixtures and alignment procedure, and measurements made on the test column. Test results are presented only as a demonstration of the effectiveness of the equipment.
"To report on the properties of metals that affect buckling of Columns and to make recommendations for analytical and experimental studies needed".

The collection of compression stress-strain diagrams for various metals, multiple sample tests, and the determination of typical minimum tangent modulus curves for specific materials were suggested. Mr. Templin stated that his sponsoring organization had data related to this subject which could be made available to the Committee on Research.

8. FURTHER ASSIGNMENTS TO COMMITTEE ON RESEARCH - The following motion was adopted:

"To refer the list of column research problems contained in 'Summary of Answers to Questionnaire' dated March 31st, 1947, to the Committee on Research for evaluation and review, and to ask that committee to report back to the Technical Board with recommendations for analytical and/or experimental projects."

9. IMPULSE LOADING - Dr. Marcus discussed the possible importance of dynamic tests of columns which prompted discussion for an additional Committee on Research subcommittee. The Technical Board requested Dr. Marcus to address a letter to the Committee on Research on this subject, which had previously been suggested once (Item VII - 9) in the "Summary of Answers to the Questionnaire."

10. The meeting was adjourned at 4:10 p.m.

Respectfully submitted

Bruce G. Johnston
Secretary, Technical Board.
Literature on columns has been under review at the Fritz Engineering Laboratory for some time. Tests are known of this type made on structural steel rolled sections. Dr. W. R. Osgood used a similar test device for round tubular columns of aluminum and steel. The fixture, however, provided elastic restraint without introducing definite end rotations or moments.

In England, Baker and Roderick are conducting a significant program entitled, "Investigation into the Behavior of Welded Rigid Frame Structures" under the auspices of the British Welding Research Association. Five interim reports have been published by this group. Additional tests have been made and reports are being prepared. Studies have been confined to rectangular and small I-sections, which constitutes the significant difference between their program and that reported on herein. The two investigations should support one another.

For the test condition in which a concentric load is applied with no end moments, the buckling theory is well established. The Column Research Council is planning to recommend adoption of the tangent modulus theory which gives,

\[ \sigma_{cr} = \frac{\pi^2 E'}{(2/\lambda)^2} \]

in which \( \sigma_{cr} \) = the buckling load, the point where an initially straight column starts to deflect.

\( E' \) = the tangent Modulus of Elasticity

\( 1/\lambda \) = the slenderness ratio.

2) Of particular importance are the third and 4th, "Behaviour of Stanchions Bent in Single Curvature", and the
1) "Column Strength of Tubes Elastically Restrained Against Rotation at the Ends", by W. R. Osgood. NACA T.R. # 615, 1938
humbert - Bath
In the elastic region of stress the work of Dr. E.E. Lundquist at NACA will be of particular value in making comparison with experimentally determined values of stiffness and carry-over.

There will be some discrepancy in the deflection curve due to the insertion of very stiff sections (base plate, web of end fixture, knife edge seat) between the end of the column and the knife edge. Using the method of Dr. Osgood's paper to which reference has been made, the error for the shortest test column amounts to less than 1/2% and will be neglected. See Appendix III.

One application of the results of this research is in the development of a so-called "plastic (or 'limit') design procedure". It is the impression of numerous investigators that a more rational design procedure would be one in which design would be based on the true load-carrying capacity of the structure rather than the at the point of first initial yield. The first step in such a program is to understand the behavior of the frame and its members in both the elastic and, in particular, the plastic region of stress.

and J. W. Roderick


2) "Plastic Theory-- Its Application to Design", by J. F. Baker

and "Theory of Limit Design", by J. A. Van den Broek
Specimens

Two different structural steel members were selected in the original program to give a wide variation in the slenderness ratio, \( l/r \). Tests were proposed on 8 x 8 WF 31-lb and 4 x 4 WF 13-lb members in lengths of 8, 12, and 16 feet. The variation in \( l/r \) thus provided is from 27.6 to 111.5.

In the pilot test conducted, it was determined that the most slender column was tested, a 16-foot \( \text{W} \times \text{W} \) member with four-inch section, since it presented the most difficult problems from an equipment and measurement point of view. This test column is shown in Fig 13.

Application of Direct Concentric Load

An 800,000-lb. Riehle testing machine was used to apply the axial load. Fig. 3 shows the frame and column assembly positioned in the universal testing machine. The balance is sensitive to \( \text{W} \times \text{W} \) loads of the order of 50 to 100 pounds. The details of applying the axial load through bearing blocks and knife edges into the test member is described in the section "Column end support."

In order to provide a means of applying known moments (or angle changes) at the column ends and at the same time determine to be able to accurately the magnitude of axial load (and to control it), the general arrangement shown generally in Fig. 20 was adopted, shown photographically in Figs 1 and 2.

* At this point it would be helpful to the reader to open Fig. 20 for reference.
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Application of End Moments

To provide complete control and flexibility in applying end moment or end angle change, a system was evolved in which accurately measured forces, $F$, could be applied in either direction at the ends of lever arms at one or both ends of the test column. See accompanying sketches and may be followed in more detail in Fig. 20 for details.

The Test Frame (or moment loading frame—Fig. 20) was developed to provide a suitable support for the thrust-producing and measuring devices. The latter consist of tension-compression hydraulic jacks connected in series with load-measuring dynamometers as described below.

The adjustable cross beams of the frame accommodate the various length columns, transmitting the thrust from the moment producing moment arm fixture to the vertical frame members. The method of transfer of thrust in the lever arm is shown in Fig. 7. Fig. 8 shows the upper array of Column End Details.

In the description of the column end details follows first downward from the column through to the base of the machine and then up from the column to the testing machine head. All connections and fixtures have been designed to be extremely heavy to minimize slipping and elastic displacements. A general reference to figures 1 and 20 (which may be opened for reference during reading) will aid in understanding in following the various details.
The END FIXTURE (Figs. 4, 6, 10, 13) serves to transmit the bending moment to the ends of the column and to provide a foundation for the knife edge seats. It provides controlled angle change or moment at each end. It consists of a subway H-section to which is welded two channel sections as moment arms. The pin recess shown is on the same level as the knife edge.

KNIFE EDGES, WEDGE BLOCKS, AND CYLINDRICAL BEARINGS are best seen in Fig 5, though shown in many other photographs. The double system of knife edges was developed so that the end point of rotation and application of concentric load, the center of moment, point of lateral support, and end of the actual column section could be brought as close as possible to the same horizontal plane. The double knife-edge block and seat arrangement is shown diagrammatically in Fig. 215. Refering to Fig 5, the knife edge seat is secured to the web of the end fixture by bolts, being made more a less a permanent part of the end fixture. It could have been permanently welded into place. The cylindrical bearings provide a plane surface for the knife of the knife edge and that of the top of edge block, since the top of the frame base may not be plane.
Test Apparatus (Cont'd)

The Wedge blocks provide for adjustment of the column so that it may be lined up with the axis of the testing machine. In Fig. 5 will also be noted the device by which the blocks are positioned and held in place while the end fixture and column are being assembled.

TIE RODS are attached to the upper and lower end fixtures on the axis of rotation of the knife edges to carry any side thrust developed in the fixture by the column. The ends are anchored through a slot in the moment frame. A difference will be noted between the lower tie rods and the upper ones which have been fitted with flex-bars, since the upper end of the column will be pushed downward with respect to the frame under load. Compare photographs Fig. 4 with Figs. 9 and 10. Figs 5, 8, and 11 show the means of anchoring the ends of the tie rods. The arrangement in which the rods act in tension only. A typical system of forces is shown in the sketch.

The remaining important detail to describe is the UPPER DIRECT LOAD ASSEMBLY shown photographically in Figs. 18, 19. It accomplishes for the upper end of the column the same functions as the wedge blocks and cylindrical bearings on the bottom. The extra hangers and rings shown are required as a measure of safety in case sudden buckling occurs. The upper hanger is bolted directly to the testing machine head, but under load...
these hangers and those on the lower rollers appear in Fig. 18.

\[ \text{The upper head applies the}\]

load thru the upper bearing plate to the 4\" roller thence to the load distributing beam, the small rollers, and finally to the two knife edges. Since the column is pin-ended in both directions, it is necessary to install wedge blocks, \( W \), after an initial application of load to "fix" the upper end in the direction normal to the axis of rotation.

Erection and Alignment

The detailed procedure for erecting the column in the test frame, installing the frame in the universal testing machine and accomplishing final alignment is described in Appendix 2.

In broad outline the erection scheme followed is that shown in the sketch.

Wedge blocks, cylindrical bearings \( A \) and \( B \), end fixture assemblies \( 2 A \) and \( 2 B \), are placed on the frame, assembly (1). The column with assembly (3), upper end fixture attached is then lowered down thru the frame, held in position while the base plate is bolted to the lower fixture. Following alignment, unit (4) is positioned.

After a slight initial load, the jacks and dynamometers to be used in the test are installed when end moments are to be applied or measured.
Test Apparatus (Cont'd)

Proper alignment involves placing the column squarely in line with the testing machine axis and the moment-producing thrust in the plane of the column web, making certain that the axis of the knife edges is normal to this same plane.

The accuracy of the end fixture is the key to the matter. Accurate scribed lines were applied to it. Before erection the knife edge seats were bolted to the end fixtures (as previously described -- see Fig. 10) being carefully thus controlling the position of the E. B. blocks aligned with the scribe lines. The bolted base plates were welded to the column ends in a jig, the column being supported along its length and a careful welding sequence being followed.

Thus the axes of the column and those of the end fixtures were made to coincide. Initial twist in the column could not be corrected... but this slenderest of columns in which the twist would probably have been the worst showed no such twist.

With the double knife edge system, the accurate alignment is even more essential. In Fig. 23b is shown the Knife edge seats attached to end fixture. Accuracy of workmanship insures that distances "a" will be equal and the angle, ε, be 90°.

The lateral support devices turned out to be very helpful, since with them, as seen if Fig. 23b, the "2" axis of the end fixture and column could be turned to be aligned with that of the frame.

Reference to Fig. 23 serves to further demonstrate...
loaded columns as a stress problem by defining the failure load as that load
which produces the beginning of yielding in the fibers subject to maximum comp-
ression. Under the assumption that the modulus of elasticity remains constant
up to the yield point the deflection of the center line is given by the equation

\[ y = \left( \frac{\cos \alpha \left( \frac{L}{2} - x \right)}{\cos \alpha \frac{L}{2}} - 1 \right) e \]

\[ \alpha = \sqrt{\frac{P}{EI}} \]

where \( e \) is the eccentricity of the load \( P \). Denoting \( y_m \) as the deflection
at \( x = \frac{L}{2} \), the maximum fiber stress at mid-length of column is

\[ \sigma = \frac{P}{A} + \frac{P(y_m + e)}{\bar{I}} c \] (33)

where \( c \) is the distance of the extreme fibers from the centroidal axis. Upon
introducing

\[ y_m = \left( \frac{1}{\cos \alpha \frac{L}{2}} - 1 \right) e \]

into equation (33) and replacing \( \bar{I} \) by \( A \alpha \frac{L}{2} \) we arrive at the so-called secant
formula

\[ \sigma = \frac{P}{A} \left( 1 + \frac{ec}{\alpha} \sec \frac{L}{2} \sqrt{\frac{P}{EI}} \right) \] (34)

Upon replacing, in equation (34), \( \sigma \) by the given value \( \sigma_y \) of the
yield strength a critical value of \( \sigma_c = \frac{P_c}{A} \), the average stress determining
the carrying capacity \( P_c \) of the column, is defined. If \( n \) is the factor of safety,
\( \frac{P_c}{n} \) is the allowable column load.

The inter-relation between the critical load as given by equation (34)
and the actual buckling load is readily seen when we again consider the \( (\sigma_c, y_m) \)
curve as derived, for instance, by the method discussed in Section 8. In Fig. 24
\( OB \) is a straight line and point \( B \) corresponds to that value of \( \frac{P}{A} \) at which the
yield point is reached in the fibers of maximum stress of the bent column. There-
fore the ordinate \( \sigma_{cs} \) of point \( B \) indicates the critical value of \( \frac{P}{A} \) as given by
The problems of alignment and their solution. Four separate sets of axes (1, 2, and 3) must be aligned. Axes "2" and "3" of the frame were matched with those of the machine (actually it was only necessary that their intersections coincide.). When the column base had been bolted to the end fixture -- in which the "2" and "3" axes are made to coincide by accuracy of workmanship --, the "1" axis of column and testing machine were made to coincide. The screws of the testing machine head were used as a guide for measurements in both the "2" and "3" directions.

Alignment was completed. The only remaining alignment is that of the "2-3" axes of the column with those of the frame, so that the moment would be properly applied. With the aid of the lateral support threaded rods this was easily controlled at the moment arm edge of the frame.

The maximum error measured during alignment of the "1" column axis of the pilot test was observed to be 1/36" in both directions.

Hydraulic system: pumps, jacks, and tubing

As mentioned previously, the application of end moment was accomplished with tension-compression jacks in series with load measuring dynamometers. Fig. 20. Two pumps were connected to each jack...one for use in tension, the other for use in compression. In each case the idle pump is left with its relief valve open. The pumps were
In attempting to arrive at a tolerance for alignment, a study of ref. (2) indicates the following for tolerances allowed in structural practice, tabulated for various lengths:

<table>
<thead>
<tr>
<th>Cause of Eccentricity</th>
<th>8'</th>
<th>12'</th>
<th>16'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial crookedness</td>
<td>(\frac{3}{32})</td>
<td>(\frac{1}{8})</td>
<td>(\frac{3}{16})</td>
</tr>
<tr>
<td>End obliquity</td>
<td>(\frac{3}{16})</td>
<td>(\frac{1}{4})</td>
<td>(\frac{3}{8})</td>
</tr>
<tr>
<td>Out of line of ends</td>
<td>(\frac{1}{8})</td>
<td>(\frac{3}{16})</td>
<td>(\frac{1}{4})</td>
</tr>
</tbody>
</table>
Hydraulic system (cont'd)

procured commercially, the dynamometer having been designed and constructed at the Fritz Laboratory. Any hydraulic fluid is suitable. A total of 18 quarts should be sufficient for a complete system.

A reference to Figs. 3, 4, 6, 7, and 8 should be sufficient for an understanding of the system.

The dynamometers shown in the photograph consist of aluminum tubes with heavy ends threaded to receive the strain jack and connector connections. Four SR-4 gages, type AD-1, were installed with a strain indicator, furnishing the method for measuring the load. The dynamometer was calibrated in a Baldwin Southward hydraulic testing machine and the whole assembly (dynamometer, jacks, and pumps) assembled in the same machine as an overall proof test.

In order to use one strain indicator, a household type four-pole double-throw switch was used. Fig. 25. Repeated tests were conducted and now "witch effect" was observed. (Fig. 7)

The dial gages (Bourdon type) attached to high pressure pumps were not used except as a check against the dynamometer loads indicated by strain gages.

The arrangement of strain gages, Fig. 25, is one in which both the active and compensating gages are mounted on the aluminum tubing, the D gages being mounted at right angles to the A's to increase sensitivity. The use of two gages in each direction increases sensitivity to axial load and enables cancellation of any bending stresses.

Measurements

The action of the column under load was determined with the assistance of four techniques. Lateral deflections were measured with a taut wire and mirror arrangement. Strains were measured with SH-8 gages as a check against end moments and to determine the strain distribution as a function of distance from the ends. Angular rotations at each end were measured with a level bar. Finally, whitewash was used to detect mill-scale flaking and the progression of yield in the later stages of the test.

Lateral Deflections

The taut-wire and mirror deflection gage is shown in use in Fig. 15. Paper scales were glued to mirrors which were themselves attached to the test column with an asphaltic base adhesive which retains some plastic properties upon drying does not dry brittle. By lining up the wire with its mirror image a ready could be made on the scale, from which the lateral deflection of the column at each end could be computed.

Four wires were arranged around the section so that lateral deflections in both directions and torsional displacements could likewise be measured. The wire was anchored at the base of the column and strung over a pulley attached to the top. Weights were then hung at the free end of the wire. Figs. 16, 14.

A total of 28 gages, 4 at a section, spaced at 2'-0" intervals were installed. The scale length, (the depth of the column) is 4". Smaller scales could be used at the ends and on the flanges. Fig. 9, 12, 15, 13, 26.

** "Miracle Adhesive," manufactured by engine-divided

Scales procured in 18" lengths from Dietzgen Co.
strain Gages

13/16 " gage length

Forty SR-4 gages, type A-l, were installed arranged on 5 sections (8 per section). Fig. 27. The sections were:
two at the ends, the mid-section and the two quarter-points. Use may be made of the data to check end
moments (indicated extent of knife edge friction), from initial
readings indicate initial effective eccentricity, strain distrib-
ution changes for constant loading along length of the
beam column and changes in strain distribution across a section
under varying load.

As described in a preceding section, SR-4's were also
used on the two dynamometers. Figs. 24, 25.

Gages at the quarter point are seen in Fig. 15. See also
photographs Figs. 14, 13, 12, 6. In Fig. 3 may be seen the
leads from the column multiple selection box to which SR-4 gage were connected.

Level Bars

A level bar (Fig. 17) was used to indicate angle changes
at both ends of the test column, one level bar being used.
The arrangement was such as to facilitate the possibility to use one bar at both sections. Fig. 28.

A level bar support bracket designed to provide the measurement at
the actual end of the column and at the same time clear the end fixture is
shown in Fig. 28. (condition "b", loads 41-65)

Under some condition of test the level bar was used to hold the
end "fixed", the end being so considered when there was no
angle change.

Our photographs showing the level bar: Figs. 4, 6, 11, 14.
Whitewash

In order to observe the progression of yielding in the test column, hydrated lime was applied as a whitewash. The slightly above the yield point flaking of mill scale was then made apparent. Fig. 12. In Fig. 13 the column is shown prior to application of the lime.
TESTING PROCEDURE

Program of Tests

The table of column tests, proposed to be studied, will be found in Table I, indicating four conditions of test:

(a) Equal moments on the ends
(b) One end fixed - moment on other end.
(c) Equal and opposite moments on the ends
(d) Moment on one end -- pin ended on other end.

Tests on Column No. 1 were of a pilot nature to study the apparatus. Thus an additional condition of test was involved: Axial load alone -- no end moments or fixity.

The "d" and "b" conditions were also applied to the column. See the Test Program, Table II.

Notes on Table II:

1) For loads 32 thru 60 the axial load as indicated by the balance bar was corrected by an amount equal to the moment-producing thrust. From the mechanism of the apparatus it is seen that this thrust is applied to the column but is not "measured" by the machine. Fig 31.

2) Commencing with load 41, the condition (b) requires that the bottom end be held "fixed". The term "measure" in the last column indicates the operation performed -- the thrust was read after the load condition had been reached, the level bar having been used as a control device to bring the column base to the position where 

3) Loads 60 thru 65 were a series under condition (b) in which the moment was increased until plasticity was assured. Actually, the maximum was between 5.0 and 6.0 kips thrust so that all readings after load 60 were equilibrium conditions.
Testing Procedure (Cont'd)

Testing

The order of erection of the test apparatus, alignment, and assembly of apparatus in testing machine has previously been described.

Condition (e): Since the test column is in the range where the critical buckling load is given by the Euler formula, this was used to estimate the buckling load. Fig. 29. Should l/r have been 100 or less the Tangent Modulus load would have been used another estimating basis. During the early stages of the test an experimental estimate was obtained by "Southwell's method". The calculated load was 86 kips, the plotted value, 80 kips. Column length was measured to be the distance between.

As is seen from table II, increments of load were then chosen to give a reasonable number of points (actually 12).

In this series of tests, it was not necessary to make any adjustments of load while deflection, strain, and level bar readings were being taken. Complete readings were not taken at every load. Only at nos. 8, 10, 13, 22, 31, and on occasions, additional Center line readings taken at other loads.

Condition (d): (pin-end at bottom, moment applied at top, constant axial load maintained on column). The actual values for moment and load were selected as follows:

(a) The constant axial load was desired to be somewhat greater than the buckling load. 40 kips was selected. Fig. 30.

(b) The moment was then calculated which would cause a

* CE 212.34, and 204.11(6)
* also Timoshenko, "Theory of Elastic Stability" p. 177
Testing Procedure (Cont'd)

maximum stress equal to 24 kips. Several increments were then selected to get a variation. Direction of deflection to be same as in condition "c" series.

As previously mentioned, the axial load weighed by the testing machine -- the "apparent axial load" -- is not actually in which moment applied at the ends. The moment producing thrust was so directed that it would cause the column to deflect in the same direction as in the condition "c" test.

The axial load on the column under a condition A correction must be made equal to the amount of thrust applied to the column, namely, force at the end of the lever arm. Thus in Table I, load must be reduced by the amount for loads of 16 as noted previously, in the same.

The application of end moments causes the column to bend, slightly shortening it. Thus, since the upper head is not moved in the process, the load indicated by the machine falls off considerably. It was thus found convenient to use the following scheme for loading: At any particular load number: Load condition:

1. Apply the upper moment.
2. Adjust the axial load.
3. Repeat (1) and (2) as often as necessary.

Condition (b): (Constant axial load, maintained on column. Moment applied at top, bottom held "fixed").

The same considerations as for condition "d" governed selection of axial load and moment values for the various loads. Also, equilibrium for a given condition was reached similarly by adjusting the moment, then the axial load, the change of moment having a more pronounced effect on the "apparent axial load" than vice versa.

With the procedures described above, strains, and levels could all be read, the load being
with no change maintained exactly in all but a very few cases.

Prior to testing or welding the end plates, the specimens were accurately measured, determining I sections furnished by which had been cut and A sections were obtained from the fabricator from representative sections of the rolling. Test coupons were cut from these for determining tensile and compressive properties.